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Reinvestigating the environmental Kuznets curve (EKC) of carbon emissions and ecological footprint in 147 countries: a matter of trade protectionism

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Environmental degradation has profoundly impacted both human society and ecosystems. The environmental Kuznets curve (EKC) illuminates the intricate relationship between economic growth and environmental decline. However, the recent surge in trade protectionism has heightened global economic uncertainties, posing a severe threat to global environmental sustainability. This research aims to investigate the intricate pathways through which trade protection, assessed by available trade openness data, influences the nexus between economic growth and environmental degradation. Leveraging comprehensive global panel data spanning 147 countries from 1995 to 2018, this study meticulously examines the non-linear dynamics among trade, economy, and the environment, with a particular emphasis on validating the EKC hypothesis. This study encompasses exhaustive global and panel data regressions categorized across four income groups. The research substantiates the validity of the EKC hypothesis within the confines of this investigation. As income levels rise, the impact of economic growth on environmental degradation initially intensifies before displaying a diminishing trend. Additionally, trade protection manifests as a detriment to improving global environmental quality. The ramifications of trade protectionism display nuanced variations across income strata. In high-income nations, trade protection appears to contribute to mitigating environmental degradation. Conversely, within other income brackets, the stimulating effect of trade protection on environmental pressure is more conspicuous. In other words, trade protectionism exacerbates environmental degradation, particularly affecting lower-income countries, aligning with the concept of pollution havens. The study's results illuminate nuanced thresholds in the relationship between trade, economic growth, and environmental degradation across income groups, emphasizing the heterogeneous impact and underlying mechanisms. These findings provide valuable insights for policymakers, urging collaborative efforts among nations to achieve a harmonious balance between economic advancement and environmental preservation on a global scale.

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Introduction

The significance of both economic growth and environmental sustainability has gained global attention. Environmental sustainability represents a shared challenge and responsibility for the world. In recent decades, the conspicuous occurrences of climate change and global warming have brought substantial focus to environmental degradation. Increasing treaty provisions have been enacted to reduce carbon emissions. The Paris Agreement requires countries to make independent contributions and commitments to reduce carbon emissions (Winning et al. 2019). Governments are required to adopt more rigorous measures to attain their carbon peak and carbon neutrality objectives. The 26th United Nations Climate Change Conference (COP26) in Glasgow witnessed nations reaffirming their commitment to prior climate agreements and making strides toward achieving the Paris Agreement's objective of restricting global warming to 1.5 degrees Celsius (Scott and Gössling 2021). The environmental Kuznets curve (EKC) is a classic hypothesis explaining the relationship between economic growth and environmental degradation. Among the indicators for studying EKC, carbon dioxide emissions are popular. The ecological footprint, encompassing biologically productive areas such as farmland, pasture, woodland, construction land, fossil energy land, and oceans, is regarded as a more comprehensive measure of environmental degradation. The advancement of Earth's ecological overload day implies an impending increase in human ecological debts and a greater consumption of ecological products and services, pushing the Earth's limits (Sarkis 2019). Therefore, investigating the realms of economic and environmentally sustainable development holds paramount significance.

The rise of trade protectionism in recent years has increased the instability of economic development, presenting new challenges to environmental sustainability. Global trade protection measures witnessed a substantial increase following the international financial crisis. More recently, influenced by the COVID-19 pandemic, numerous countries have implemented trade restrictions, resulting in a significant decline in international trade and investment (Barlow et al. 2021). The outbreak of the Russia-Ukraine war in 2022 has further fueled the ascent of trade protectionism (Del Lo et al. 2022). Reverse globalization has introduced profound and intricate challenges to global economic growth, causing increasing uncertainties in environmental protection. Consequently, there is a pressing need for a comprehensive examination of the interplay between trade, economy, and the environment.

Consensus remains elusive regarding the environmentally sustainable implications of trade. The pollution paradise hypothesis posits that developing nations, compelled by the imperative of rapid development, tend to adopt less stringent environmental regulatory policies. This serves as an expedient route for developed countries to shift industries with high energy consumption. Consequently, trade activities are implicated in environmental degradation (Gyamfi et al. 2021; Chen et al. 2022). The pollution halo hypothesis suggests that foreign direct investment, combining capital and technology, can introduce positive energy-efficient technology benefits to the host country. Technological improvements help reduce energy consumption, enhance energy efficiency, lower carbon emissions, and positively impact the host country's ecological environment (Neves et al. 2020; Tong et al. 2021). A more in-depth examination is imperative to comprehend the intricate interplay between trade and the environment. Matters on international trade, economic growth, and environmental protection necessitate unified deliberation on a global scale.

In the context outlined, this paper aims to address three pivotal questions utilizing panel data encompassing 147 chosen countries spanning the period 1995 to 2018: (1) Within the ambit of the study's scope, does empirical evidence lend support to the EKC hypothesis? (2) In the economic growth-environmental degradation model, what is the role of trade protection measures? Are there discernible nonlinear effects inherent in this relationship? (3) To what extent does the observed effect differ among countries, contingent upon their respective income levels?

The applied threshold panel regression model in this study incorporates trade as the threshold variable to examine the nonlinear relationship among trade, the economy, and the environment. This study aims to understand how trade protectionism, measured by current trade openness data, influences the environmental Kuznets curve. In doing so, it provides a new perspective on how trade works. Additionally, employing a global panel and four income-level panels, the study unveils heterogeneous effects of trade protection on the EKC. The results show exactly how trade affects the link between economic growth and things like carbon emissions and ecological footprint. This has important implications for policies. By providing comprehensive insights into the integrated development of trade and environmental sustainability, especially across varied income categories, this study contributes nuanced and extensive information. The following sections are organized as follows: Section "Literature review" reviews existing literature, Section "Data and methods" elaborates on methodology and data sources, Section "Empirical results" presents findings and results, Section "Discussion" delves into discussion, and Section "Conclusions, implications, and limitation" summarizes the conclusions and implications.

Literature review

The correlation between environmental protection and economic development has been discussed in previous literature. In 1991, American economists Grossman and Krueger conducted the first empirical research on the relationship between environmental quality and per capita income. Their findings revealed that pollution increases with GDP per capita at low-income levels but decreases with GDP growth at high-income levels (Grossman and Krueger 1991). Panayotou introduced the environmental Kuznets curve to depict the relationship between environmental quality and per capita income (Panayotou 1993). Subsequently, the focal point of discussions and debates gradually shifted towards the EKC. The traditional EKC represents an economic theory that elucidates the correlation between environmental pollution and economic development (Wang et al. 2023a). The fundamental model of the traditional EKC takes the form of an inverted U-shaped curve. Environmental pollution tends to intensify as the country's economic growth level rises, reaching a peak, and subsequently declining after surpassing a certain threshold. The curve's assumption implies that initially, as the economy expands, industrialization and urbanization processes contribute to an increase in environmental pollution. However, as the country attains economic prosperity and heightened environmental awareness, the reinforcement of environmental protection measures, promotion of technological innovation, and overall environmental pollution gradually diminish. Some existing research findings corroborate this hypothesis (Murshed et al. 2020; Akadırı et al. 2021; Balsalobre-Lorente et al. 2021). Scholars have amassed evidence supporting the establishment of the EKC using diverse models and methodologies. Destek and Sarkodie (2019) examined the relationship between economic growth, energy consumption, financial development, and ecological footprint to determine the validity of the EKC hypothesis. To analyze panel data spanning eleven newly industrialized countries from 1977 to 2013, this study employed the augmented mean group (AMG) estimator and the heterogeneous panel causality method. The results unveiled an inverted U-shaped relationship between economic growth and ecological footprint. Using the simultaneous equations framework, Yin et al. (2021) examined the causal relationship between FDI, CO_2 emissions, and economic growth for 101 countries and four different income groups. Their findings support both the Pollution Paradise Hypothesis and the EKC hypothesis. Farooq et al. (2022) examined the relationship between globalization and carbon dioxide emissions using data from 180 countries between 1980 and 2016. The study unearthed compelling evidence suggesting that economic globalization adversely affects environmental sustainability, and the EKC was validated across all models. Zhang et al. (2019) tested the EKC hypothesis using data on CO2 emissions from manufacturing and construction in 121 countries from 1960-2014 and calculated the inflection points for countries that validate the EKC hypothesis.

Conclusions drawn in certain studies cast doubt on the traditional EKC theory (Pata and Aydin 2020; Alola and Donve 2021). The findings of these studies suggest that the relationship between environmental issues and economic development is more intricate and cannot be easily elucidated by traditional EKC theory. Wang et al. (2021) used the Tapio method and the EKC model to evaluate and predict the status of urban economic development and MSW in China, and the results confirmed the N-shaped and inverted N-shaped relationships between them in different regions. Liu et al. (2021) investigated provincial-level changes in annual fertilizer application in China from 1978 to 2017, and the panel regression revealed an N-shaped shift in the EKC. Moreover, Koc and Bulus (2020) tested the EKC assumptions for South Korea from 1971 to 2017 by examining the dynamic short-run and long-term relationships between per capita GDP, per capita energy consumption, per capita renewable energy consumption, trade openness, and per capita CO_2 emissions. Their empirical results identified an N-type relationship between carbon emissions and GDP. Balsalobre-Lorente et al. (2022) investigated the relationship between economic complexity and CO_2 emissions in Portugal, Ireland, Italy, Greece, and Spain using a dynamic ordinary least squares estimator. Empirical evidence suggested that they had an inverted U-shaped and further N-shaped relationship.

Furthermore, the existing EKC-related literature can be divided into two categories according to the research area. One is research on a country or a region, for example, France (Pata and Samour 2022), India (Ozcan and Ulucak 2021), and China (Yilanci and Pata 2020; Pata and Caglar 2021). The other is on some selected countries for research, for example, European Union (Dogan and Inglesi-Lotz 2020), sub-Saharan African countries (Tenaw and Beyene 2021), and OECD countries (Isik et al. 2021).

In general, the traditional EKC has undergone extensive examination in scholarly literature. However, consensus needs clarification due to variations among countries and approaches. Moreover, there is a necessity to broaden the exploration of the traditional EKC from a new perspective. A systematic examination of the trade-economy-environment nexus offers valuable insights in this regard.

Incorporating trade variables into the economic-environmental research framework and re-evaluating the EKC assumption from the perspective of trade offers a novel standpoint for this study. To comprehensively analyze the relationship between them, the application of a nonlinear threshold panel regression model is deemed appropriate. The panel threshold regression model captures the relationship at different stages by combining the nonlinear features of panel data with threshold variables (Wang et al. 2023b). The model divides the observed data into different stages by introducing threshold variables to establish different regression models in different stages. This model is popular in the field of energy economics. Wang and Shao (2019) employed a panel threshold regression technique to observe the non-linear impact of formal and informal environmental regulations on G20 green growth between 2001 and 2015. Additionally, Zhou and Li (2020) studied the non-linear impact of industrial restructuring on economic growth and carbon dioxide emissions in 32 countries. Li et al. (2022) explored carbon emissions in the transportation industry across 30 provinces in China, employing a methodology that combines the decoupling index and panel threshold analysis. Zeitun and Goaied (2021) examined the non-linear relationship between foreign ownership and firm leverage decisions, investigating whether thresholds on foreign ownership levels moderate the effects of capital structure determinants. Another study used linear and nonlinear models to explore factors affecting carbon emissions (Li et al. 2021). To sum up, the panel threshold model is mature and recognized by scholars from various countries. This paper investigates the non-linear effects of trade on the economy and the environment, and it is appropriate and reliable to apply this model.

Grossman and Krueger proposed the three-effect theory, namely the scale effect, composition effect, and technical effect (Grossman and Krueger 1995), which is applicable to research on the environmental impact of economic growth/trade. There is no consensus on the impact of trade on environmental sustainability. The specific impact of trade on the environment is contingent upon the interplay between positive and negative effects resulting from the joint action of these three factors. In accordance with the scale effect, economic growth requires an increase in input, subsequently escalating resource use, and higher output contributing to an increase in pollution emissions (Hao et al. 2020). The technical effect reflects that cleaner and more advanced technologies are replacing technologies that cause significant environmental pollution, which aids in improving environmental quality (Sinha et al. 2020). The composition effect measures changes in output and input structure as income levels increase. The economy transitions to low-polluting service and knowledge-intensive industries, leading to lower emissions per unit of output and an enhancement in environmental quality (Ahmad et al. 2020). Thus, previous research has widely used the three-effect theory (Park et al. 2018; Le and Ozturk 2020).

The economic and environmental issues stemming from the surge in trade protectionism have garnered global scholarly attention. Research exploring the connection between trade protection and environmental policy is prevalent. Copeland (2000) believed that in the case of non-global pollution, trade liberalization that does not restrict environmental policies leads to a non-cooperative game among countries on pollution policies. The argument posits that the anticipated environmental repercussions of free trade are pertinent to trade policy preferences (Bechtel et al. 2012). Quantitative measures of trade protection remain uncertain. Limited research has directly investigated the impact of trade protection on the environment, with most of the existing literature considering trade openness as an inverse indicator of trade protection.

In existing studies, two hypotheses offer distinct perspectives to elucidate the impact of trade on the environment. The Pollution Paradise Hypothesis contends that trade liberalization results in the relocation of highly polluting industries from countries with stringent environmental regulations to those with lax environmental regulations. Findings from several studies further provide theoretical support for this viewpoint. Drawing on the establishment of China's intellectual property protection system, integrated trade, Foreign Direct Investment (FDI), and Outward Foreign Direct Investment (OFDI) into a unified international technology spillover framework (Hao et al. 2021). They analyzed the impact of international technology spillovers on China's carbon emissions, revealing that trade, FDI, and OFDI contribute to an increase in regional carbon emissions. Wang et al. (2021) investigated the mechanism of FDI's effect on carbon emissions through energy intensity, and the results revealed that FDI is one of the reasons for the increase in emissions in China at this stage, and FDI can also increase carbon emissions indirectly through increasing energy intensity. Vural (2020) investigated the effects of output, trade, and renewable and non-renewable energy on carbon emissions in Sub-Saharan African countries. Long-term empirical findings suggest that nonrenewable energy and trade contribute to the increase in carbon emissions. Liu et al. (2022) investigated the impact of tourism development, economic growth, energy consumption, trade openness, and foreign direct investment on Pakistan's ecological footprint using the EKC. The findings revealed that trade has an ecological footprint and that foreign direct investment contributes to environmental degradation. Abid et al. (2022) investigated the connection between renewable energy consumption and ecological footprint in Saudi Arabia, contending that capital and trade openness are factors contributing to environmental degradation. Yasmeen et al. (2022) formulated three simultaneous equations to evaluate the effects of Foreign Direct Investment (FDI) inflow, technological innovation, natural resources, and population density on biomass energy consumption and ecological footprint. The empirical findings revealed that FDI has not led to environmental improvement in the Belt and Road region. Nathaniel and Khan (2020) investigated the relationship between urbanization, renewable energy, trade, and ecological footprint in ASEAN countries, confirming the role of trade in environmental degradation. Another study investigated how globalization and electricity consumption are driving Ghana's human demand for ecological resources. Evidence suggests that globalization has a significant impact on the environmental footprint (Langnel and Amegavi 2020).

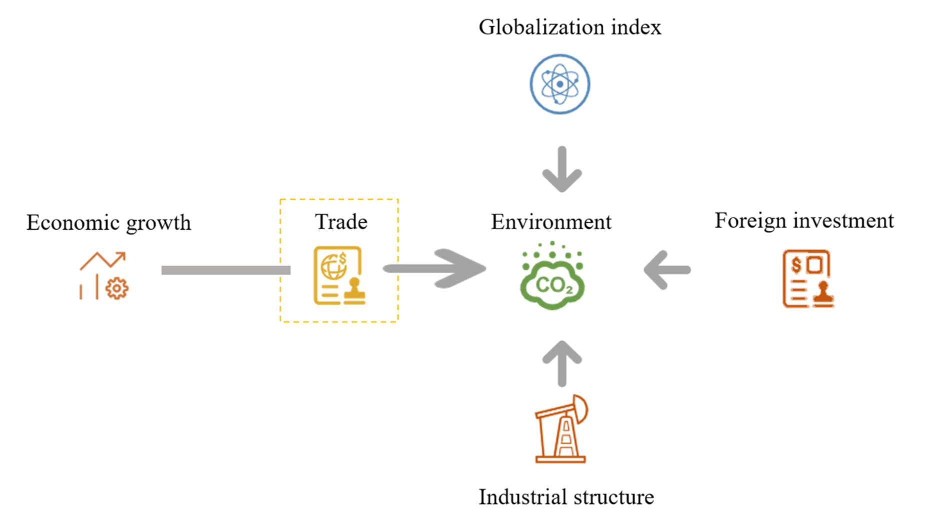
The pollution halo hypothesis posits that trade liberalization facilitates the globalization of multinational corporations, often introducing higher environmental standards and technologies into new markets. It could result in advancements in environmental technology and management, leading to improved environmental quality. Some academics endorse this viewpoint. Liu et al. (2021) revisited the relationship between FDI-trade-innovation and carbon emissions in China. The findings revealed that carbon dioxide is inversely related to foreign trade, renewable energy, and technology. Ge et al. (2022) investigated associations between foreign private investment, carbon dioxide emissions, energy consumption, trade openness, and sustainable economic growth using random effects, generalized least squares, and panel VAR estimators. The findings revealed that investment in emerging and advanced economies enhances domestic business contribution and contributes to environmental sustainability in the national economy. Khan et al. (2020) investigated the relationship between G7 countries' trade, income, eco-innovation, renewable energy, and consumption-based carbon dioxide emissions. Exports have been shown to help with environmental sustainability. Wahab et al. (2021) reached a similar conclusion. Shahbaz et al. (2019) incorporated energy consumption, trade openness, and foreign direct investment into the carbon emission function in the United States, and the results demonstrated that trade openness reduces carbon dioxide emissions. Jiang et al. (2022) investigated the relationship between trade diversification, income inequality, renewable energy, and ecological footprint in 17 Asia-Pacific Economic Cooperation (APEC) countries, concluding that globalization and export diversification reduce ecological footprint. Usman et al. (2021) sought to investigate the determinants of ecological footprint and economic growth in order to assess the effectiveness of financial development, renewable and non-renewable energy use, and economic growth in the 15 highest emitting countries. The Augmented Mean Group (AMG) estimation method revealed that trade openness, financial development, and renewable energy all have a significant impact on overcoming environmental degradation. Zafar et al. (2019) applied the ARDL model to examine the impact of natural resources, human capital, and foreign direct investment on the ecological footprint. The results showed that foreign direct investment significantly reduces the ecological footprint of the United States.

In general, the relationship between trade and the environment is contentious. It is not a straightforward one-way effect but rather a combination of multiple influences. While traditional EKC assumptions have been validated in numerous studies, there is a need for systematic research on trade, economics, and the environment, calling for a re-examination of EKC from a fresh perspective (Wang et al. 2023c). The non-linear effects of trade on the environment warrant attention. Additionally, most existing studies focus on a single environmental indicator, prompting the necessity for a more comprehensive comparative analysis of environmental indicators. Moreover, most studies concentrate on individual countries or economic regions, underscoring the need for comparative research across regions with varying levels of development.

Therefore, this study makes the following contributions: 1) This paper innovatively investigates the environmental Kuznets curve from the perspective of trade protection, extending the traditional EKC theory. By considering the three dimensions of trade, economy, and environment, it highlights the role of trade factor in sustainable development, providing policymakers with insights into identifying environmental impact mechanisms. Unlike traditional ecological studies focused on the relationship between organisms and the environment, this study treats nature, trade activities, and the economy as a composite ecosystem. It incorporates the impact of human activities and studies the driving effect of trade development on ecological restoration from a systemic perspective. 2) This paper employs the threshold panel regression model, using trade as the threshold variable and industrial structure, foreign direct investment, and the globalization index as control variables to analyze the impact mechanism of trade on economic growth, carbon emissions, and ecological footprint. Additionally, the research extends to the perspectives of carbon emissions and ecological footprint, comprehensively analyzing the results for these two environmental variables. By investigating the economic-environmental correlation, this paper integrates various elements into a unified assessment framework, providing a comprehensive understanding of sustainability covering various factors. 3) Considering the heterogeneity of different research objects, this study analyzes the regression results of panel data from 147 countries worldwide and the panel data of four income groups. It examines the EKC curve from the perspective of different income groups, observing the heterogeneous effect of trade on countries with varying income levels.

Data and methods

Data sources. This paper aims to investigate the nonlinear impact mechanism of global trade on the environmental Kuznets curve. We examine the dynamic relationship between GDP per capita, trade, industrial structure, foreign direct investment, the globalization index, and the environment using a panel dataset spanning 147 countries from 1995 to 2018. This paper uses carbon dioxide emissions and ecological footprint as indicators of environmental degradation. GDP per capita is the explanatory variable, and data are in constant 2015 US dollars. Trade is the threshold variable. The explained variables are per capita carbon dioxide emissions



Type	Variable	Symbol	Meaning
Threshold variable	Trade	TRA	Merchandise trade as a share of GDP is the sum of merchandise exports and imports divided by the value of GDP.
Explanatory variable	Economic growth	PGDP	Regional GDP per capita.
Explained variable	Carbon dioxide emissions	CO2	Regional per capita carbon dioxide emissions.
	Ecological footprint	EF	Regional per capita ecological footprint. The biologically productive areas that can continuously provide resources or consume waste.
Control variable	Industrial structure	IS	The ratio of industrial added value to GDP.
	Foreign investment	FI	Net foreign direct investment inflows as a share of GDP.
	Globalization index	GI	The KOF Globalization Index measures the economic, social and political dimensions of globalization.

Fig. 1 Interconnections and brief descriptions of variables.

and per capita ecological footprint. Control variables include industrial structure, FDI, and the globalization index. They are indicators that are closely linked to globalization. The ratio of industrial added value to GDP is used to determine the industrial structure. The Globalization KOF Index assesses globalization's economic, social, and political dimensions. Trade liberalization has provided more opportunities and potential for the industrial sector. Globalization can facilitate technological innovation and the diffusion of knowledge, bringing new opportunities and competitive advantages to industrial sectors. However, industrial activities are usually accompanied by energy consumption, material utilization and waste discharge, which may lead to environmental problems. Globalization can promote the transfer and innovation of environmental technology and management, and promote the development of environmentally friendly industries. Figure 1 depicts the interdependence and a brief description of all variables. World Bank (World Bank 2022), Global Footprint Network (Global Foofprint Network 2022), and KOF Swiss Economic Institute (KOF Swiss Economic Institute 2022) are data sources.

Considering the heterogeneity of economic development and environmental governance in different countries, this study divides the countries into four income groups according to the World Bank criteria, as shown in Supplementary Fig. A1. This study also reports in detail the countries included in this paper in Supplementary Table A1 of Appendix A.

Proposed econometric models. To test the validity of the EKC hypothesis, environmental degradation is often described as a function of GDP per capita, GDP per capita squared, industrial structure, foreign direct investment, and globalization index. We convert the dataset of some of the considered variables to a natural logarithmic format to reduce possible data outliers and avoid multicollinearity issues (Li et al. 2021). The logarithms of CO2, EF, PGDP, IS, GI, and TRA are represented by LnCO2, LnEF, LnPGDP, LnIS, LnGI, and LnTRA, respectively. According to the studies of Pata (2018), Shokoohi et al. (2022) and Ozgur et al. (2022) the panel version of the empirical model can be expressed as follows:

$$\mathrm{LnCO2} = \alpha_0 + \alpha_1(\mathrm{LnPGDP}) + \alpha_2\left(\mathrm{LnPGDP}^2\right) + \alpha_3(\mathrm{LnIS}) + \alpha_4(\mathrm{FI}) + \alpha_5(\mathrm{LnGI}) + \mu \tag{1}$$

$$\mathrm{LnEF} = \alpha_0 + \alpha_1(\mathrm{LnPGDP}) + \alpha_2\left(\mathrm{LnPGDP}^2\right) + \alpha_3(\mathrm{LnIS}) + \alpha_4(\mathrm{FI}) + \alpha_5(\mathrm{LnGI}) + \mu \tag{2}$$

It is common and credible to test EKC models using the GDP per capita square as an explanatory variable. When the coefficient of LnPGDP^2 in the regression model's calculation results is negative, the EKC hypothesis is considered valid; that is, the relationship between economic growth and environmental degradation presents an inverted U-shape.

This study constructs nonlinear threshold models of trade on the economy and the environment and explores the validity of the EKC hypothesis from a new perspective. With trade as the threshold variable, the formula of the single threshold model is as follows:

$$\mathrm{LnCO2}_{i,t} = \alpha_1\mathrm{LnPGDP}_{it}I\left(\mathrm{LnTRA}_{i,t} \le \lambda_1\right) + \alpha_2\mathrm{LnPGDP}_{it}I\left(\mathrm{LnTRA}_{i,t} > \lambda_1\right) + \alpha_{01}\mathrm{LnIS}_{i,t} + \alpha_{02}\mathrm{LnFI}_{i,t} + \alpha_{03}\mathrm{LnGI}_{i,t} + \mu_i + \varepsilon_{i,t} \tag{3}$$

$$\mathrm{LnEF}_{i,t} = \alpha_1\mathrm{LnPGDP}_{it}I\left(\mathrm{LnTRA}_{i,t} \le \lambda_1\right) + \alpha_2\mathrm{LnPGDP}_{it}I\left(\mathrm{LnTRA}_{i,t} > \lambda_1\right) + \alpha_{01}\mathrm{LnIS}_{i,t} + \alpha_{02}\mathrm{LnFI}_{i,t} + \alpha_{03}\mathrm{LnGI}_{i,t} + \mu_i + \varepsilon_{i,t} \tag{4}$$

where i consigns to an individual country, t is the time dimension. λ represents the threshold value. $\varepsilon_{i,t}$ is the random error term. μ_i. is the individual effect.

The formula of the double threshold model is as follows:

$$\begin{aligned}\mathrm{LnCO2}_{i,t} = {} & \alpha_1\mathrm{LnPGDP}_{it}I\left(\mathrm{LnTRA}_{i,t} \le \lambda_1\right) \\ & + \alpha_2\mathrm{LnPGDP}_{it}I\left(\lambda_1 < \mathrm{LnTRA}_{i,t} \le \lambda_2\right) \\ & + \alpha_3\mathrm{LnPGDP}_{it}I\left(\mathrm{LnTRA}_{i,t} > \lambda_2\right) + \alpha_{01}\mathrm{LnIS}_{i,t} + \alpha_{02}\mathrm{LnFI}_{i,t} \\ & + \alpha_{03}\mathrm{LnGI}_{i,t} + \mu_i + \varepsilon_{i,t}\end{aligned} \tag{5}$$

$$\begin{aligned}\mathrm{LnEF}_{i,t} = {} & \alpha_1\mathrm{LnPGDP}_{it}I\left(\mathrm{LnTRA}_{i,t} \le \lambda_1\right) \\ & + \alpha_2\mathrm{LnPGDP}_{it}I\left(\lambda_1 < \mathrm{LnTRA}_{i,t} \le \lambda_2\right) \\ & + \alpha_3\mathrm{LnPGDP}_{it}I\left(\mathrm{LnTRA}_{i,t} > \lambda_2\right) + \alpha_{01}\mathrm{LnIS}_{i,t} + \alpha_{02}\mathrm{LnFI}_{i,t} \\ & + \alpha_{03}\mathrm{LnGI}_{i,t} + \mu_i + \varepsilon_{i,t}\end{aligned} \tag{6}$$

Empirical methodology. Apreliminary analysis of panel data is necessary before estimating the threshold model. The unit root test is used to find out whether the data for the selected variable is stationary (Li et al. 2023). Panel unit root test refers to the unit root test of each cross-sectional series of variables in the panel data as a whole. Panel data can be divided into two types: homogeneous panel and heterogeneous panel, according to the different data generation methods.

Two unit root test methods, LLC (Levin et al. 2002) and IPS (Im et al. 2003), are used in this study. The LLC test adopts the form of the ADF test, but the LLC test assumes the homogeneity of each cross-section unit; that is, the regression coefficient of the first-order lag term of each longitudinal section time series must be the same. $\rho_i = \rho$. Moreover, it also requires each section to be independent of each other. The test formula is as Eq. (7).

$$\Delta y_{i,t} = \rho y_{i,t-1} + \sum_{L=1}^{P_i} \beta_{iL}\Delta y_{i,t-L} + z'_{i,t}\gamma_i + \varepsilon_{i,t}, \quad \alpha = \rho - 1 \tag{7}$$

where, $z_{i,t}$ represents the fixed effect or time trend term, $z_{i,t} = \{0\}$, $z_{i,t} = \{1\}$, $z_{i,t} = \{0,1\}$. γ_i is the coefficient vector, and $\varepsilon_{i,t}$ is the stationary process.

The null and alternative hypotheses are as follows:

$$H_0 : \rho = 0;\ H_1 : \rho < 0 \tag{8}$$

Compared to LLC, IPS relaxes the assumption of homogeneity. It proposes a unit root test for heterogeneous panel data, which allows ρ_i to take different values in different cross-sectional units and performs unit root test with the mean t-bar of the DF statistics of each cross-sectional unit. The method is based on the following panel data model:

$$\Delta y_{i,t} = \rho_i y_{i,t-1} + \sum_{L=1}^{p_i} \beta_{iL}\Delta y_{i,t-L} + z'_{i,t}\gamma_i + \varepsilon_{i,t}, \quad i = 1, 2, \cdots, N;\ t = 1, 2, \cdots, T \tag{9}$$

The null and alternative hypotheses of IPS are: H_0: $\rho_i = 1$, which is true for all i. H_1: $\rho_i < 1$, true for at least one i. The test statistic is defined as follows:

$$\mathrm{t-bar} = \frac{1}{N}\sum_{i=1}^{N} t_i \tag{10}$$

IPS has given the critical value of the statistic t-bar at different levels of significance by means of stochastic simulation. It perfects the panel unit root test theory and is suitable for balanced panel data.

After determining the stability of the panel data, regression calculations can be performed on the data. This paper applies the threshold panel regression model proposed by Hansen (1999). The basic setting of the single threshold model is shown in Eq. (11).

$$Y_{i,t} = \alpha_0 R_{it} + \alpha_1 X_{it} I(q_{it} \le \lambda_1) + \alpha_2 X_{it} I(q_{it} > \lambda_1) + \mu_i + \varepsilon_{i,t} \tag{11}$$

where $Y_{i,t}$ is the explained variable. q_{it} is the threshold variable. X_{it} is the explanatory variable. R_{it} is the variable that has significant effect on the explained variable in addition to the core explanatory variable. I $(\cdot)$ is an indicative function, and the value in the corresponding brackets is 1 when the condition is satisfied, and 0 when the condition is not satisfied.

The estimation of the threshold λ_1 is shown in Eq. (12), and the applied method is ordinary least squares.

$$\widehat{\lambda_1} = arg\ \min S_1\left(\lambda_1\right) \tag{12}$$

The arg min function represents the set of λ_1 corresponding to the minimum sum of squared residuals. Then, the estimator of parameter α is: $\widehat{\alpha}(\lambda_1) = \left\{X^*(\lambda_1)'X^*(\lambda_1)\right\}^{-1}\left\{X^*(\lambda_1)'\lambda_1^*\right\}$. The residual vector is: $\widehat{\varepsilon}^*(\lambda_1) = Y^* - X^*(\lambda_1)\alpha^*(\lambda_1)$. The residual sum of squares is: $S_1(\lambda_1) = \widehat{\varepsilon}^*(\lambda_1)'\widehat{\varepsilon}^*(\lambda_1)$. The residual variance is: $\widehat{\sigma}^2\left(\widehat{\lambda_1}\right) = \varepsilon^{*\prime}\varepsilon^*/N(T-1) = S_1(\widehat{\sigma})/N(T-1)$.

In this paper, the Bootstrap method is used to test the model to test whether the threshold effect is statistically significant. We define the null hypothesis that there is no threshold effect, which is expressed as: H_0: $\alpha_1 = \alpha_2$. The alternative hypothesis is: H_1: $\alpha_1 \ne \alpha_2$. Constructing the F statistic to test the null hypothesis, $F_1 = \frac{S_0 - S_1\left(\widehat{\lambda_1}\right)}{\widehat{\sigma}^2}$. where, S_0 and S_1 are the residual sum of squares of the null hypothesis and the alternative hypothesis, respectively.

Table 1 Descriptive analysis of variables in 147 countries.

	Mean	Median	Max	Min	Sd	Skewness	Kurtosis	*N*
LnCO2	0.6002	0.8753	3.4174	−4.1158	1.5402	−0.6555	2.6546	3528
LnPGDP	8.4380	8.3684	11.3849	5.3900	1.4085	0.0753	2.1273	3528
LnTRA	4.0340	4.0200	5.8391	2.0549	0.5167	0.0663	3.0456	3528
LnEF	0.9253	0.9093	2.6328	−0.7132	0.6944	0.0002	2.0247	3528
LnIS	3.2440	3.2433	4.4402	2.0167	0.3788	0.0582	3.3783	3528
FI	4.9536	2.7169	449.0828	−40.0811	15.8228	17.0032	375.0253	3528
LnGI	4.0358	4.0477	4.5079	3.1068	0.2773	−0.3582	2.6082	3528

The rejection of the null hypothesis means that there exists threshold effect.

The next step is to test whether the threshold value is equal to the true value. Set the null hypothesis that the threshold value is equal to the true value. The likelihood ratio statistic is: $LR(\lambda_1) = \frac{S_1(\lambda_1) - S_1(\widehat{\lambda_1})}{\widehat{\sigma^2}}$. Suppose C($\alpha$) is a non-rejection interval, $C(\alpha) = -2\ln\left(1 - \sqrt{1-\alpha}\right)$, and α is the significance level. If $LR(\lambda_1) < C(\alpha)$, the null hypothesis is accepted, that is, the threshold estimate is considered meaningful when the significance level is α, and vice versa.

The basic setting of the double threshold model is:

$$Y_{i,t} = \alpha_0 R_{it} + \alpha_1 X_{it} I\left(q_{it} \le \lambda_1\right) + \alpha_2 X_{it} I\left(\lambda_1 < q_{it} \le \lambda_2\right) + \alpha_3 X_{it} I\left(q_{it} > \lambda_2\right) + \mu_i + \varepsilon_{i,t} \tag{13}$$

The estimation of the second threshold λ_2 is as Eq. (14).

$$S_2^{\lambda}(\lambda_2) = \begin{cases} S\left(\widehat{\lambda_1}, \lambda_2\right) & \widehat{\lambda_1} < \lambda_2 \\ S\left(\lambda_2, \widehat{\lambda_1}\right) & \lambda_2 < \widehat{\lambda_1} \end{cases} \tag{14}$$

$\widehat{\lambda}_2^{\lambda} = \arg\min S_2^{\lambda}(\lambda_2)$. The F_2 statistic is constructed to test which is more significant with single threshold and double threshold. $F_2 = \frac{S_1\left(\widehat{\lambda_1}\right) - S_2^{\lambda}\left(\widehat{\lambda_2^{\lambda}}\right)}{\widehat{\sigma^2}}$. If the value of F_2 is larger, the double threshold effect is more significant.

Empirical results

Unit root test. We first conduct an empirical analysis through a descriptive analysis of the variable's descriptive statistics. Table 1 summarizes descriptive statistics for all variables in 147 countries. The current study is conducted for a sample size of 3528 observations.

The results show that the average per capita carbon dioxide emissions over the study period is 1.8225 metric tons, the average per capita ecological footprint is 2.5226 gha, and the average per capita GDP is $4619.31. Table 2 presents descriptive statistics for the four income groups. High-income countries have the largest per capita carbon emissions and ecological footprints, while low-income groups have the smallest. High-income countries have the largest trade volume, with the mean being 64% over the study period. The results of descriptive statistics are realistic and confirmed in most studies.

Table 3 presents the unit root test results for panel data of all variables. The stationarity test is significant in econometric analysis to avoid spurious regression traps. This study applies two-panel stationarity tests, LLC and IPS unit root tests. Results for the global and four income groups show that all variables of interest are first-difference stationary. This situation is appealing because the variables are consistent with constant variance and zero mean.

Cointegration test. This paper uses the Pedroni cointegration test to explore whether there is a long-term correlation between variables. This lays the foundation for further regression analysis. The cointegration test results are shown in Tables 4 and 5. When carbon dioxide is used as an indicator of environmental pollution, the Pedroni test constructs seven statistics, and the results show that four of them reject the null hypothesis at the significance level of 1% or 5%. This proves a long-term stable cointegration relationship between LnCO2 and other variables. When ecological footprint is used as an indicator of environmental degradation, more than half of the seven statistics constructed by the Pedroni test for each study area pass the 1% or 5% significance test. There is a long-term equilibrium relationship between LnEF and other variables.

Threshold effect test. Carbon dioxide emissions and ecological footprint were used as explained variables respectively, and a nonlinear threshold panel model was constructed. Table 6 shows the threshold effect test results of panel data from 147 countries worldwide. Further, Table 7 presents the calculation results of the estimated value of the threshold. The double threshold effect of trade on the economic growth-carbon emission model passes the 10% significance level test. The two estimated threshold values are 4.188 and 5.019. The double threshold effect is significant at 10% when the ecological footprint is used as the explained variable. The estimated threshold values are 2.979 and 5.540.

Table 8 shows the threshold effect test results for the high-income group, the upper middle-income group, the lower middle-income group, and the low-income group. When carbon dioxide emissions are the explained variable, trade as the threshold variable shows a significant double threshold effect in the models of the four income groups. At the 5% level, the double threshold effect of high and lower middle-income groups is significant. For the upper middle- and low-income groups, the significance of the double threshold effect is 10%. In the model of trade on economic-ecological footprint, the four income groups face two scenarios: the single threshold effect and the double threshold effect. The single threshold effect is significant in the upper middle- and upper-income groups. The double threshold effect of low and lower middle-income countries passes the 5% significance level test.

Table 9 also displays the calculated results of threshold estimated values and 95% confidence intervals for the four income groups. It was discovered that different threshold effects and estimated values in the nonlinear trade models on carbon emissions and ecological footprint exist in the same income group countries. When comparing different income groups, the thresholds are also heterogeneous. As a result, it is critical to compare and study the various results in different regions.

Threshold estimation results. The threshold regression results for global panel data are shown in Table 10. Results demonstrate

Table 2 Descriptive analysis of variables in four income groups.

Grouping		Mean	Median	Max	Min	Sd	Skewness	Kurtosis	N
High income group	LnCO2	2.0763	2.0820	3.4174	0.3008	0.5079	−0.3146	3.5956	1056
	LnEF	1.7042	1.7043	2.6328	0.2300	0.2958	0.0765	4.1670	1056
	LnTRA	4.1590	4.0938	5.8391	2.6424	0.5479	0.2220	3.1235	1056
	LnPGDP	10.1431	10.3116	11.3849	8.5043	0.6124	−0.3312	2.3036	1056
	LnIS	3.2674	3.2433	4.3056	2.2256	0.3569	0.4236	3.9657	1056
	FI	7.8374	3.0609	449.0828	−40.0811	27.7358	10.2126	128.5140	1056
	LnGI	4.3095	4.3569	4.5079	3.7945	0.1570	−1.1440	3.5834	1056
Upper middle income group	LnCO2	1.0627	1.0592	2.7112	−0.7548	0.6772	0.0337	2.6146	1008
	LnEF	0.9421	0.9475	1.9145	0.0715	0.3409	0.0708	2.6374	1008
	LnTRA	4.0858	4.1032	5.2581	2.1977	0.4686	−0.3437	3.3909	1008
	LnPGDP	8.5477	8.5533	9.6078	6.6450	0.4780	−0.5741	3.5692	1008
	LnIS	3.3188	3.2962	4.4402	2.4077	0.3592	0.2536	2.9514	1008
	FI	4.4062	3.4140	55.0703	−10.2567	4.8999	3.4521	28.9854	1008
	LnGI	4.0453	4.0699	4.3993	3.4212	0.1869	−0.5764	2.8420	1008
Lower middle income group	LnCO2	−0.2764	−0.2515	2.0647	−2.5626	0.9598	0.2237	2.8469	1080
	LnEF	0.4372	0.3315	2.3646	−0.7132	0.5309	0.8286	3.7528	1080
	LnTRA	3.9970	3.9822	5.2780	2.7668	0.5018	−0.0569	2.4504	1080
	LnPGDP	7.4291	7.4414	8.6330	5.9496	0.5634	−0.1226	2.3626	1080
	LnIS	3.2543	3.2677	4.2866	2.0167	0.3702	−0.3570	3.9257	1080
	FI	3.2774	1.9842	43.9121	−37.1727	4.6079	2.6367	27.5745	1080
	LnGI	3.8802	3.9010	4.3146	3.1570	0.2075	−0.5916	3.2749	1080
Low income group	LnCO2	−2.2075	−2.3806	0.1303	−4.1158	0.8320	0.4815	3.2927	384
	LnEF	0.1121	0.0575	0.9523	−0.6762	0.3022	0.3645	2.5594	384
	LnTRA	3.6584	3.6516	4.5981	2.0549	0.3864	−0.1449	3.1788	384
	LnPGDP	6.2988	6.2833	7.9093	5.3900	0.4838	1.2422	5.4287	384
	LnIS	2.9543	2.8688	3.9665	2.2235	0.3801	0.5897	2.8517	384
	FI	3.1744	2.1037	46.2752	−5.1118	5.3631	4.1330	25.6464	384
	LnGI	3.6960	3.7133	3.9889	3.1068	0.1903	−0.6852	3.0904	384

Mean is the average, Sd is the standard deviation, Min is the minimum, Max is the maximum, and N is the number of observations.

Table 3 Unit root test of panel data.

Grouping			LnCO2	LnEF	LnTRA	LnPGDP	LnIS	FI	LnGI
Global	LLC	Level	−1.5151*	−1.3727*	−5.2113***	−2.0586**	−3.7848***	−8.1952***	−20.9845***
		Δ	−21.9756***	−23.3730***	−26.1267***	−16.7324***	−23.0929***	−28.2324***	−16.9986***
	IPS	Level	4.2705	−0.0850	−3.2912***	7.7419	−1.6851**	−12.1151***	−8.8335***
		Δ	−25.1832***	−30.5066***	−28.7285***	−18.5245***	−25.5569***	−35.0238***	−21.9993***
High income group	LLC	Level	1.58975	0.3096	−3.9189***	−6.2679***	−3.0327***	−4.1623***	−13.3297***
		Δ	−10.8512***	−13.7932***	−17.3535***	−12.2076***	−14.4835***	−14.8399***	−13.8794***
	IPS	Level	3.5837	1.3037	−1.5992*	−0.3689	−0.1752	−7.0497***	−6.6802***
		Δ	−14.0676***	−17.1413***	−15.8293***	−10.7254***	−15.1854***	−18.6725***	−14.2162***
Upper middle income group	LLC	Level	−3.3229***	−3.1226***	−2.1038**	−1.9991**	−2.0498**	−5.6241***	−13.1403***
		Δ	−14.4875***	−12.5038***	−13.7813***	−9.3888***	−12.1044***	−15.7143***	−7.0174***
	IPS	Level	−0.3412	−3.6305***	−1.5797*	4.8363	−1.2069	−7.1434***	−6.2053***
		Δ	−14.4603***	−16.1859***	−15.6977***	−10.7313***	−11.8744***	−19.0199***	−10.1499***
Lower middle income group	LLC	Level	−0.8635	−0.0192	−3.2901***	1.8218	−0.6548	−3.7609***	−9.6961***
		Δ	−10.0075***	−9.7364***	−13.7099***	−5.8446***	−11.0891***	−15.4811***	−5.8504***
	IPS	Level	3.6113	1.9531	−2.2660**	8.1468	−0.6334	−5.5920***	−2.9512***
		Δ	−12.8022***	−15.7484***	−16.1752***	−8.3137***	−13.7475***	−19.5200***	−10.3563***
Low income group	LLC	Level	0.3151	1.2570	0.0938	−1.2919*	−1.6084*	−2.6184***	−4.7603***
		Δ	−8.1311***	−11.0318***	−5.1347***	−5.4419***	−7.7659***	−9.5113***	−7.1226***
	IPS	Level	1.4979	0.1872	−0.9643	2.5799	−1.7995**	−4.0796***	−0.6943
		Δ	−8.1057***	−11.4075***	−8.2687***	−7.0341***	−9.9892***	−11.6435***	−9.2941***

Note: *, **, *** represent 10% significant level, 5% significant level and 1% significant level respectively. Δ represents the first difference.

that using trade as a threshold variable divides the effect of economic growth on carbon emissions into three intervals. When LnTRA is less than 4.188, the impact coefficient of per capita GDP on carbon dioxide is 0.3845. When LnTRA is between 4.188 and 5.019, the regression coefficient is 0.3766. When LnTRA is greater than 5.019, the coefficient is 0.3613. The positive effect of economic growth on carbon emissions gradually diminishes as trade crosses the two thresholds. Trade has a positive impact on improving global environmental quality. The nonlinear impact of trade on the GDP per capita-ecological footprint model has three stages as well. When trade is less than 19.67% of GDP, the positive coefficient of per capita GDP to per capita ecological

Table 4 Pedroni residual cointegration test results (CO2).

Series: LnCO2, LnTRA, LnPGDP, FI, LnGI, LnIS

Grouping		Statistic	*P*-value		Statistic	*P*-value
Global	Panel v-Statistic	−4.1635	1.0000	Group rho-Statistic	9.1996	1.0000
	Panel rho-Statistic	4.5700	1.0000	Group PP-Statistic	−7.9447***	0.0000
	Panel PP-Statistic	−7.8948***	0.0000	Group ADF-Statistic	−8.3655***	0.0000
	Panel ADF-Statistic	−8.4703***	0.0000			
High Income	Panel v-Statistic	−2.2600	0.9881	Group rho-Statistic	5.2669	1.0000
	Panel rho-Statistic	1.7863	0.9630	Group PP-Statistic	−3.6072***	0.0002
	Panel PP-Statistic	−6.7003***	0.0000	Group ADF-Statistic	−2.6794***	0.0037
	Panel ADF-Statistic	−6.4451***	0.0000			
Upper Middle Income	Panel v-Statistic	−3.2288	0.9994	Group rho-Statistic	4.2934	1.0000
	Panel rho-Statistic	1.6090	0.9462	Group PP-Statistic	−5.0498***	0.0000
	Panel PP-Statistic	−5.8643***	0.0000	Group ADF-Statistic	−5.2018***	0.0000
	Panel ADF-Statistic	−7.3357***	0.0000			
Lower Middle Income	Panel v-Statistic	−3.6238	0.9999	Group rho-Statistic	6.5462	1.0000
	Panel rho-Statistic	4.8010	1.0000	Group PP-Statistic	−7.2087***	0.0000
	Panel PP-Statistic	−3.9794***	0.0000	Group ADF-Statistic	−6.8838***	0.0000
	Panel ADF-Statistic	−3.3952***	0.0003			
Low Income	Panel v-Statistic	−4.0565	1.0000	Group rho-Statistic	6.1567	1.0000
	Panel rho-Statistic	4.6556	1.0000	Group PP-Statistic	−8.2960***	0.0000
	Panel PP-Statistic	−1.9222**	0.0273	Group ADF-Statistic	−1.9399**	0.0262
	Panel ADF-Statistic	−2.8809***	0.0020			

Table 5 Pedroni residual cointegration test results (EF).

Series: LnEF, LnTRA, LnPGDP, FI, LnGI, LnIS

Grouping		Statistic	*P*-value		Statistic	*P*-value
Global	Panel v-Statistic	−2.1190	0.9830	Group rho-Statistic	7.3062	1.0000
	Panel rho-Statistic	4.7494	1.0000	Group PP-Statistic	−18.3612***	0.0000
	Panel PP-Statistic	−7.2941***	0.0000	Group ADF-Statistic	−15.0766***	0.0000
	Panel ADF-Statistic	−8.2713***	0.0000			
High Income	Panel v-Statistic	−1.0009	0.8416	Group rho-Statistic	4.7009	1.0000
	Panel rho-Statistic	1.9205	0.9726	Group PP-Statistic	−11.3476***	0.0000
	Panel PP-Statistic	−6.7122***	0.0000	Group ADF-Statistic	−8.5196***	0.0000
	Panel ADF-Statistic	−7.4156***	0.0000			
Upper Middle Income	Panel v-Statistic	−1.0212	0.8464	Group rho-Statistic	3.2303	0.9994
	Panel rho-Statistic	1.1110	0.8667	Group PP-Statistic	−11.3459***	0.0000
	Panel PP-Statistic	−6.6471***	0.0000	Group ADF-Statistic	−10.2345***	0.0000
	Panel ADF-Statistic	−7.6193***	0.0000			
Lower Middle Income	Panel v-Statistic	−2.2089	0.9864	Group rho-Statistic	4.4106	1.0000
	Panel rho-Statistic	4.1882	1.0000	Group PP-Statistic	−9.3047***	0.0000
	Panel PP-Statistic	−2.5286***	0.0057	Group ADF-Statistic	−8.5867***	0.0000
	Panel ADF-Statistic	−5.9406***	0.0000			
Low Income	Panel v-Statistic	−0.5564	0.7110	Group rho-Statistic	3.1306	0.9991
	Panel rho-Statistic	1.7173	0.9570	Group PP-Statistic	−7.4826***	0.0000
	Panel PP-Statistic	−4.8723***	0.0000	Group ADF-Statistic	−5.7020***	0.0000
	Panel ADF-Statistic	−5.0736***	0.0000			

Table 6 Test of the threshold effect in 147 countries.

Explained variable	Threshold number	F-value	*P*-value	Critical value		
				1%	5%	10%
LnCO2	Single	27.950**	0.024	35.494	22.367	16.305
	Double	25.891*	0.074	56.984	32.162	21.469
LnEF	Single	16.506*	0.086	32.685	20.723	15.265
	Double	10.655*	0.060	42.533	11.564	8.629

Note: ***, **, * represent significance at the significance level of 1%, 5%, and 10% respectively.

footprint is 0.2818. The coefficients are 0.2727 and 0.2915 when LnTRA crosses two thresholds (2.979 and 5.540). The coefficient change follows a U-shaped pattern. The estimated value of the second threshold, on the other hand, is greater, and the data on trade crossing the second threshold is less. As a result, trade reduces the positive impact of economic growth on the environment degradation. The trend of coefficient change caused by the threshold effect is depicted in Fig. 2. From the new perspective of trade as a threshold variable, we find that it is the obvious effect of trade on mitigating environmental pressure.

The environmental effects of control variables are also investigated. The structure of the industrial sector has a significant positive impact on carbon emissions and the environmental footprint. Because industrial development consumes a lot of energy, it inevitably increases environmental pressure. This corresponds to prior research Hu et al. (2020). The regression results for foreign investment are insignificant. Globalization index promotes carbon emissions and ecological footprint. The promoting effect of globalization on environmental degradation has also been confirmed in Adebayo and Kirikkaleli (2021)'s research.

Various income groups have different policies according to their economic development and environmental governance levels. This study takes into account regional heterogeneity and then performs regression analysis on the threshold model of the four income groups. The regression results of the two models for each income group are shown in Table 11.

The double threshold effect of trade on PGDP-CO_2 is significant for the high-income group, with two estimated threshold values of 4.075 and 4.925. The coefficient is 0.0609 when LnTRA is less than 4.075; and 0.0545 when LnTRA is between 4.075 and 4.925. The coefficient is 0.0362 when LnTRA is greater than 4.925. The threshold effect gradually reduces the promotion of economic development on CO_2 emissions. This is consistent with the regression results of panel data from 147 countries. The difference is that the coefficients in high-income countries are smaller. When ecological footprint is used as the explained variable, similar results are obtained. Trade divides the PGDP-EF model into two intervals under the single threshold effect. The coefficient is 0.2754 when LnTRA is less than 4.931. When LnTRA exceeds 4.931, the coefficient decreases to 0.2645. Trade development in high-income countries contributes to environmental improvement. Figure 3 depicts the trend of nonlinear coefficient change caused by the threshold effect.

The results of the calculation for the upper middle-income group are intriguing. When carbon dioxide emissions are the explained variable, trade divides the threshold model into three stages. The positive coefficient of PGDP to CO2 is 0.4941 when LnTRA is less than 3.675. The coefficient rises to 0.5109 when LnTRA is greater than 3.675 but less than 4.022. When LnTRA exceeds 4.022, the coefficient falls to 0.5041. The coefficient exhibits an inverted U-shaped trend, which is consistent with the EKC hypothesis. There is a single nonlinear effect of trade on the ecological footprint. The coefficients are 0.3252 and 0.3315 before and after the threshold value (3.706). Upper middle-income countries' trade openness has a positive impact on environmental degradation. Figure 4 depicts the changing trend of the coefficients. Economic growth in upper middle-income countries has a greater positive impact on environmental pressures than economic growth in high income countries. Trade has the opposite effect as well.

Both models with the explained variables of carbon emissions and ecological footprint exhibit a double threshold effect in the regression results for the lower middle-income group. With coefficients of 0.7340,0.7502, and 0.7766, the trade variable divides the economic impact on carbon emissions into three stages. Trade expansion raises the coefficient. Economic growth has a smaller positive impact on the environment than carbon emissions. When the trade share of GDP is less than 32.98%, the regression coefficient is 0.2579. When the trade openness is between 32.98% and 142.17%, the coefficient is 0.2687. When the trade exceeds 142.17, the coefficient rises to 0.2979. The regression coefficients are all significant at the 1% level. This is the inverse trend of the coefficient change observed in high-income countries. This also lends support to the pollution paradise hypothesis (Guzel and Okumus 2020). Trade, in both

Table 7 Estimated threshold value in 147 countries.

Explained variable		Estimated threshold value	95% confidence interval
LnCO2	λ_1	4.188	[4.173, 4.230]
	λ_2	5.019	[4.864, 5.040]
LnEF	λ_1	2.979	[2.787, 3.062]
	λ_2	5.540	[2.787, 5.540]

Table 8 Test of the threshold effect in four income groups.

Grouping	Explained variable	Threshold number	*F*-value	*P*-value	Critical value		
					1%	5%	10%
High income	LnCO2	Single	82.643***	0.002	47.259	32.577	22.432
		Double	21.324**	0.032	29.317	19.484	13.388
	LnEF	Single	29.627*	0.058	48.847	31.238	22.677
Upper middle income	LnCO2	Single	32.382**	0.018	45.014	22.083	16.643
		Double	10.029*	0.084	26.539	13.535	9.074
	LnEF	Single	12.980***	0.078	29.153	15.584	11.028
Lower middle income	LnCO2	Single	24.649*	0.052	42.945	24.757	17.284
		Double	17.696**	0.044	33.147	16.088	11.822
	LnEF	Single	38.759***	0.000	23.428	14.125	9.757
		Double	22.013***	0.010	22.607	12.679	9.407
Low income	LnCO2	Single	11.954**	0.048	18.933	11.860	8.748
		Double	9.827*	0.090	21.744	13.648	9.162
	LnEF	Single	12.469**	0.034	21.609	11.350	8.684
		Double	6.990**	0.024	9.613	5.637	4.082

Note: ***, **, * represent significance at the significance level of 1%, 5%, and 10% respectively.

models, increases environmental stress in lower middle-income countries. Figure 5 depicts the trend of the coefficient change. In the lower middle-income group, trade contributes to environmental degradation. This corresponds to the investigation of Muhammad et al. (2020).

Table 9 Estimated threshold value in four income groups.

Grouping	Explained variable		Estimated threshold value	95% confidence interval
High income	LnCO2	λ_1	4.075	[4.050, 4.083]
		λ_2	4.925	[4.862, 4.931]
	LnEF	λ_1	4.931	[4.912, 5.025]
Upper middle income	LnCO2	λ_1	3.675	[3.652, 3.695]
		λ_2	4.022	[3.698, 4.295]
	LnEF	λ_1	3.706	[2.880, 4.841]
Lower middle income	LnCO2	λ_1	3.267	[3.164, 4.417]
		λ_2	4.714	[4.653, 4.756]
	LnEF	λ_1	3.496	[3.354, 3.594]
		λ_2	4.957	[4.892, 4.974]
Low income	LnCO2	λ_1	3.142	[2.964, 3.269]
		λ_2	3.811	[2.964, 3.880]
	LnEF	λ_1	3.562	[3.541, 3.568]
		λ_2	3.595	[2.964, 4.558]

Table 10 Regression results of threshold model in 147 countries.

Variable	Threshold model (LnCO2)	Threshold model (LnEF)
LnPGDP	0.3845^{***} ($q \leq 4.188$) (16.81)	0.2818^{***} ($q \leq 2.979$) (17.89)
	0.3766^{***} ($4.188 < q \leq 5.019$) (16.41)	0.2727^{***} ($2.979 < q \leq 5.540$) (17.42)
	0.3613^{***} ($q > 5.019$) (15.53)	0.2915^{***} ($q > 5.540$) (17.09)
LnIS	0.3000^{***} (11.51)	0.1133^{***} (6.38)
FI	0.0004 (1.43)	−0.0001 (−0.51)
LnGI	0.4987^{***} (10.76)	0.0270 (0.86)
Constant	-5.6015^{***} (−36.23)	-1.8545^{***} (−17.64)
R^2_w	0.3438	0.2002
F-test	258.12	144.81
NG	147	147
N	3528	3528

Note: *, **, *** represent 10% significant level, 5% significant level and 1% significant level respectively. Figures in parentheses are the t-statistics of the coefficients. NG represents the number of groups. *N* is the number of observations.

The coefficients of the three regression intervals divided by the trade-carbon emissions threshold model are 0.6716, 0.6459, and 0.6619 for low-income countries. The coefficients become smaller first, then larger. The trade-ecological footprint model has two thresholds: 3.562 and 3.595. When the trade share is less than 35.23%, the regression coefficient is 0.1732. When the trade is between 35.23% and 36.42%, the positive effect becomes stronger (the coefficient is 0.1898). When trade openness exceeds 36.42%, the coefficient decreases to 0.1794. In an inverted U-shape, the coefficient changes. Figure 6 also displays the nonlinear results. At the 1% level, the regression results are highly significant.

When comparing the regression results longitudinally across the four income groups, the regression coefficient of economic growth on carbon emissions is lowest for high-income countries and highest for lower-middle-income countries. The positive effect of per capita GDP on ecological footprint is smallest in high-income countries, while the coefficient is greatest in upper-middle-income countries. As income levels increase, the impact of economic growth on environmental pressure initially grows and then diminishes, aligning with the EKC hypothesis. The level of economic development in low-income countries is lower, resulting in a lower degree of environmental pollution. However, as per capita income increases, the degree of environmental degradation tends to rise in tandem with economic growth. The regression coefficients are larger in lower middle income and upper middle-income countries. When economic development reaches a tipping point, with additional increases in per capita income, environmental pollution tends to fall from high to low, and environmental quality gradually improves. Economic growth shows the least but positive effect on environmental pressures in the high-income group. In other words, high-income countries with a high technological content, good economic efficiency, low resource consumption, and fully utilized human resource advantages represent the future path of industrial development. We also discovered heterogeneity in the mechanisms by which control variables affect environmental degradation.

Discussion

This study investigates the non-linear effect of trade protection on the environmental Kuznets curve. Section "Empirical results" systematically analyzes the impact mechanism of trade on the relationship between economic growth and carbon emissions/ecological footprint from both the global perspective and the

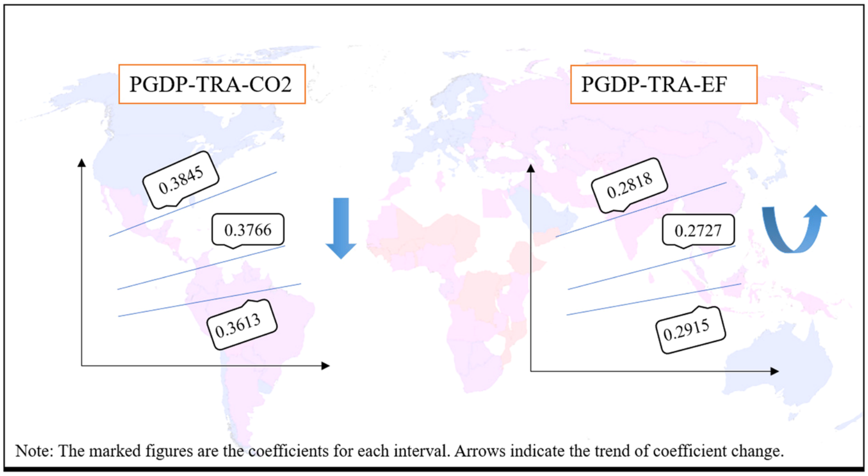


Fig. 2 Nonlinear coefficient change trend in global.

Table 11 Regression results of threshold model of four income groups.

Variable	High Income		Upper Middle Income		Lower Middle Income		Low Income	
	(LnCO2)	(LnEF)	(LnCO2)	(LnEF)	(LnCO2)	(LnEF)	(LnCO2)	(LnEF)
LnPGDP LnTRA $\le \lambda_1$	0.0609** (1.98)	0.2754*** (8.83)	0.4941*** (13.47)	0.3252*** (12.46)	0.7340*** (15.37)	0.2579*** (8.60)	0.6716*** (8.73)	0.1732*** (5.02)
LnPGDP (λ_1 < LnTRA $\le \lambda_2$)	0.0545* (1.78)		0.5109*** (13.86)		0.7502*** (15.65)	0.2687*** (8.91)	0.6459*** (8.41)	0.1898*** (5.43)
LnPGDP(LnTRA > λ_2)	0.0362 (1.17)	0.2645*** (8.43)	0.5041*** (13.63)	0.3315*** (12.63)	0.7766*** (15.98)	0.2979*** (9.77)	0.6619*** (8.81)	0.1794*** (5.24)
LnIS	0.6717*** (18.09)	0.6682*** (17.67)	−0.2754*** (−5.77)	−0.0012 (−0.03)	0.2036*** (4.14)	−0.0314 (−1.01)	0.1827*** (2.90)	−0.0596** (−2.01)
FI	0.0003* (1.85)	−0.0001 (−0.79)	0.0092*** (6.18)	0.0068*** (6.44)	−0.0029* (−1.76)	−0.0010 (−1.00)	0.0040* (1.69)	0.0041*** (3.69)
LnGI	0.4353*** (5.70)	0.2398*** (3.13)	−0.1945** (−2.18)	−0.1388** (−2.20)	0.3780*** (4.14)	0.2230*** (3.90)	0.3938*** (3.89)	−0.3101*** (−6.64)
Constant	−2.5618*** (−7.69)	−4.2931*** (−13.06)	−1.5864*** (−5.92)	−1.3449*** (−7.11)	−7.9765*** (−30.30)	−2.3100*** (−13.99)	−8.3337*** (−22.24)	0.3039* (1.77)
R^2_w	0.2902	0.2979	0.3844	0.3259	0.5391	0.3409	0.5173	0.1544
F-test	216.05	60.41	273.32	125.64	225.62	204.94	113.47	200.62
N	1056	1056	1008	1008	1080	1080	384	384
NG	44	44	42	42	45	45	16	16

Note: *, **, *** represent 10% significant level, 5% significant level and 1% significant level respectively. Figures in parentheses are the t-statistics of the coefficients. NG represents the number of groups. N is the number of observations.

standpoint of four income groups. Several intriguing findings are worth discussing and provide insights into addressing the research questions posed in this paper.

(i) The EKC assumption holds within the study's scope. The 147 countries analyzed in this paper are categorized into four income groups based on World Bank criteria. Low-income countries typically denote those with relatively underdeveloped economies. In the regression results of the threshold model, the positive coefficient of economic growth for low-income groups on carbon emissions falls between 0.6 and 0.7. As the income level increases, in lower-middle-income countries, the positive coefficient of economic growth on carbon emissions becomes more substantial, ranging from 0.7 to 0.8. After the income level crosses the inflection point of the EKC, the coefficient diminishes. The regression coefficient of economic growth on carbon emissions in the upper-middle-income group is around 0.5. High-income countries, characterized by a relatively developed economy, exhibit the smallest positive effect of the economy on environmental degradation, with a coefficient of less than 0.07. Overall, the changes in the coefficients display a U-shaped curve pattern. In other words, as the level of economic development improves, environmental quality initially deteriorates and then gradually improves. This trend is also observed when the explained variable is the ecological footprint. The findings affirm the presence of the EKC, aligning with prior research findings (Farooq et al. 2022). Economic development in low-income countries tends to rely more heavily on the exploitation of natural resources, including mining, deforestation, and agriculture. This economic structure contributes to the over-exploitation of resources and environmental damage. Additionally, these countries often lack robust environmental policies and regulatory systems (Iyamu et al. 2020). Middle-income countries may experience more pronounced environmental degradation compared to low-income countries. Typically, these countries have achieved certain level of economic development, with accelerated industrialization and urbanization processes. Consequently, large-scale industrial activities, infrastructure construction, and urban sprawl in middle-income countries result in substantial consumption of natural resources and contribute significantly to environmental stress and pollution (Martínez-Zarzoso and Maruotti 2011). Despite achieving some economic development, middle-income countries may still fall behind in environmental technology and innovation. Additionally, there might be a time lag between the emergence of environmental problems and the realization of corresponding measures due to economic development issues. High-income countries generally exhibit higher environmental quality, primarily because they typically possess advanced technology and robust infrastructure. This enables them to implement effective environmental protection measures and pollution control (Hoareau et al. 2021). Furthermore, high-income countries typically boast a diversified economic structure, not solely dependent on natural resource extraction but also emphasizing the development of service industries, technological innovation, and the knowledge economy. This diversified economic structure contributes to a reduction in environmental pressure, resource consumption, and pollution emissions.

(ii) Trade protectionism exacerbates environmental degradation. The impact of trade protection exhibits non-linear effects in the economic growth-environmental degradation model (Ge et al. 2022). In essence, trade openness is beneficial for enhancing the quality of the global

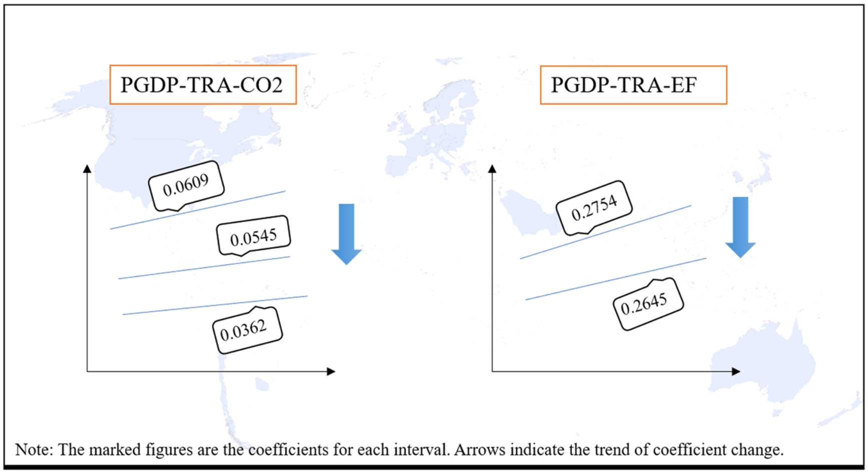


Fig. 3 Nonlinear coefficient change trend in high income group.

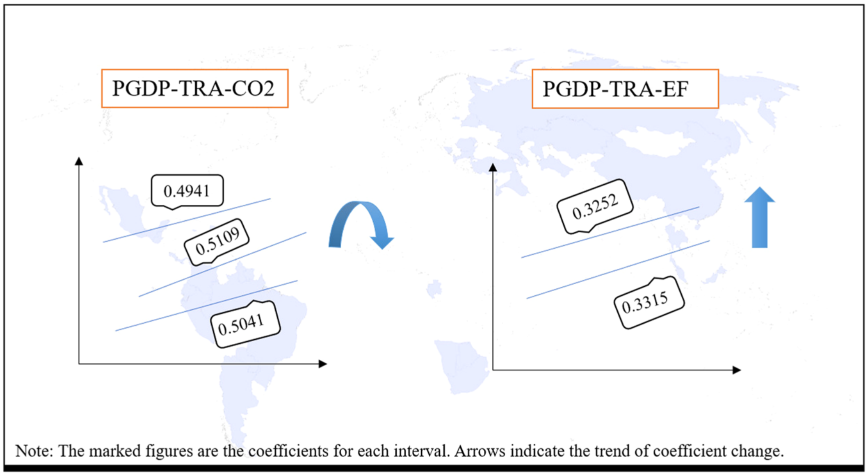


Fig. 4 Nonlinear coefficient change trend in upper middle-income group.

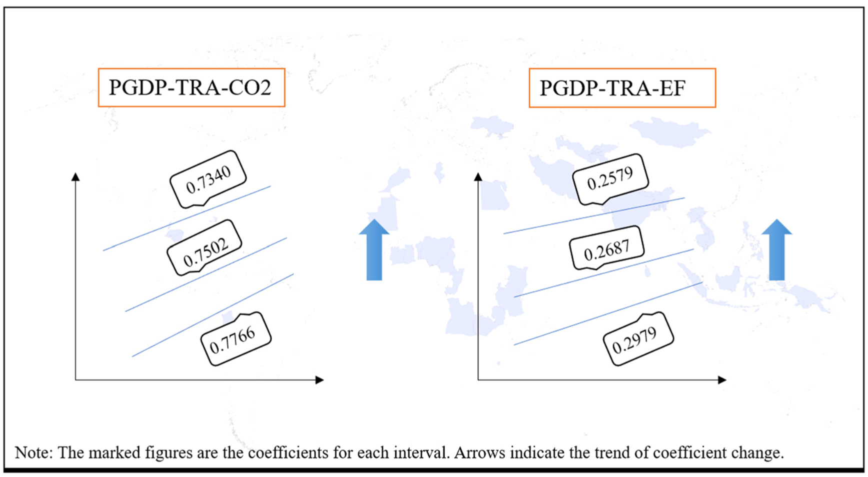


Fig. 5 Nonlinear coefficient change trend in lower middle-income group.

environment (Jiang et al. 2022). Results show that the influence of economic growth on carbon emissions gradually diminishes as trade successively surpasses thresholds. Openness to trade fosters technological innovation and the transfer of knowledge. Through international trade, enterprises and individuals can access new technologies, advanced management practices, and innovative ideas from other countries, thereby promoting technological progress and economic development. Furthermore, trade openness has facilitated advancements in environmental technology and standards. In the realm of international trade, countries are compelled to adhere to requirements and standards for

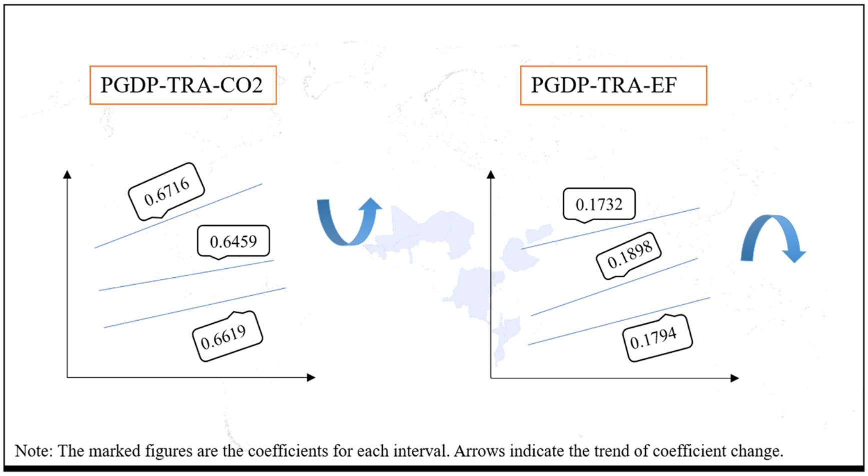


Fig. 6 Nonlinear coefficient change trend in low-income group.

environmental protection, fostering the development and application of eco-friendly technologies. This, in turn, aids in the reduction of environmental pollution and the efficient use of resources. This paper also provides another interesting finding. In the threshold regression results concerning trade's impact on the ecological footprint, there is a U-shaped change in the positive coefficient of economic growth as trade increases. The larger estimate for the second threshold provides fresh insights. It is crucial to note that trade openness may also have adverse effects on the environment, such as the over-exploitation of resources. Consequently, to maximize the positive impact of trade openness, the international community should adopt appropriate environmental protection measures and sustainable development strategies, ensuring a balance between economic growth and environmental conservation.

(iii) For countries with diverse income levels, there exists heterogeneity in the non-linear impact of trade protection on the economy-environment relationship. As trade increases, the positive coefficient of economic growth in relation to carbon emissions and ecological footprint within the high-income group exhibits a declining trend. Trade has the potential to enhance environmental quality in high-income countries. However, it contributes to environmental degradation to varying extents in upper-middle-income, lower-middle-income, and low-income countries. These findings align with the pollution haven hypothesis (Gyamfi et al. 2021). When a country or region enforces more stringent environmental protection laws and regulations, high-pollution industries may relocate to countries or regions with less stringent environmental laws and regulations, giving rise to what is commonly known as a "pollution haven." Enterprises in pollution-intensive industries tend to establish themselves in countries or regions with comparatively lower environmental standards (Banerjee and Murshed 2020). Free trade facilitates the transfer of high-carbon industries across borders, with developed countries benefiting and experiencing an improvement in environmental quality. Conversely, developing countries, acting as host nations for foreign investment, often face environmental degradation as a consequence (Essandoh et al. 2020).

Conclusions, implications, and limitation

Conclusion. This study conducted a comprehensive investigation into the intricate relationship between economic growth, trade protectionism, and environmental indicators across 147 countries, segmented into four income groups. The utilization of the Pedroni cointegration test further validated the existence of stable long-term correlations between carbon emissions, ecological footprint, and other variables, establishing the groundwork for nuanced regression analyses. Notably, the study pioneered the exploration of threshold effects, unveiling non-linear relationships between trade, economic growth, and environmental outcomes across income groups. The elucidation of threshold models revealed intriguing insights, showcasing varying impacts of trade on economic growth, carbon emissions, and ecological footprints. Particularly noteworthy were the distinct thresholds identified across income groups, delineating changes in the relationships between trade, economic growth, and environmental impacts. These findings underscored the nuanced nature of economic development's impact on environmental degradation, supporting theories such as the EKC within specific income brackets while uncovering divergences in others.

(i) The study supported the EKC, revealing an inverted U-shaped relationship between economic growth and environmental degradation. The degree of environmental pollution in low-income countries is relatively low, and the regression coefficient of economic growth on environmental degradation is relatively small. The coefficient values become larger for lower-middle-income and upper-middle-income countries. High-income countries have the smallest coefficients. This corresponds to the EKC assumption. With the increase of income level, the pressure of economic growth on the environment first increases and then decreases.

(ii) The study revealed the nuanced impact of trade protectionism on environmental degradation. While trade openness globally enhanced environmental quality, nonlinear effects were evident in models examining the relationship between economic growth and environmental degradation. Trade played a pivotal role in promoting technological innovation, fostering economic development, and elevating environmental standards. However, maintaining an optimal balance is imperative to avoid the over-exploitation of resources.

(iii) Heterogeneity in the non-linear effects of trade protectionism was apparent across income groups. For different income groups, trade openness reduces environmental degradation in the high-income group but has the opposite effect in the upper-middle and lower middle-income groups, supporting the pollution haven hypothesis. This underscores the importance of implementing stringent environmental regulations and adopting sustainable development strategies to counterbalance trade-induced environmental impacts in developing economies.

Policy implication. This comprehensive analysis highlights the multidimensional interplay between economic growth, trade openness, and environmental quality. It underscores the necessity for tailored policies that take into account income-specific dynamics. These insights carry significant implications for global policymakers, urging the adoption of sustainable development strategies that harmonize economic progress with environmental preservation. This approach ensures a balanced and equitable trajectory toward global sustainability. The paper derives actionable policy recommendations from the conclusive findings:

Environmental Kuznets Hypothesis and Global Collaboration. The globally recognized Environmental Kuznets Hypothesis emphasizes that economic growth doesn't inherently harm the environment. By contrast, it can spur improved environmental governance. To advance this trajectory, global cooperation should intensify to establish and implement emission reduction targets and facilitate a transition towards clean energy. Developed nations should significantly increase development aid and resource transfers, assisting developing countries in implementing policies and projects for environmental protection and sustainable development. This concerted effort aims to foster a more balanced and environmentally conscious global economy.

Trade policies and environmental balance. Recognizing that trade protectionism impedes both global economic progress and environmental improvement, countries should actively advocate for environmentally friendly trade agreements. It is crucial to strike a balance between trade liberalization and environmental protection. Making meaningful progress in international cooperation and dialog on trade and the environment is essential, involving collaboration among international organizations, governments, and businesses. Strengthening cross-border environmental governance is critical, especially in collectively addressing transnational environmental challenges like climate change and biodiversity conservation.

Pollution haven hypothesis and tailored strategies. The validation of the pollution haven hypothesis underscores the differential impact of globalization across various income groups. Developed nations resort to trade protectionism to foster domestic markets and productivity. Each country should tailor its policies to meet its unique developmental needs, with a focus on promoting environmentally sustainable practices. Recognizing the disparities in economy and technology between developed and developing nations, the former adhere to stricter environmental standards and invest more significantly in environmental protection. Developing countries should actively introduce advanced technology and seek high-quality foreign investment to improve environmental quality. Simultaneously, there should be an emphasis on achieving trade sustainability by adopting green trade practices and regulating the import and export of high-pollution and high-energy-consuming products. In the era of globalization, increasing the proportion of the tertiary industry in foreign direct investment within developing countries proves to be an effective avenue for alleviating environmental pressures.

Limitations and future research. This research introduces a robust and comprehensive nonlinear model system that intricately integrates trade, economy, and the environment, making a significant contribution to existing scholarly literature. By delving into deeper layers of nonlinear relationships, it significantly enhances our understanding of the complex interplay between environmental factors and economic growth. Specifically designed for scrutinizing the impact of trade on the economy-environment relationship through panel data analysis, this model provides theoretical insights relevant to exploring threshold effects across diverse economies. Future investigations may extend variable transformations to uncover additional nonlinear relationships among a myriad of variables.

Meanwhile, this article acknowledges its limitations and outlines potential future research avenues. The current study's geographical scope encompasses 147 countries within the time range of 1995–2018, constrained by the availability of panel data. Future investigations could mitigate these limitations by expanding the dataset, extending the research period, and augmenting the sample size. This expansion aims to yield more precise and comprehensive research outcomes. Moreover, while the present study employs an appropriate regression method, future research could benefit from the utilization of more advanced econometric techniques. These advanced methods could serve as supplementary approaches, enriching the depth and rigor of analysis within this paper. Further research opportunities lie in exploring potential alternative hypotheses or additional variables that could enhance the overall understanding of the topic. By considering these factors, future studies can provide a more nuanced and comprehensive view of the relationships between trade, economy, and the environment. Additionally, future research endeavors will emphasize a deeper examination of the substantive implications derived from the empirical exercises conducted in this study. This approach ensures a more profound understanding of the practical implications and outcomes, contributing significantly to the field's development.

Data availability

The datasets publicly available are through https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/VOQYZF.

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Author contributions
QW: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Supervision, Writing- Reviewing and Editing. XW: Methodology, Software, Data curation, Investigation Writing- Original draft, Writing- Reviewing and Editing. RL: Conceptualization, Methodology, Data curation, Investigation Writing- Original draft, Writing- Reviewing. TJ: Writing- Original draft preparation, Writing- Reviewing.

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