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Ecological footprint, air quality and research and development: The role of agriculture and international trade

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ABSTRACT

With economic development, there is a growing demand for food and manufactured products that put direct pressure on air and soil quality, limiting sustainable development. The Sustainable Development Goals (SDGs) formulated by the United Nations establish 17 objectives that guide public policies within countries. The achievement of the SDG6, SDG7, SDG11, SDG12, SDG14 and SDG15 goals, which are totally or partially related to environmental quality, depends mainly on the ability to generate new processes and industrial products friendly to the environment. Innovation arising from research and development (R&D) can be decisive in mitigating the adverse effects of climate change. The objective of this research is to examine the effect of R&D on environmental degradation as measured by ecological footprint and air quality, including the role of agriculture and trade. The theoretical framework that supports the methodological strategy is the environmental Kuznets curve. To capture the role of geography, we used the World Bank classification of *regions*. Using second-generation cointegration techniques and panel data for 77 countries during 1996–2016, we found a cointegration relationship between R&D and environmental degradation, agriculture, and trade. The results of the FMOLS model suggest a heterogeneous impact of research and development on environmental degradation. Likewise, our results show that there is bidirectional causality between air quality R&D and between the ecological footprint and R&D. In East Asia and the Pacific region, there is a two-way causality between air quality and R&D, and a one-way causal relationship ranging from the ecological footprint to R&D. In the Middle East and North Africa, we find a one-way causal relationship ranging from the ecological footprint to R&D. Finally, we find that there is one-way causality from R&D to ecological footprint in North America, Europe, and Central Asia. The investigation ends with a call for policymakers to use R&D, agriculture, and trade as mechanisms to mitigate air and soil degradation.

1. Introduction

The Sustainable Development Goals (SDG) formulated by the United Nations Organization in 2015, constitute a guide for the public policies of the countries that are oriented to the search for mechanisms that mitigate environmental challenges in a highly globalized context. However, the achievement of SDGs implies strict and unrealistic preconditions because policymakers seek to maximize income to maintain or achieve economic development. This reality contrasts with the need to reduce the large-scale environmental degradation facing the environment in recent years. In the particular scope of SDG6, SDG7, SDG11, SDG12, SDG14, and SDG15; which have a close relationship with environmental quality (clean water and sanitation, affordable and non-polluting energy, sustainable cities, responsible production and consumption, underwater life, and life of terrestrial ecosystems), depend on the realization of significant changes in current production processes based on the maximization of consumption. The innovation associated with research and development can contribute significantly to the achievement of products and industrial processes that

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are more environmentally friendly, without limiting the search for economic development. The challenges for those responsible for economic policy that come from environmental degradation increase with economic growth (Ponce and Alvarado, 2019). Efforts to measure, monitor and reduce environmental burdens and ensure sustainability represent a severe challenge for researchers, non-governmental organizations and public policymakers (Čuček et al., 2012; Viglia et al., 2018; Schmidt-Traub et al., 2017). In recent literature, several investigations have emphasized specific aspects of environmental SDGs. For example, regarding SDG6, Luo et al. (2020) point out that adequate water management is a necessary condition to achieve sustainable development in contexts of growing urban population with limited water resources. SDG7 seeks to promote access to affordable, reliable, and sustainable energy for society. However, there are some risks to accessing sustainable energy. Bhattacharyya (2012) highlights that programs that promote access to energy are not sustainable and may have a limited contribution to development. Likewise, sustainable development implies that cities do not face a trade-off between economic or social development and environmental pollution (Martínez-Bravo et al., 2019). Sustainable development of cities is emphasized in SDG7, which implies that economic, social, and ecological indicators converge in the same direction. The sustainability of cities means that environmental indicators improve with economic and social aspects (Laslett and Urmee, 2020). To achieve sustainable production and consumption (SDG12) involve significant changes in the current patterns that predominate in these aspects. Hence, sustainable consumption and production are essential requirements for sustainable development (Wang et al., 2019a,b). Ahmad and Khattak (2020) show that per capita consumption is one of the determinants of environmental pollution in the short and short term. In parallel, the literature has neglected the sustainability of the oceans, seas, and marine resources promoted in SDG14. Virto (2018) points out that the information on the sustainability of the oceans is limited, hence improving the available indicators to facilitate decision-making. Finally, terrestrial ecosystems require more considerable attention in countries with high biodiversity, where there are severe risks of losing species, vegetation cover, and the natural wealth associated with forests (SDG15). The importance of ecosystems and, in particular, forests in the global carbon process motivates their urgent conservation in the long term (Köhl et al., 2020). The government, companies, and researchers must focus their efforts on activities facilitating the achievement of the environmental SDGs. In this context, the role of R&D processes plays a crucial role. In parallel, international trade has increased significantly in recent years (World Bank, 2020). Several empirical researches have shown that trade is one of the obstacles to limit air and soil pollution (Al-Mulali and Ozturk, 2015). Similarly, intensive agriculture requires large amounts of land for crops, which may be the result of the expansion of the agricultural frontier. This fact causes agriculture to increase environmental degradation; in particular it has a negative effect on the ecological footprint (Olanipekun et al., 2019). (see Figs. 1 and 2)

When more countries reach a high threshold of development, one of the immediate consequences is that people consume more products and services, causing air and soil pollution to increase. The demand for products and services reaches consumers through international trade, facilitating the flow of products around the world at affordable costs for the consumers. Therefore, one of the sources of increasing environmental degradation is the trade. Likewise, the increase in population and urbanization increases the demand for food, putting pressure on the soil's ability to produce food without damaging its fertility. The growing world demand for food has caused the agricultural frontier to expand, diminishing the soil's ability to regenerate and offer future generations' sustainability. Finally, current environmental degradation levels motivate the search for new pollution transition mechanisms and channels aimed at proposing policies that mitigate the adverse effects of climate change. Various authors have shown that industrialization generates a significant impact on environmental degradation, with direct implications for quality of life (Awan et al., 2018; Zhou et al., 2018). The economic development associated with industrialization increases the demand for new infrastructure, reinforces consumption, and encourages the expansion of the agricultural frontier, putting water and soil conservation at risk and increasing air pollution. This fact jeopardizes the natural regeneration capacity of the environment (Lipovina-Božović et al., 2019). In this context, empirical evidence shows that technology can play an essential role in mitigating the harmful impacts of industrialization on the environment and achieving sustainable development goals (Ahmad et al., 2020a,b).

Moreover, the economic activity generates environmental pollution in many aspects. However, soil and air pollution capture a relevant part of environmental degradation. One of the most used measures of air quality is carbon dioxide emissions, which are primarily responsible for global warming (Alvarado et al., 2019). According to the World Bank (2020), per capita carbon dioxide emissions increased widely between 1960 and 2014. The stylized facts show that the emission of pollutant gases from a country is proportional to the level of production (World Bank, 2020; Alvarado et al., 2018). The Nuclear Forum (2015) notes that total emissions in 2013 registered a cumulative increase of 57.9% compared to 1990. China, United States, India, Russia, and Japan form the quintet of most polluting countries. The 5 countries emit 60 percent of greenhouse gas emissions. Inekwe et al. (2020) highlight the prominent role of China and the US in overall CO2 emissions. In parallel, the ecological footprint has undergone significant changes as a result of agricultural activities. According to the Global Ecological Footprint Institute, in 2018, the economies had an ecological footprint that exceeds biocapacity by more than 50 percent. This fact implies that the environment requires 1.5 years to regenerate what the world consumes in one year. This overshoot depletes the natural capital on which human life depends. The same report indicates that if current consumption patterns are maintained, by 2020, the demand for ecosystems will exceed what nature can regenerate by approximately 75 percent. The interest in environmental problems is reflected in the formalization of the externalities generated by economic activity.

Several theoretical approaches explain the impact of economic activities on the environment. One of the most widely used theories in empirical evidence is the Environmental Kuznets Curve (EKC). The EKC poses a possible solution to long-term environmental pollution with the economic and social development of countries (Grossman and Krueger, 1995; Dietz and Rosa, 1997). The initial evidence of these authors is that the countries' economic development would lead to reaching a maximum point of polluting emissions, but that later the contamination would decrease. If per capita consumption continues to rise, and more and more people join in overconsumption as more countries reach development, environmental pollution will continue to increase. However, achieving a high level of income does not guarantee that all industrial processes are friendly to the environment, where new forms of environmental degradation arise. In this context, it is logical to think that new innovative products and processes may occur as a result of research and development, which can contribute significantly to mitigate global warming. Specifically, R&D can become the engine of sustainable economic growth (Krekel et al., 2018) as a process that involves the majority of economic agents (Fernández et al., 2018). In this context, this document examines the effect of spending on R&D, GVA for agriculture,

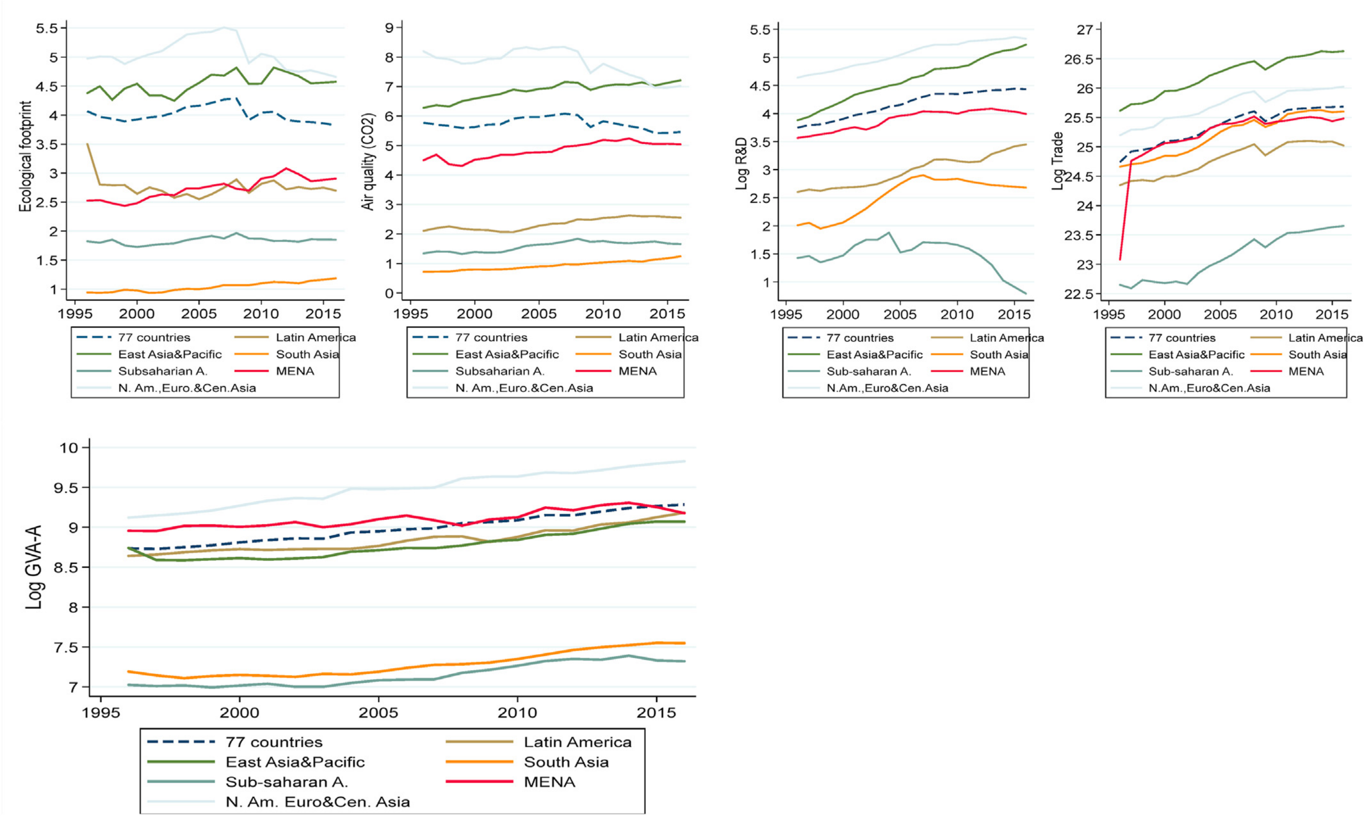

Fig. 1. Evolution of variables by region.

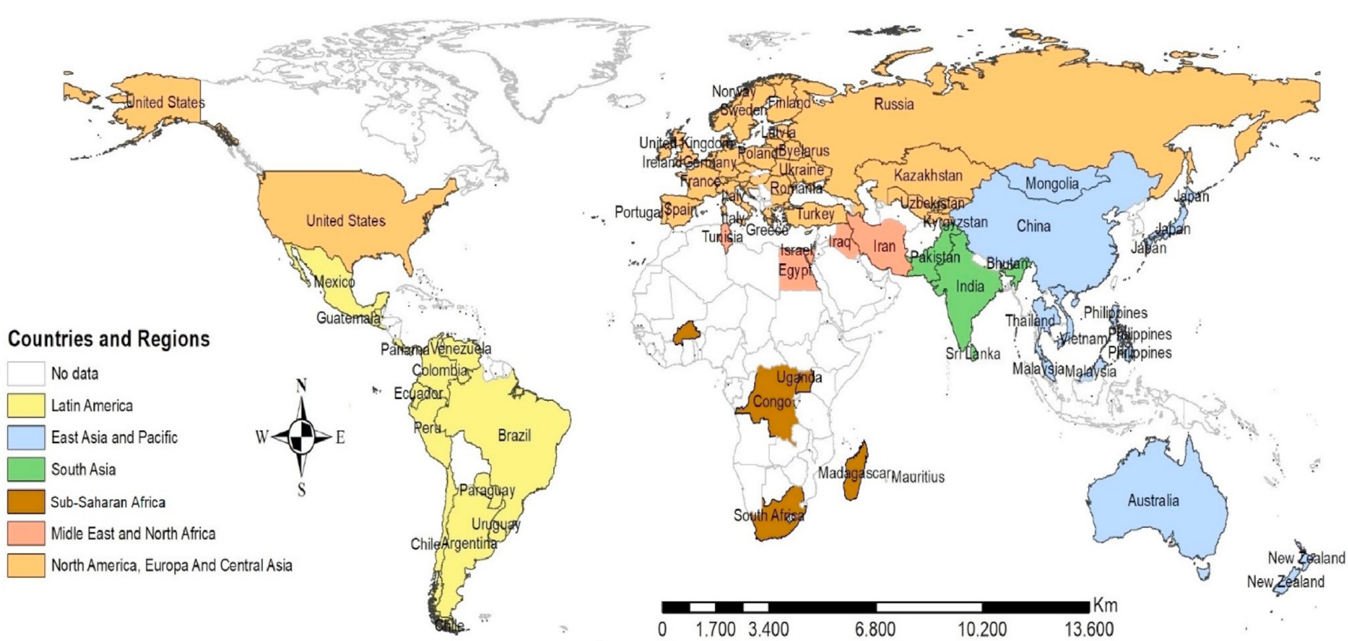

Fig. 2. Research coverage and classification of countries into regions (World Bank, 2020).

and trade on environmental degradation as measured by ecological footprint and air quality. We used a balanced data panel from 77 countries classified in six regions during 1996–2016: East Asia and the Pacific; North America and Europe; Latin America and the Caribbean; the Middle East and North Africa; South Asia and Sub-Saharan Africa. This fact allows capturing geographical, cultural, and economic heterogeneity; and establish policy implications based on the results of each *region*.

To achieve the research objective, we proposed a set of econometric panel data models based on the EKC and similar investigations. We chose the second-generation panel data tests because of the bias caused by omitting cross-sections dependence. The Pesaran test (2004, 2015) suggests that there is enough evidence to reject the hypothesis of cross-sections dependence. Our results are divided into three parts. First, the test of homogeneity in the slope of Pesaran and Yamagata (2008) show that there is homogeneity in the slope between the panels. Second, the Westerlund (2005, 2007) cointegration model indicates that there is a long-term relationship between the series. Third, using the causality test of Dumitrescu and Hulin (2012), we find the existence of a bidirectional causal relationship between air quality and R&D, and between the ecological footprint and R&D in 77 countries. There is also a unidirectional causal relationship that ranges from R&D to the ecological footprint in North America and Europe. Our results contribute to the debate that relates innovation to the search for environmental sustainability through the achievement of the SDGs. The results obtained support the hypothesis that R&D is a mechanism to mitigate air and soil pollution. Consequently, R&D is a mechanism to mitigate air and soil pollution. Our analysis contributes to the debate on environmental degradation with new conclusions and policy implications. We include in the debate the role of R&D, agriculture, and trade in determining air and soil quality using new available databases. In our understanding, there are no identical investigations that use the same variables and methodology that we apply in this article. Second, we use a solid approach through the use of methods that allow us to determine the existence of a long-term relationship among the series and propose specific public policies for each region. Third, we implicitly incorporate geographic heterogeneity between countries, avoiding using the traditional classification of countries' development levels. It is well known that geography implies significant differences among the countries, especially in economic agents' behavior and the performance of economies. Fourth, our research is not limited to carbon dioxide emissions as the only form of environmental degradation. This fact is consistent with the fact that productive activities also harm the ecological footprint.

After the introduction, the second section contains a review of the previous theoretical and empirical literature. The third section describes the data and formalizes the econometric strategy to verify the hypothesis. The fourth section presents the results of the investigation and conducts a discussion with previous empirical theory and evidence. The fifth section contains the conclusions and implications of public policy.

2. Review of previous literature

The empirical evidence and institutional data show that environmental degradation is one of the most pressing problems facing society (Rosenfeld et al., 2014; Jepsen and de Bruyn, 2019; Xu et al., 2019). Pollution has become widespread and may be visible in the oceans, air, and soil. The environmental pollution is observable and quantifiable, especially in health and agriculture. However, pollution is more natural to assess in the air and soil, but it is difficult to measure the pollution of the oceans and attribute them to a particular country. Virto (2018) made a first attempt to quantify sustainable development goals in aspects related to the oceans. However, the difficulty lies in the availability of up-to-date and reliable data, both for academics and policymakers. Data on air quality and ecological footprint show that pollution has reached a worrying level that requires solutions that are difficult to apply (Al-Mulali et al., 2015; Olanipekun et al., 2019; Pacheco et al., 2018). Following the logic behind the EKC, the arguments that support this hypothesis differ between developed and developing countries. In the first group of countries, the arguments are based on the fact that in high-income countries, there is greater environmental awareness and that the regulation of production processes is stricter than in developing countries. However, practice shows that these countries need to maintain the levels of product per capita achieved or even increase it (Scherer et al., 2018). Consumption patterns and high urban primacy limit the decrease in pollutant gas emissions caused by economic activity and energy consumption from polluting sources (Banerjee and Gupta, 2017; Bampatsou and Halkos, 2019; Ponce and Alvarado, 2019). While, in developing countries, environmental regulation is more permissive, the exploitation of natural resources is excessive and polluting, and the increase in urbanization leads to higher pollution of the environment permanently (Alvarado and Toledo, 2017; Shahbaz and Sinha, 2019). Although the ecological footprint and carbon dioxide emissions are not perfect measures of soil and air degradation (Galli et al., 2016), they allow quantifying and standardizing the current degradation facing the environment, using indicators comparable over time and between countries. Several researchers believe that the ecological footprint is a useful aggregate measure because it accurately measures environmental degradation that has direct implications on people's quality of life. Consequently, policies on land use, carbon taxes, and clean energy subsidies can contribute to a cleaner and healthier environment (Solarin and Bello, 2018).

It is well known that, in the stages of high economic growth, there is a more significant environmental deterioration due to the use of intensive methods in agriculture, due to the increase in industrial activity and the growing demand for consumer goods, which implies an increase in the level and toxicity of pollutant gas emissions. In general, air quality is directly related to the use and type of energy source, manufacturing and urbanization rate (Iwata et al., 2010; Kang et al., 2016; Alvarado et al., 2018). Also, since the late 1990s, globalization has been characterized by moving production plants to places where production costs are low and environmental regulation is more permissive. This reality has caused manufacturing, as the primary source of pollution, to be loose among countries. Cherniwchan points out that manufacturing companies have few incentives to adopt technologies and processes that reduce pollutant gas emissions, mainly when there is no regulatory framework that forces companies to reduce pollution. In general, there is a broad consensus that the adverse effects of global warming are increasingly visible and quantifiable and that a significant part of the sources of pollution comes from the internalization of production (Alvarado et al., 2018; Cohen et al., 2018; Hajilary et al., 2018). Environmental degradation has become a problem for health and quality of life, which attracts the attention of organizations and authorities, particularly in countries with high levels of pollution (Liu et al., 2017). The concern for achieving more sustainable development has been systematized in the SDGs raised by the UN in 2015. The SDGs not only seek to resolve air quality as an environmental policy objective but also raises the need to achieve water clean and sanitation, affordable and non-polluting energy, sustainable cities, responsible production and consumption, underwater life, and life of terrestrial ecosystems. These aspects are contained in SDG6, SDG7, SDG11, SDG12, SDG14, and SDG15. Although the SDGs are not without criticism, these objectives reflect the main objectives that guide the search for more sustainable economic development (Scherer et al., 2018; Bello et al., 2018). The sustained increase in soil and air degradation represents a severe threat to the achievement of the SDGs. The initial conditions of several countries lead us to believe that several SDGs will not be fully achieved in 2030, in part due to the possible dilemma between social and environmental objectives (Schmidt-Traub et al., 2017). It is well known that the achievement of social objectives implies higher levels of income, which contrasts with the environmental SDGs, in particular between SDG1 and SDG10 versus SDG6, SDG13, and SDG15 (Scherer et al., 2018). Hence the importance of the search for a harmonized balance in achieving the SDGs related to environmental quality. Moghaddam, Nazari & Soufizadeh (2018) point out that to achieve sustainable development, it is necessary to incorporate a set of ecological, social, and economic indicators in the planning of public policies.

In terms of regulation, public policy can direct the behavior of people and companies related to the protection of the environment through trade policies. Empirical evidence shows that international trade has an allocating role of resources and environmental externalities in a highly globalized world (Jiang et al., 2019; Kolcava et al., 2019). The volume of the world trade flow is, in itself, an indicator of the role of trade in modern economies. In this sense, the inclusion of international trade as a variable that affects environmental pollution, either in emissions of pollutant gases or in the ecological footprint is reasonable (Koengkan, 2018; Essandoh et al., 2020). On the other hand, despite efforts to get the most polluting countries to carry out more concrete actions to curb climate change, the facts indicate that it is difficult to reach binding agreements that combine government policies, business practices, the influence of non-organizations, government and knowledge generated in the academy (Silvestre and Ţîrcă, 2019). The behavior of some political leaders in some developed countries leads us to believe that they do not consider the planet to be finite and that environmental degradation can be an irreversible long-term phenomenon (Brausmann and Bretschger, 2018). In this unfavorable scenario for nature, the literature related to environmental quality and technological progress shows that innovation can play an essential role in achieving higher environmental quality (Sinha et al., 2020). Similarly, Khan et al. (2019b) demonstrate that research and development and financial development also improve carbon emissions. The innovation processes associated with R&D spending can generate biodegradable products that minimally pollute the soil or emit greenhouse gases in a reduced way. In this sense, one of the most important mechanisms to promote sustainable economic development and achieve structural change is technological innovation. Amir (1995) points out that technological progress allows society to experience sustainable development indefinitely. In this sense, R&D can become the engine of economic growth with equity, but that pollutes less (Fernández et al., 2018). In recent years, there is a broad consensus that technological change is the most realistic mechanism to achieve sustainable economic development (Krekel et al., 2018; Lee and Min, 2015). In the same direction, Wiebe (2018) shows that a change in favor of the environment in technology causes emissions caused by the manufacturing industry to decrease over time. For example, today's cars pollute less than those made several decades ago.

The efficiency of technology to mitigate climate change and global warming requires that the solution strategies associated with technological progress be reinforced with more restrictive environmental regulation policies (Venselaar, 1995; Bosetti et al., 2011) and a more effective environmental education (Hale, 1995), so the expansion of per capita income does not translate into more significant environmental pollution (Aydin et al., 2019). Likewise, technological progress can contribute to the reduction of fossil fuel energy consumption (Gu and Wang, 2018). In this context, technological progress has been successful in the identification and generation of energy from non-polluting sources, such as solar, wind, hydroelectric, and nuclear energy (Bello et al., 2018; Zhang et al., 2017). In general, there are sufficient contributions from recent empirical work that support the hypothesis that R&D spending can be a mechanism to mitigate the problem of environmental degradation and the search for sustainable economic growth, consistent with the SDGs.

3. Data and methodology

3.1. Statistical sources

Our research uses databases from official statistical institutions. Specifically, the annual series used were extracted from three data sources. The two dependent variables capture a significant part of the problem of air and soil pollution. Both forms of environmental pollution are the direct result of the non-sustainable productive activity aimed at maximizing income. Air quality comes from the Emissions Database for Global Atmospheric Research (EDGAR, 2019). The Ecological Footprint comes from the Global Footprint Network (2019). Air quality is quantified by per capita emissions in metric tons of carbon dioxide and the ecological footprint in hectares per capita, research and development were obtained from the United Nations Educational, Scientific and Cultural Organization-UNESCO science and technology database. Meanwhile, the added value of agriculture and trade capture the part of production that is related to agriculture and livestock production and the internalization of output. We hope that these economic activities have an immediate effect on environmental degradation. In focus of our research, ecological footprint is a measure of demand from biologically productive surfaces by the people of an economy. Our research has coverage for 77 countries ($n = 1, \ldots, 77$) from 1996 to 2016 ($t = 1, \ldots, 21$). The sample of countries was selected based on data availability. In the literature on environmental economics, some authors have used similar variables in recent empirical research about the role of technological innovation (Sinha et al., 2020), the role of agriculture (Olanipekun et al., 2019; Kolcava et al., 2019) and international trade (Jiang et al., 2019). Table 1 characterizes the variables, an extended description and the measurement of the data.

In parallel, several authors have identified and verified that geography plays a vital role in economic development processes (Gallup et al., 1999; Bosker and Garretsen, 2012). Recently, evidence suggests that consumption patterns associated with geography can directly affect environmental degradation (Bednář and Šarapatka, 2018; Zhou et al., 2019).

In order to capture the role of geographical factors on environmental degradation, the countries analyzed were classified by *regions* following the grouping carried out by the World Bank (2020). The classification of countries in *regions* is as follows: East Asia and Pacific, North America, Europe and Central Asia, Latin America and the Caribbean; Middle East and North Africa, South Asia, and Sub-Saharan Africa. The availability of data for all the variables during the period analyzed determined the selection of countries within the regions. Table 2 shows the descriptive statistics and the correlation matrix of the variables used in the econometric estimates. The high positive and statistically significant correlation between the two environmental degradation measures suggests that air and soil pollution are reinforced over time.

Several arguments support the hypothesis that the effect of R&D spending is having a different impact on environmental degradation according to geography. First, the existence of spatial contagion of ecological pollution is evident (Cheng, 2016), particularly in countries with vigorous industrial activity. Second, geography strongly influences the determination of productive activities (Bednář and Šarapatka, 2018). Third, regional integration processes can reinforce the productive similarity between countries with geographical proximity. These arguments support the imperative need to include the role of geography in environmental

Table 1
Description of variables and data sources.

Variable	Symbol	Description	Measure	Data source
Ecological footprint	EF	EF is a measure of demand (consumption) from biologically productive surfaces by the people of an economy.	Hectares per capita	Global Footprint Network database.
Air quality	AQ	CO2 emissions capture the amount of greenhouse gases in the air.	Metric tons per capita	EDGAR Database.
Research and development	R&D	R&D measures the total expenditure on research and development for each country.	US Dollar per capita	UNESCO Institute for Statistic (UIS).
Agriculture, forestry, and fishing, value added	GVA-A	The Gross Value Added (GVA) is a measure of the intensity of the agricultural sector in the economy, weighted by the number of workers.	US Dollar per worker	World Bank.
Trade	TR	T is a measure of the internationalization of production processes.	US Dollar per capita	World Bank.

Table 2
Descriptive statistics and correlation matrix.

	EF	AQ	R&D	GVA-A	TR
Mean	4.010	5.739	4.162	8.985	25.35
Std. Dev. (Overall)	2.399	4.583	1.996	1.457	1.713
Std. Dev. (Between)	2.352	4.527	1.971	1.441	1.676
Std. Dev. (Within)	0.542	0.875	0.386	0.266	0.396
Min.	0.74	0.043	−2.55	5.568	16.45
Max.	17.02	26.30	7.572	14.10	29.21
N	1617	1617	1617	1617	1617
Countries	77	77	77	77	77
Time	21	21	21	21	21
EF	1.000				
	–				
AQ	0.8695*	1.000			
	(0.001)	–			
R&D	0.7571*	0.7419*	1.000		
	(0.002)	(0.001)	–		
GVA-A	0.7039*	0.6585*	0.8354*	1.000	
	(0.001)	(0.002)	(0.000)	–	
TR	0.4512*	0.5504*	0.7374*	0.5803*	1.000
	(0.004)	(0.002)	(0.000)	(0.001)	–

The p-values are reported in parentheses, and * denotes the level of significance of 1%.

degradation and to obtain specific conclusions for each region. Besides, political implications may be more realistic and applicable because countries interact within areas in commercial, property, investment, and institutional agreements.

3.2. Strategy econometric

Based on the theoretical framework of the environmental Kuznets curve widely discussed by Grossman and Krueger (1995), we propose a set of econometric techniques. These methods are developed in this section. The choice of econometric strategy is associated with the objective of the research and is based on two aspects. First, the stages of the methodology are planned so that the results lead to the achievement of the research objective. Second, we follow the econometric strategy applied in similar research within the environmental pollution literature (Ahmad et al., 2019; Altıntaş and Kassouri, 2020; Khattak et al., 2020). The objective of this research is to examine the effect of research and development, GVA agriculture and trade on environmental degradation measured by air quality and ecological footprint. In order to achieve this goal, we propose a set of econometric panel data techniques. First, we use the cross-sections dependence test of Pesaran (2004, 2015) in order to verify whether changes in a variable in one country have an impact on the values of that variable in the rest of the countries. The two cross-sections' dependence leads to a better understanding of the behavior of the variables in the panels. Equation (1) formalized this test.

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij}\right) \quad (1)$$

Second, the results obtained in the estimation of Equation (1) suggest that there is enough evidence in favor of the hypothesis of independence in the cross-sections in the five-panel series. This result determines the use of the unit root estimate and the second-generation panel data cointegration tests. Specifically, we use the cross-sectional dependence tests proposed by Pesaran (2004) and weak cross-sectional dependence formalized by Pesaran (2015). The first test formulates the null hypothesis that there is the independence of the cross-section. In contrast, the second test measures the strength of the cross-dependence of the errors, and the null hypothesis is that the error terms depend weakly on the cross-section. Although the data panel used in our investigation is relatively large, the use of two different unit root tests seeks to provide consistency in the results given the possible limitations that may arise from the size of T and N, which are not large enough (Chang, 2015). According to the theoretical and empirical literature on panel data econometrics, most of the panels contain dependence on the cross-sections (Ponce and Alvarado, 2019). This issue leads to the need to estimate unit root tests that implicitly include non-independence in cross-sections. Two of the most commonly used tests in recent empirical research are tests formalized by Pesaran (2004) and Breitung (2000). Where cross-sectional dependence is present, Equation (2a) formalizes the unit root test for the first test, while Equation (2b) formalizes the unit root test for the second test.

$$\Delta y_{it} = \alpha_i + \varphi_i y_{i\,t-1} + \beta_i \bar{y}_{t-1} + \sum_{j=0}^{k}\theta_{ij}\Delta\bar{y}_{it-j} + \sum_{j=0}^{k}\gamma_{ij}y_{it-1} + \varepsilon_{it} \quad (2a)$$

$$\Delta y_{it} = \alpha_{i0} + \sum_{j=1}^{k}\alpha_{ij}\Delta y_{it-j} + u_{it} \quad (2b)$$

Where, $\bar{y}_t$ is the cross-sectional mean of time t, k is the optimal lag length determined by the information criteria of Akaike (1974), ε_{it} is the error term. In order to validate the existence of an equilibrium relationship between the environmental degradation, research and development, GVA agriculture, and trade, in the third stage we using the Westerlund (2005). In this test, the null hypothesis is of non-cointegration versus the alternative cointegration hypothesis. Two arguments support the use of a cointegration model. First, the cointegration test is a technique that allows verifying the long-term balance between the series. Second, we draw on recent empirical research that analyzes the sources of environmental pollution (Ahmad et al., 2019). Equation (3) formalizes the cointegration model:

$$y_{it} = d_t'\widehat{\delta}_i + x_{it}'\widehat{\beta}_i + \widehat{e}_{it}; \quad \textit{where } \widehat{e}_{it} = \rho_i \widehat{e}_{it-1} + v_{it} \tag{3}$$

Where y_{it} is the environmental degradation measured by air quality and ecological footprint, while x_{it} is a matrix that contains the variables research and development, gross value added of agriculture, and trade. In Equation (3), $i = 1, \ldots, N$ represents the panel country, $t = 1, \ldots, T$ refers to time, d_t is a vector of the deterministic component that includes a constant component and a part that captures the time trend. Following Westerlund (2005), the vector d_t can take two options: $d_t = 1$ and $d_t = (1, t).'$ In this context, if there is enough evidence to reject the null hypothesis of non-cointegration between y_{it} and x_{it}, the error term $\widehat{e}_{it}$ is stationary. In practice, in this research, we estimate two independent models. In the first model, the dependent variable is air quality and the independent one is research and development, GVA of the agriculture, and trade, while in the second model the independent variable is maintained and the dependent variable is the ecological footprint. The use of two different measures of environmental degradation offers a broader view of the environmental pollution reflected in the soil and air caused by economic activity. In parallel, Westerlund (2007) offers a methodological framework to estimate long-term equilibrium. In the recent empirical literature of panel data, they use this technique to verify the null hypothesis of non-cointegration (Shahbaz and Sinha, 2019; Sharif et al., 2019; Baloch and Wang, 2019; and others). Equation (4) formalizes the Westerlund second-generation test (2007) as follows:

$$\Delta y_{it} = \delta_t' d_t + \alpha_i (y_{it-1} - \phi_i' x_{it-1}) + \sum_{j=1}^{pi} \alpha_{ij} \Delta y_{it-j} + \sum_{j=-qi}^{pi} \gamma_{ij} \Delta x_{it-1} + \varepsilon_{it} \tag{4}$$

Finally, in the last stage, we analyze the causal relationships between the variables and estimate the existence and direction of causality for Granger-type panel data formalized by Dumitrescu and Hurlin (2012). This test allows us to consider the heterogeneity of the causal relationships and the heterogeneity of the regression model used to prove the causality among the panel series. In order to examine the causal relationships between the variables of interest, we applied the causality test of the Dumitrescu & Hurlin panel (2012). This method allows to show the existence of causality between the variables and the direction of the relationship. The Dumitrescu & Hurlin causality model has some advantages since it does not require that N be greater size than T, and the results are consistent in the presence of cross-sections dependence on the variables and heterogeneity in the error term. Equation (5) formalizes the panel data causality test proposed by Dumitrescu and Hurlin (2012) as follows:

$$\Delta y_{it} = \alpha_i + \sum_{k=1}^{K} \gamma_i^{(k)} \Delta y_{it-k} + \sum_{k=1}^{K} \beta_i^{(k)} \Delta x_{it-k} + \varepsilon_{it} \tag{5}$$

The null hypothesis that verifies this model is that there is no Granger-type causality between the pairs of variables. In Equation (5), α_i represents the constant vector, $\gamma_i^{(k)}$ is the lag parameter, $\beta_i^{(k)}$ is the slope of the coefficient, and K denotes the lag length. The results of the estimation of the four stages are reported and discussed in the next section.

4. Results and discussion

This section shows the results found after applying the econometric strategy proposed in the previous section. First, the dependency test in the cross-sections of Pesaran (2004) and Pesaran (2015) indicates that the five-panel series has a cross-sections dependence. The results of transversal dependence are reported in Table 3, which offers empirical support to vehemently reject the null hypothesis of transversal independence for the five variables under analysis. The existence of cross-correlation in the data panel variables makes it necessary to use unit root tests and the application of second-generation cointegration tests. The existence of cross-sections dependence can support the design of public policies in favor of the environment between countries with trade, investment agreements, and any territorial integration policy.

The strength of the results with panel data from temporal and transversal information depends on the homogeneity of the panels (Blomquist and Westerlund, 2013). It cannot be assumed that the slope coefficients in the proposed model are homogeneous among the individual units. Consequently, we estimate the homogeneity test of the slope of Pesaran and Yamagata (2008). The results presented in Table 4 show that there is sufficient evidence to reject the null hypothesis of homogeneity in the panel slope coefficients. This result implies the existence of heterogeneity for all five variables included in the investigation. Therefore, we must use heterogeneous panel methods in which the parameters differ between the individual cross-sections within the panels. The pending homogeneity test has recently been used in the empirical evidence of environmental degradation (Mensah et al., 2019; Altıntaş and Kassouri, 2020), allowing to verify the existence of homogeneity or heterogeneity in the slope. The simple and adjusted -Δ test evaluates the dispersion in the cross-sections of the dispersion of the cross-section of individual slopes weighted by their relative accuracy (see Table 5).

In order to verify the existence of unit roots, we use the second-generation tests of Pesaran (2007) and Breitung (2000) formulated in Equations (2a) and (2b). The two tests were applied without effects of time and with the effect of time. Table 1 reports the results of the unit root test for air quality, ecology footprint, and research and development, GVA agriculture and trade, respectively. The two tests confirm that the first difference in the series eliminates the problem of the unit root. Consequently, the five-panel series has an order of integration I(1). These results are consistent with the conclusions obtained in recent research in the environmental economics literature that use panel data (Al-Mulali et al., 2015; Solarin and Bello, 2018; Ponce and Alvarado, 2019 Destek and.Sinha et al., 2020; Sinha et al., 2020; among others). The process of differentiation allows to correct the stationarity and avoid spurious results in all regions for the variables air quality, ecological footprint and research and development. The results are statistically significant at 1%.

In the second stage, the results obtained from the Westerlund (2005) heterogeneous cointegration test presented in Equation

Table 3
Cross-sectional dependence test analysis.

Variables	Pesaran (2004)		Pesaran (2015)	
	Statistics	p-value	Statistics	p-value
EF	18.394	0.000	244.056	0.000
AQ	9.028	0.000	243.146	0.000
R&D	132.038	0.000	225.910	0.000
GVA-A	119.212	0.000	247.756	0.000
TR	210.169	0.000	247.854	0.000

Table 4
Test for slope homogeneity of Pesaran and Yamagata (2008).

Tests	Delta	p-values
– Δ	24.802***	0.000
– Δ_{adj}	29.347***	0.000

H0: slope coefficients are homogenous.

(3) are reported in Table 6. Similar to the results in Table 1, the estimators are reported globally and for the 77 countries grouped in the six *regions* classified by the World Bank (2020). Table 6 reports the estimators obtained within the dimensions and between the dimensions for the relationship between air quality with research and development and the added value of agriculture, and trade; and for the relationship between the ecological footprint with research and development, the added value of agriculture, and trade, respectively. To compare the results, we report the results with and without transversal averages, both with the trend and without a trend. One of the advantages of the Westerlund long-term cointegration test (2005) is that it allows heterogeneity between the panels. This fact implies that it allows testing the hypothesis of non-cointegration only in some or all panels. The results are reported for the two models with the two measures of environmental degradation: air quality and ecological footprint. The results reported in Table 6 offer sufficient evidence to reject the null hypothesis of non-cointegration. Consequently, we can conclude that there is a long-term equilibrium relationship between environmental degradation and research and development, the GVA of agriculture and trade, both globally and in the six regions. Khan, Bin & Hassan (2019)a and Rahman et al. (2019) demonstrate that agriculture and trade impacts the amount of polluting gas emissions in Pakistan. This result implies that, in the long term, environmental degradation, research and development, the GVA of agriculture and commerce, there is a simultaneous movement over time. The cointegration model results support the validity of the environmental Kuznets curve, particularly in the fact that there is an equilibrium relationship between environmental degradation and R&D spending. Our results are relatively similar to the conclusions obtained by recent empirical research. These authors find that the income of natural resources, renewable energy, and urbanization reduces the ecological footprint. Furthermore, the results obtained by Ahmad et al. (2019) show that the shocks of innovation have a significant impact on carbon dioxide emissions. Our results also suggest that research and development have a negative effect on environmental degradation measured by ecological footprint and air quality. Several empirical investigations indicate that the ecological footprint is a good indicator of environmental degradation and that it may better reflect the harmful effects of economic activity on nature (Aydin et al., 2019). In this sense, the mitigation of environmental degradation measured by the ecological footprint may be possible through an increase in research and development that encourages the emergence of new products and processes that are more environmentally friendly. In this sense, the most polluting countries are those with high rates of industrialization and human capital; therefore, it is possible to

Table 5
Results of the second-generation unit root test.

Regions	Variables	CADF test		Breitung test	
		Level	First difference	Level	First difference
Global	EF	−2.531	−2.467***	0.259	−7.304***
	CO2	−2.137	−2.194***	1.059	−3.476***
	R&D	−2.288	−2.231***	2.236	−3.372***
	GVA-A	−2.138	−2.289***	1.120	−5.495***
	T	−2.555	−2.447***	1.448	−4.900***
Latin America	EF	−2.017	−3.443***	−0.553	−3.584**
	CO2	−2.574	−3.682***	−0.258	−2.385***
	R&D	−1.825	−3.186	0.317	−2.241***
	GVA-A	−1.372	−3.223***	2.148	−1.658***
	T	−2.103	−2.689***	2.278	−0.577***
East Asia and Pacific	EF	−1.645	−2.491*	−0.811	−3.790***
	CO2	−1.781	−2.307***	0.924	−0.781**
	R&D	−0.979	−3.260***	1.522	−1.127***
	GVA-A	−2.182	−3.340***	0.099	−2.845***
	T	−2.069	−2.700***	1.642	−0.845**
South Asia	EF	−2.833	−2.911***	0.116	−2.499***
	CO2	−2.024	−2.070***	−0.562	−0.169*
	R&D	−3.679**	−4.631*	1.3224	−1.994**
	GVA-A	−3.084	−4.261***	−0.500	−0.636***
	T	−1.834	−2.410***	0.406	−0.643***
Africa Sub-Saharan	EF	−1.465	−4.251***	−0.871	−3.136*
	CO2	−2.779	−4.052*	0.458	−2.705***
	R&D	−2.103	−3.136***	1.045	−0.997
	GVA-A	−2.289	−2.611***	1.044	−2.285***
	T	−2.826	−3.496**	−0.405	−0.022*
Midle East and North Africa	EF	−2.178	−2.136***	0.239	−3.079***
	CO2	−1.034	−2.990**	0.430	−0.963**
	R&D	−1.983	−3.335***	1.128	−2.567*
	GVA-A	−1.217	−3.980*	1.836	−0.835*
	T	−2.337	−3.212***	0.799	−2.005*
North America, Europa And Central Asia	EF	−2.685	−3.267*	−0.518	−4.243**
	CO2	−2.290	−3.372*	0.572	−2.215***
	R&D	−2.374	−2.645**	2.162	0.076*
	GVA-A	−1.856	−3.101**	0.739	−4.300**
	T	−2.484	−3.182**	−0.127	−3.896**

Note: the values indicate statistical significance of * $p < 0.05$, ** $p < 0.01$ and $p < 0{,}001$***.

Table 6
Result of the Westerlund long-term cointegration test (2005).

Variance ratio	Without cross-sectional averages				With cross-sectional averages			
	Without time trend		With time trend		Without time trend		With time trend	
Dependent variable: *Ecological footprint*								
	Statistic	p-value	Statistic	p-value	Statistic	p-value	Statistic	p-value
Test some panels	−2.872 ***	0.000	- 5.380 ***	0.000	−2.995 ***	0.001	−5.987 ***	0.000
	Statistic	p-value	Statistic	p-value	Statistic	p-value	Statistic	p-value
Test all panels	−2.189 *	0.014	−3.725 ***	0.000	−2.075 *	0.019	−3.671 ***	0.000
Dependent variable: Air qualityrowhead								
	Statistic	p-value	Statistic	p-value	Statistic	p-value	Statistic	p-value
Test some panels	−2.281 *	0.011	−3.756 ***	0.000	−1.606 ***	0.000	−3.929 ***	0.000
	Statistic	p-value	Statistic	p-value	Statistic	p-value	Statistic	p-value
Test all panels	−2.846 **	0.002	−3.535 ***	0.000	−2.423 ***	0.000	−3.692 ***	0.000

Note: the values indicate statistical significance of * $p < 0.05$, ** $p < 0.01$ and $p < 0{,}001$***.

apply policies that promote the emergence of new products that reduce current levels of pollution. The sustained growth of technological innovation would lead economies to increase production and decrease emissions of polluting gases (Dinda, 2018).

After verifying the cointegration between environmental degradation, R&D, the GVA of agriculture, and world trade, it is possible to obtain the fully modified ordinary least squares-FMOLS estimators developed by Pedroni, which generate elasticities with efficient standard errors and normal distribution. FMOLS estimators correct the possible endogeneity and residual autocorrelation. Consequently, to establish the long-term relationship between the series, we estimate a FMOLS model, which allows us to explore the direction of the causal effect between the variables, considering the cross-sections dependence. The results obtained in this test are reported in Table 7, whose coefficients offer useful information in the process of understanding environmental degradation in regions of the world. One of the most stable results is that international trade increases emissions of polluting gases, the effect of which is statistically significant. This result suggests that one of the most relevant determinants of air quality in the 77 countries analyzed are world trade flows. The effect of trade on the ecological footprint differs among the regions. In South Asia and the Middle East and North Africa, when spending on research and development increases, the ecological footprint also increases. While in North America, Europe, and Central Asia, the rise in R&D reduces the ecological footprint. In the rest of the regions, the results are not statistically significant. In practice, the FMOLS model results suggest that there is partial evidence to support the existence of the environmental Kuznets curve. The results are heterogeneous between the regions. Increases in the GVA of agriculture significantly increase pollutant gas emissions in Latin America, East Asia, and the Pacific. In the rest of the regions, the effect is not significant. Likewise, the VAG of agriculture increases the ecological footprint in East Asia and the Pacific, South Asia, the Middle East, and North Africa. At the same time, the rest of the regions, the effect is statistically significant. Finally, research and development have a positive and significant impact on polluting gases in Latin America, South Asia. In North America, Europe, and Central Asia, the effect of R&D on pollutant gas emissions is negative and significant. In parallel, the impact of R&D on the ecological footprint is negative in East Asia and the Pacific, while in North America, Europe, and Central Asia, the effect is positive. Several previous similar empirical investigations have obtained partially similar conclusions (See Khan, Ali & Ashfaq, 2018; Liu et al., 2017; Kolcava et al., 2019). Furthermore, Khattak et al. (2020) find that innovation activities have failed to alter CO2e in China, India, Russia, and South Africa, but they have had a significant impact in Brazil.

The difference between the strength of the cointegration vector between regions can be explained by several reasons. One of them is that the amount spent on research and development differs between regions. There are regions more prone to the generation of new knowledge. North America and Europe, and more recently, East Asia and the Pacific are a clear example of regions that invest a significant budget in R&D. The environmental degradation measured by the ecological footprint is growing at higher rates than the environmental degradation measured by the air quality. According to Scherer et al. (2018), carbon footprints grow at an annual average of 0.8%, while water and land footprints increase by 1.4% and 2.1%, respectively. Third, like air quality, the levels of the ecological footprint vary over time and between regions and countries according to their level of development achieved (Wackernagel et al., 2019). It is well known that there are significant

Table 7
Long run elasticity estimates from panel FMOLS.

Country	Variables	Latin America	East Asia And Pacific	South Asia	Africa Sub-Saharan	Middle East and North Africa	North America, Europa And Central Asia
Dependent variable: Ecological footprint	R&D	−0.07	−0.06**	−0.03	0.08	0.02	0.51**
	t-stat	(-0.49)	(-2.52)	(-0.44)	(1.64)	(0.74)	(2.21)
	GVA-A	0.28	0.63**	0.19**	0.10	0.29**	0.21
	t-stat	(1.89)	(5.47)	(2.55)	(1.54)	(5.04)	(1.76)
	TR	0.05	−0.29	0.15**	0.11	0.30**	−0.54**
	t-stat	(0.68)	(0.63)	(3.36)	(-0.49)	(3.16)	(-4.48)
Dependent variable: Air quality	R&D	0.28**	0.03	0.15**	0.20	0.08	−1.60**
	t-stat	(5.19)	(1.37)	(3.92)	(0.04)	(0.34)	(-6.94)
	GVA-A	0.26**	0.75**	0.21	0.23	−0.07	−0.16
	t-stat	(3.59)	(4.77)	(1.23)	(3.10)	(1.30)	(-0.52)
	TR	0.21**	0.77***	0.10**	0.27**	0.18**	1.11**
	t-stat	(4.46)	(7.30)	(2.19)	(3.18)	(2.89)	(9.77)

Note: the values indicate statistical significance of * $p < 0.05$, ** $p < 0.01$ and $p < 0{,}001$***.

differences between countries, even within the same region. Other research has also evaluated the role of agriculture in determining environmental quality. For example, Hafeez et al. (2020) find that the demand for agriculture causes an increase in environmental degradation.

Finally, Table 8 reports the results obtained from the causality test formalized in Equation (5), both globally and by region. This result complements the previous cointegration analysis. Similar to the previous empirical econometric strategy, the results are reported per a couple of relationships separately. On the one hand, we find that there is a two-way causality between air quality and R&D expenditure, and between the ecological footprint and global R&D expenditure. These results reinforce the preliminary idea that research and development can contribute to mitigating the environmental degradation that was discussed in the cointegration results. However, due to the role that geography plays, the results differ within regions. Changes in research and development spending allow the prediction of changes in air quality and ecological footprint. Also, in East Asia and the Pacific region, there is a two-way causality between air quality and R&D spending, and a unidirectional causal relationship that ranges from the ecological footprint to R&D spending. In the Middle East and North Africa region, we find a unidirectional causal relationship that ranges from the ecological footprint to R&D spending. Finally, we find that there is unidirectional causality from R&D spending to the ecological footprint in the region of North America, Europe and Central Asia. The reported results do not offer enough evidence to support causality in any direction in the other regions analyzed. Therefore, in these regions, the changes produced in the expenditure on research and development do not allow us to predict the changes that take place in the environmental degradation measured by the air quality and the ecological footprint or vice versa. These results are partially consistent with the conclusions obtained by Lee and Min (2015). Recent research suggests that contamination has not yet reached the maximum threshold (Ahmad et al., 2020a). Consequently, the role of policies is necessary to mitigate the adverse effects of air degradation.

Empirical evidence shows that the main determinants of air quality are the consumption of energy from fossil sources, urbanization, and manufacturing (Iwata et al., 2010; Alvarado et al., 2020). This research focuses on the possible changes that research and development can generate in the process of sustainable growth. At the same time, the countries that pollute the air the most or have the most significant impact on the ecological footprint are the countries with a robust industrial specialization; therefore, they have the industrial base to direct the production processes through public policies so that the new products and processes are responsible with the environment. Other research indicates that the food sector determines the ecological footprint of all income groups, because, globally, this sector comprises 28% of the carbon footprint of households, while energy use occupies the second place with 19%, in particular the electricity generated from coal (Scherer et al., 2018). On the other hand, the primary sources of environmental degradation in developing countries come from the deforestation of threatened ecosystems and the advancement of agriculture with harmful processes that weaken the ecosystem and decrease its protection services, making the soils they become vulnerable to environmental shocks (Alvarado and Toledo, 2017; Brausmann and Bretschger, 2018). From an environmental and practical point of view, in order to reduce the degradation of the

Table 8
Results of the Dumitrescu & Hurlin causality test (2012).

	Variables	EF	CO2	R&D	GVA-A	T
Global	EF					2.59* (0.000)
	CO2					1.77*** (0.001)
	R&D	4.76*** (0.00)				0.09*** (0.001)
	GVA-A	1.09*** (0.00)	4.08*** (0.000	15.63(0.008)		13.15* (0.031)
	T		2.18 (0.200)	0.83** (0.003)		
Latin America	EF					6.09* (0.000)
	CO2					
	R&D	2.59*** (0.00)			9.11* (0.041)	
	GVA-A	2.18*** (0.00)	1.55** (0.010)	16 .6322		13.25* (0.011)
	T	0.23** (0.00)	1.76** (0.001)	0.68** (0.004)		
East Asia And Pacific	EF					
	CO2					
	R&D		1.16* (0.041)			1.09* (0.021)
	GVA-A		1.55** (0.023)			
	T	2.44*** (0.08)	6.27*** (0.000)			
South Asia	EF					2.42* (0.015)
	CO2			6.27*** (0.000)	6.27*** (0.000)	6.27*** (0.000)
	R&D				9.59 (0.001)	7.76* (0.034)
	GVA-A		6.19*** (0.000)			
	T	1.03*** (0.02)	1.55*** (0.001)		14.85 (0.091)	
Africa Subsahariana	EF			2.10* (0.035)		2.58 (0.074)
	CO2					
	R&D		4.33*** (0.001)		2.76 (0.301)	
	GVA-A	2.56 *(0.01)	4.22*** (0.001)			
	T	2.45** (0.00)	9.33*** (0.001)		0.99* (0.025)	
Midle East and North Africa	EF			3.05* (0.035)		1.78 (0.074)
	CO2					
	R&D					
	GVA-A	2.56 *(0.010)	3.15*** (0.000)			
	T	3.45** (0.003)	1.01*** (0.001)		2.33* (0.021)	
North America, Europa And Central Asia	EF			2.22* (0.035)		
	CO2			2.91* (0.035)		
	R&D	5.71* (0.020)				1.56* (0.034)
	GVA-A	3.09 *(0.010)	−0.16**(0.002)			
	T	2.25** (0.003)	−0.16*(0.042)	2.33* (0.015)	−2.19* (0.023)	

environment, there must be significant changes in research and development that allow for internalizing environmental costs (Gu and Wang, 2018). Despite the importance of research and development to reduce environmental degradation, innovation policies themselves are unlikely to stabilize the global temperature, especially when they are not considered more optimal global innovation policy agreements (Bosetti et al. 2011). It is clear that all the solution of the environmental problems that allow the achievement of the SDGs of the United Nations depends on other factors and not only on technology (Venselaar, 1995). However, technology plays an essential role in determining air quality and ecological footprint for its direct and indirect influence on industrial products and processes. The most effective control of environmental degradation can be strengthened with other tools and better planning for sustainable development (Moghaddam et al., 2018) proposed in the SDGs by the United Nations. This result is consistent with the political implications proposed by Jaffe et al. (2002) and Sinha et al. (2020).

5. Conclusions and policy implications

The increasing environmental degradation caused by economic activity, mainly due to excessive overexploitation of natural resources and manufacturing activity, encourages the search for new mechanisms to mitigate global warming. In this research, we use two measures of environmental degradation: the ecological footprint and air quality. We explored the role of geography in environmental degradation patterns using a panel data model for 77 countries during 1996–2016, including cross-sections dependence and homogeneity on the slope. Cross-sections dependence results suggest that changes in one country in the variables of environmental degradation, R&D, agriculture, and trade generate impacts in the rest of the nations. The underlying logic behind this conclusion is that the interdependence of trade, investment, and capital and people flow agreements leads to countries being related to each other. The heterogeneity slope implies that there is a difference in the strength of the relationship between the variables. These results support the application of policies to mitigate heterogeneous environmental degradation around the world. Those responsible for international public policy, such as the UN and the governments of the countries, should cooperate in the pursuit of the objectives of sustainable development that benefit all those involved. These findings are consistent with empirical evidence that geography produces differences in human behavior associated with economic growth; in particular, there is heterogeneity in consumption patterns. Our results show that the incorporation of geography is justified by the heterogeneity that exists between the regions.

The inclusion of the GVA of agriculture and trade allows for more robust results given the trend towards the internationalization of production and the expansion of food production from fishing, agriculture, and livestock. In general, our results show the existence of an equilibrium relationship between environmental degradation, R&D, agriculture, and trade. The achievement of SDG6, SDG7, SDG11, SDG12, SDG14, and SDG15 depends on the commitment of consumers, business managers, policymakers, and international organizations. These agents' role must have reliable academic support that offers robust and credible evidence on the real dimension of environmental degradation and the irreversible consequences of global warming. Our results provide a slight hope of limiting the increasing spread of soil pollution and air quality through research and development. R&D can contribute significantly in several dimensions: industrial processes that pollute less, manufactured goods that emit less environmental loads, garbage collectors from the oceans, and products that do not use fossil energy. Likewise, the FMOLS model results indicate that R&D negatively affects air quality in Latin America, East Asia, and the Pacific and Southeast Asia. Agriculture and trade increase environmental degradation as measured by the ecological footprint in North America, Europe, and Central Asia. We find evidence in favor of causality that goes from R&D to the ecological footprint worldwide, in Latin America, North America, Europe, and Central Asia. R&D causes air quality in East Asia and the Pacific and Sub-Saharan Africa. Besides, we also find evidence in favor of a causal relationship between agriculture and trade. Our results suggest that R&D has the expected effect on environmental degradation. This fact implies that R & D's changes have an immediate and long-term impact on the ecological footprint and air quality. Furthermore, governments can direct public spending to drive environmental innovation without limiting the expansion of production.

An implication derived from our conclusions for future empirical research is that the role of R&D in the design and application of policies that seek to reduce air and soil pollution cannot be ignored. The processes related to research and development have within their reach the solution of a problem of broad interest among policymakers and researchers with direct implications for the quality of life of the population. The opportunities for future research that this work opens are to foster the development of a strong theoretical foundation that formalizes the mechanism by which R&D can become a policy instrument to control pollution of the environment, and in general, to decrease the negative consequences of global warming. Besides, future research could focus on evaluating the disaggregated impact of different types of R&D spending (public and private) on various pollution measures. Identifying the fertility of public or private R&D would guide policymakers to decide who should make the most considerable efforts to accelerate the achievement of environmental SGDs. The constant search for new mechanisms for mitigating environmental degradation constitutes a significant contribution to the achievement of sustainable development.

CRediT authorship contribution statement

Rafael Alvarado: Supervision, Conceptualization, Methodology, Software, Data curation. **Cristian Ortiz:** Data curation, Software, Writing - original draft, preparation. **Nathaly Jiménez:** Visualization, Investigation. **Diego Ochoa-Jiménez:** Writing - review & editing. **Brayan Tillaguango:** Data curation, Software.

Declaration of competing interest

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

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