scientific reports

Check for updates

OPEN

Effects of geopolitical risk on environmental sustainability and the moderating role of environmental policy stringency

Heng Luo[1,2] & Ying Sun[1]✉

This study investigates the impact of geopolitical risk (GPR) on consumption-based carbon (CCO_2) emissions as well as the moderating role of environmental policy stringency (EPS) on the above relationship. Based on data collected from 27 countries from 1990 to 2020, the basic results from the sample of the study indicate that GPR accelerates CCO_2 emissions. Quantile regression results reveal that the effect of GPR is more pronounced in countries with higher CCO_2 emissions. Moreover, EPS weakens the escalating effect of GPR on CCO_2 emissions. The robust test results validate the findings reported in the basic regression model. The heterogeneity test indicates that the impact of GPR on CCO_2 emissions is greater in developing countries compared in developed countries. The study also proposes these policy implications based on the findings: (1) countries should ensure a stable political environment, establish a robust legal system and promote energy transition; and (2) the scope of environmental taxes should be expanded where different tax rates should be imposed in order to be useful in reducing CCO_2 emissions.

Keywords Geopolitical risk, Consumption-based CO_2 emissions, Environmental policy stringency, Quantile regression

Environmental sustainability has become a prominent issue as it is essential to both economic progress and human health. This has led to alliances among nations and international institutions to adopt efficient measures that are driven by concerns on environmental deterioration. With the goal of reducing greenhouse gas emissions and promoting environmental sustainability, nations from around the world have taken part in conferences like the Conference of Parties (COP) series as well as international agreements like the Kyoto Protocol, the Paris Agreement, and the United Nations Framework Convention on Climate Change. The COP 26, for instance, set a global goal to reduce existing carbon dioxide emissions by 50% of 2010 levels[1]. Following that, COP 27 underscored the significance of climate change and the necessity for global cooperation to attain carbon neutrality. In addition, COP 28 introduced the global stocktake and pledges to transition away from fossil fuels in energy systems.

In extant literature, scholars have paid attention to drivers of environmental degradation, such as trade diversification[2], energy consumption[3], and foreign direct investment (FDI)[4]. Meanwhile, solutions for carbon neutrality have also been widely explored. These solutions include renewable energy[5], green innovation[6], environmental taxes[7], and environmental policy stringency (EPS)[8]. However, some scholars contend that environmental degradation is challenging to address due to uncertainty[9,10]. In addition to economic uncertainty, geopolitical risk (GPR) stands as one of the most pervasive uncertainties worldwide. It encompasses tensions and uncertainty that arise from factors like war, peace threats, military buildups, nuclear threats, and terrorism. According to Fig. 1, since the Cuban Crisis in 1962, followed by events such as the Gulf War, September 11, and the Paris Terror Attacks, the Historical GPR Index has seen peaks. For instance, all these events significantly impact economic activities and investments. GPR has two opposite effects on the environment, which are the escalating effect and mitigating effect[11,12]. In the former, GPR reduces the use of renewable energy sources and increases the use of non-renewable ones like petroleum, which leads to higher CO_2 emissions. Conversely, the latter effect operates in the opposite direction. In terms of theory analysis, there is no consensus on the impact of GPR on environmental quality.

[1]School of Digital Economy and Industry, Jiangxi University of Engineering, Xinyu, Jiangxi, China. [2]School of Business and Economics, Universiti Putra Malaysia, Serdang, Malaysia. ✉email: 2398596174@qq.com

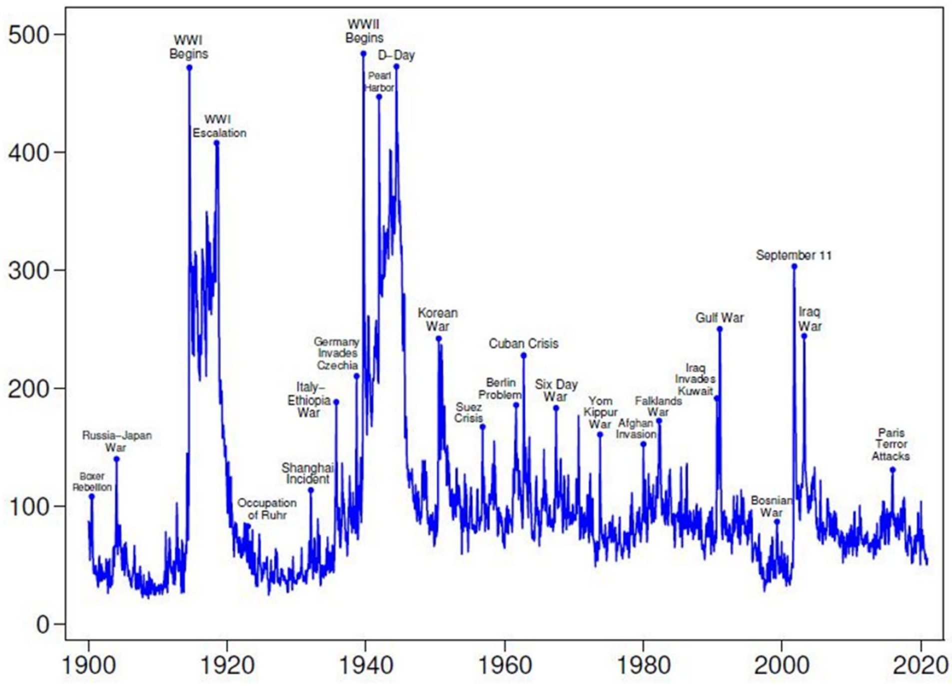

Figure 1. Historical GPR Index.

Despite the importance of examining how GPR influences environmental problems, little empirical research has been done on the issue. Hence, this study aims to analyse the influence of GPR on consumption-based carbon (CCO_2) emissions. In addition, as EPS plays a crucial role in the global path towards improving environmental quality, this study incorporates the moderating effect of EPS on the above nexus. The research makes several contributions to the existing body of literature. First, the trend of GPR world has been volatile and more dynamic over the last few years. As such, GPR has garnered significant attention from numerous experts in environmental economics literature. The Ukraine/Russia conflict and the ongoing supply chain challenges that stem from the COVID-19 pandemic underscore the significance of GPR in shaping economic and environmental dynamics. Although studies have been conducted on GPR in the environmental field, environmental degradation does not entail CCO_2. Hence, this study enriches the environmental impacts of GPR by considering CCO_2 as the proxy of environmental degradation. Following the method of past researchers[13], 11 economics were randomly selected from the entire research sample, which led to Figs. 2 and 3. This is to effectively illustrate how geopolitical threats

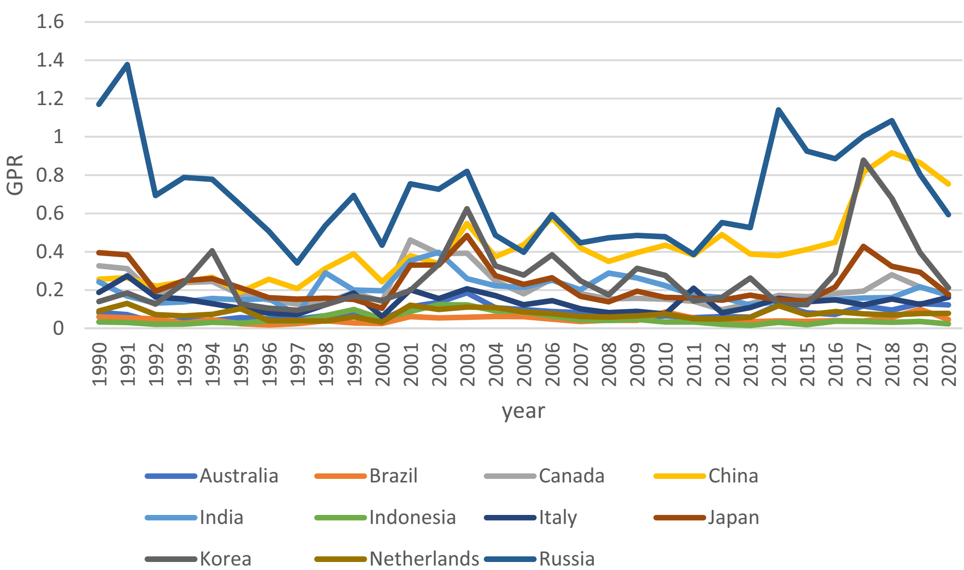

Figure 2. GPR index of 11 countries.

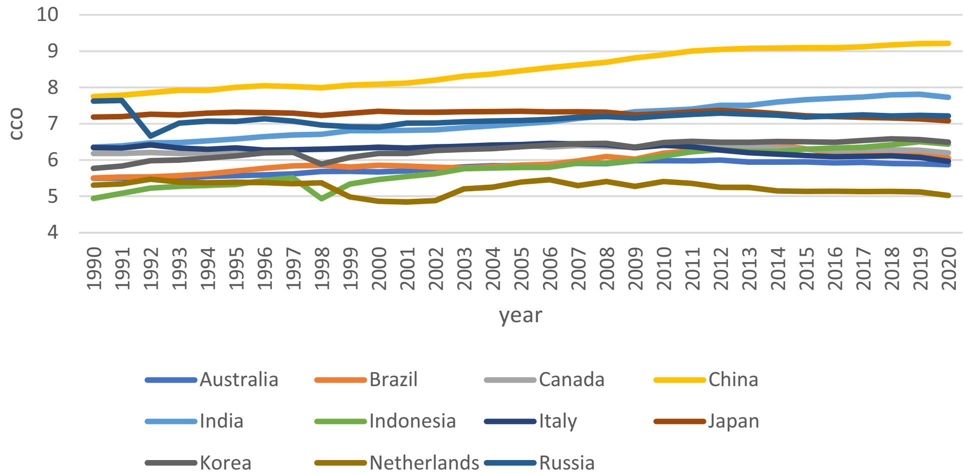

Figure 3. CCO_2 emissions(log.) of 11 countries.

and CCO_2 emissions vary among countries. To comprehensively assess the moderating effect of EPS on the nexus between GPR and CCO_2 emissions, data from three sources were utilised in this study: CCO_2 from the Global Carbon Atlas, GPR from GPR index[14], and EPS data from the OECD database. Based on data availability, a final dataset comprising 27 countries was obtained.

The use of CCO_2 emissions provide a more comprehensive metric to account for the influence of global trade. EPS data from the Organisation for Economic Co-operation and Development (OECD) database encompasses both market-based and non-market-based policies. The GPR index was based on text analysis of adverse geopolitical events in ten prominent newspapers. The index surpasses other indicators of GPR (such as war, terrorism, and political instability) due to its incorporation of eight risk categories (e.g., war threats, peace threats, military buildups, nuclear threats, and more) and its consideration of both expected and actual GPR hazards[15,16].

Ordinary Least Square (OLS), fixed effect model (FEM), random effect model (REM) and quantile regression were run in this study to obtain the final results. Then a robustness test was performed by replacing the independent variable and dependent variable and adding a new control variable. The sample was further divided into pre- and post-Kyoto protocol eras to look at the possible impact of outside events on the nexus.

The basic regression results indicated that GPR escalates CCO_2. Quantile regression results indicated that GPR increases CCO_2 emissions at all quantiles of CCO_2 emissions while the impact showed an increasing trend before the upper quantiles. Additionally, EPS weakens the positive effect of GPR on CCO_2 emissions. The robustness tests further confirmed these findings, supporting the robustness of the results. Specifically, a positive relationship was observed in the pre- and post-Kyoto protocol periods, even though the sign in terms of pre- Kyoto era was not significant. The impact of GPR on CCO_2 emissions was also found to be greater in developing countries compared to developed countries Hence, this study offers a fresh analysis of the literature as well as substantial support for the use of EPS to reduce environmental pressure.

This research makes several contributions to the existing body of literature. First, this study demonstrates that GPR is a significant factor that contributes to the increase in CCO_2 emissions. Policymakers and analysts can more effectively tackle environmental issues and promote SDG Goal 15 (Life on Land) with this perspective in mind. Second, this study documents the moderating role of EPS on the nexus between GPR and environmental quality, which has not been explored yet. While many studies[8,17] have explored the relationship between environmental regulations and environmental quality, this research sheds light on the moderating effect of EPS on the impact of GPR on CCO_2 emissions. This perspective provides a novel insight into the role of EPS. Third, besides traditional methods, this research uses the quantile regression model to capture the impact of GPR on environmental quality across different quantiles of CCO_2 emissions. Hence, the results of this paper offer policymakers a fresh perspective on how to develop tailored policies.

The remainder of the paper is organised in the following parts. "Literature review" is the literature review. "Data and methodology" describes the data and methodology. "Empirical results" reports the empirical results. The last section emphasises the key conclusions.

Literature review

Literature on the relationship between GPR and environmental sustainability

GPR, like trade conflicts and military activities, can influence economic activity and energy use that will subsequently impact CO_2 emissions[18]. GPR can influence CO_2 emissions by affecting investment decisions in green technology and causing disruptions in energy supplies. Additionally, it redirects the government's focus towards managing GPR, which is an important factor that can influence the investment decision of firms[19]. For instance, investments in cleaner technologies or renewable energy can be cut due to high levels of GPR[20], which could result in the continued reliance on fossil fuels, leading to higher CO_2 emissions[21]. Additionally, a high level of GPR can influence governments to prioritise addressing geopolitical issues over improving environmental quality[22]. This may result in a relaxation of CO_2 regulations, which would then lead to higher CO_2 emissions.

Finally, stability and security in one area is necessary for the access and free flow of energy resources[23]. However, GPR can disrupt energy supplies. Hence, countries may resort to using less environmentally-friendly energy sources or ramp up production in their existing fossil fuel sectors. Both scenarios have the potential to elevate CO_2 emissions.

In terms of the empirical results regarding the relationship between GPR and environmental sustainability, scholars have held divergent views. Some scholars contend that GPR is positively correlated with CO_2 emissions. For example, the impact of GPR on environmental quality in BRICS with continuously updated and fully modified estimators has been previously examined[22], which were concluded to degrade environmental quality. In addition, the nexus in the same sample countries through an augmented mean group has also been studied, which found that a 1% increase in GPR leads to the increase of CO_2 emissions by 13%[11]. Furthermore, GPR has been found to be positively correlated with CO_2 emissions through an examination of the nexus among 25 OECD countries[24]. Notably, the heightened risks related to mineral resources was found to primarily contribute to the carbon-increase effect of GPR. GMM results have also confirmed that GPR accelerates environmental pollution in 38 developing and industrialised countries[25]. Bootstrapped ARDL was also used in one study to examine the role of GPR in sustainable environment in China[26], which found that GPR is positively correlated with CO_2 emissions in the long and short run.

Some studies, in contrast, have documented a negative impact. For instance, GPR has been found to be negatively correlated to environmental degradation proxied by ecological footprint consumptions in E7 economies[27]. The decline in investment and consumption activity brought by high GPR was thought to be the cause of the negative link. A similar positive relationship between GPR and environment has also been documented in the context of residential and commercial sectors in the US[28] and France[29]. GPR has also been found to have no influence on environmental sustainability through an examination of the impact of GPR on environmental quality proxied by load capacity factor in India with ARDL method[30].

Finally, a non-linear relationship has also been documented, where GPR increases CO_2 emissions in countries with lower CO_2 emissions levels and lowers them in countries with lower CO_2 emissions levels in a sample of BRICST countries[31]. GPR depresses CO_2 emissions in Russia and South Africa, and the effect is opposite in other BRICS countries in a study employing the non-linear autoregressive distributed lag model[32].

Based on the inconclusive impact of GPR on environmental sustainability, this study hypothesises that GPR increases CCO_2 emissions in the sample countries of this study (hypothesis H1).

Literature on the relationship between EPS and environmental sustainability

EPS measures the level of stringency, which is defined as the implicit or explicit cost of environmentally harmful behaviour. This data originates from a comprehensive database that focuses primarily on policy tools that address climate change and air pollution. Hence, it is anticipated that stricter regulations can offset the negative effects of GPR on the environment. EPS is thought to have the ability to lessen the negative impacts of pollution by encouraging the development of "clean" technology and discouraging the use of "dirty" ones[33]. The mechanism through which EPS operates to reduce CO_2 emissions is by increasing the cost of producing "dirty" products to a point where they will not be attractive[34]. A well-designed policy can assist firms in implementing eco-friendly technologies, which can result in a reduction in pollution[35]. Following this, if the benefits of regulatory compliance outweigh the expenses, it will lead to net productivity benefits, which aligns with the "narrow" version of the theory[36]. However, the expenses associated with EPS is worth noting. EPS may potentially deter investments in green innovative technologies that consequently influences environmental quality[37]. Additionally, EPS may encourage certain kinds of innovation, which can lead to net productivity loss, aligning with the 'weak' version of the theory[36]. Hence, this empirical evidence is not harmonious as to whether EPS enhances environmental quality even though EPS was found to be effective in reducing CO_2 emissions in 20 European countries between 1995 and 2012[17].

In the case of BRICST countries, the improvement in environmental quality has been suggested to be due to EPS[2]. Similarly, for 32 OECD countries, the emission level was found to be negatively connected with EPS[8]. However, the "green paradox"[38] also exists, which claims that EPS may have unanticipated and undesired effects that worsen environmental degradation. GMM results have also indicated that environmental regulations have not been successful in regulating and reducing pollution as intended[39]. The increase in carbon emissions in Asia in particular has been found to be caused by environmental regulations[40]. Similarly, EPS has also been found to have little to no impact on CO_2 reductions[41].

Based on above discussion, the study hypothesises that EPS weakens the positive relationship between GPR and environmental sustainability (hypothesis H2).

In a nutshell, existing literature has recognised the growing importance of GPR and EPS in promoting environmental sustainability. However, current literature has not analysed the combined effect of GPR and EPS. Hence, this study addresses the first gap in the body of existing research by examining the moderating effect of EPS on the impact of GPR on environmental quality. Additionally, in the existing literature, environmental damage has often been represented by CO_2 emissions per capita from the World Development Indicators (WDI)[11,25,31] and ecological footprint[12,42]. However, a substantial body of research suggests that it is crucial to explore environmental conditions using alternative proxy variables, like CCO_2 emissions. This metric, adjusted for trade effects, takes into account the role of international trade, making it a more comprehensive index of environmental degradation. Hence, this study addresses the second gap by using CCO_2 emissions as a proxy for the environment. Furthermore, to the best of our knowledge, the analysis of the relationship between GPR and environmental quality using the panel quantile model has only been limited to BRICST countries[31], OECD countries[24], and GCC countries[43]. Hence, this study addresses the third gap by examining the GPR-environmental quality nexus using the quantile regression approach in 27 countries. The employment of this technique sets this study apart from those that merely rely on conventional mean-based regression models. As a result, this study enriches the existing body of literature by incorporating a novel approach that addresses individual and distributional heterogeneity.

Data and methodology

To analyse the influence of GPR on CCO_2 emissions, the data in this study was gathered from a variety of sources. Firstly, consumption-based carbon emissions from the Global Carbon Atlas was chosen as the dependent variable. Secondly, the GPR Index database[14] was utilised as a measure of the GPR. Thirdly, the country-level control variables such as FDI, fiscal policy, information and communications technology (ICT), and renewable energy consumption were gathered from WDI. Finally, the EPS Index, sourced from OECD database, was used as the proxy for environment policy strength and served as the moderating variable. Country-level data from the Global Carbon Atlas, GPR Index database, and OECD database were then matched. This yielded a total of 27 countries' data spanning from 1990 to 2020, based on data availability. Additionally, the CCO_2 emissions data for Norway was available starting from 2003. Hence, interpolation was employed to impute missing values for the control variables as practiced in past research[44]. Additionally, to mitigate the impact of outliers and large fluctuations, the data was winsorised at 1% and 99% levels.

Dependent variable: consumption-based carbon emission

CCO_2 emissions sourced from the Global Carbon Atlas (https://globalcarbonatlas.org/) was utilised as the dependent variable based on the approach of a previous study[5].

Independent variable: geopolitical risk

GPR was selected from the GPR Index database[14]. The number of articles related to unfavourable geopolitical events in each newspaper for each month across the archives of ten newspapers was counted to create this index. This index was composed of two types: Geopolitical Threats and Geopolitical Acts, based on different categories of words. This index has a number of benefits over existing indices that are currently in use, however, it has certain intrinsic drawbacks[14]. Firstly, the index covers a broader range of geopolitical events including wars, major economic crises, political conflicts, and climate change[45]. Secondly, this index also holds more reference value and timeliness as its data is derived from real-time media text-search results. These media sources collect the viewpoints of global investors, policymakers, and the public that reflect the real-time level of GPR. A higher value indicates a more unstable economic environment. The data is available at https://www.matteoiacoviello.com/gpr.htm. The simple average of the twelve months was taken to formulate a yearly index following the method of past studies[13,24,46].

Control variable

Previous research has indicated that the external macroeconomic environment has an impact on environmental sustainability. Foreign capital with high pollution levels has sought "pollution havens" to avoid the high costs of adhering to stringent pollution control regulations. These investors often turn to less developed nations with more lenient environmental policies, therefore, FDI enhances environmental degradation in less developed nations[47]. Next, expansionary fiscal policy involves increasing government spending, which provides the government with more funds to invest in the research and development of renewable technology and the purchase of green products[48]. Since a large number of ICT devices have high energy consumption, using ICT may result in increased CO2 emissions[49]. Also, renewable energy technology meets people's energy demands while also mitigating pollution[50]. Hence, with reference to past research[11,48–54], the following variables were chosen: (1) FDI, measured by foreign direct investment and net inflows (% of GDP); (2) fiscal policy, measured through the general government's final consumption expenditure (% of GDP); (3) ICT, measured by mobile cellular subscriptions (per 100 people); and (4) renewable energy consumption (Renew), measured by percentage of total final energy consumption.

Moderating variable: environmental policy stringency

There exists a demand for instruments to compare nations' EPS as countries implement more stringent environmental rules. This study uses the EPS index database developed by OECD based on the measurement of stringency defined as the implicit or explicit cost of environmentally harmful behaviour. This database compiles data on selected different environmental policy tools, particularly those that deal with climate change and air pollution. A smaller value indicates a less strict policy, with 0 denoting not stringent regulations.

The data for the variables above are summarised in Table 1.

Econometric model

This study employs OLS, FEM, and REM to thoroughly examine the relationship between GPR and CCO_2 emissions. The Breusch Pagan and Lagrangian Multiplier (BP and LM) test was the foremost step as this test can detect whether pooled or panel data is optimal. If the p-value of BP test and chi-square of LM test is significant at level 5%, then panel data is chosen. Both FEM and REM are employed in this study to deal with the panel data. The Hausman test is used to choose the model suitable for this research based on the null hypothesis. The FEM is chosen to analyse the data if the null hypothesis is rejected (or when the prob. < 0.05).

H0: the random effect is appropriate

H1: the random effect is not appropriate

	Variable	Symbol	Description	Source
Dependent variable	Consumption-based CO_2 emissions	CCO_2	Metric tonnes of CO_2 (log.)	(GCA, 2019 global carbon atlas) https://globalcarbonatlas.org
Independent variable	Geopolitical risk	GPR	The proxy of risk	[14]
Control variables	Foreign direct investment	FDI	Foreign direct investment, net inflows (% of GDP)	WDI
	Fiscal policy	Fiscal	General government final consumption expenditure (% of GDP)	WDI
	ICT	ICT	Mobile cellular subscriptions (per 100 people)	WDI
	Renewable energy consumption	Renew	Renewable energy consumption (% of total final energy consumption)	WDI
Moderating variable	environmental policy stringency	EPS	the proxy of environmental law	OECD database

Table 1. Variables explanations.

Quantile regression was utilised to get a comprehensive result. This method is preferred by scholars[55,56] over mean-based estimation techniques like OLS for the following reasons. Firstly, it can yield robust results even when the data exhibits heavy tails. Secondly, this statistical approach examines the influence of GPR on CCO_2 emissions across various quantiles, as illustrated in Eq. (2). Consequently, it can explain how GPR affects CCO_2 emissions at relatively lower, middle, and upper levels.

The following empirical equation was thus proposed:

$$CCO2it{=}\alpha 0+\alpha 1GPRit+\sum_{a=1}^{4}\beta aCCit+\varepsilon it \tag{1}$$

$$\mathrm{QT}(CCO2it|\,GPRitCCit)=\alpha 0\mathrm{T}+\alpha 1\mathrm{T}GPRit+\sum_{a=1}^{4}\beta a\mathrm{T}CCit+\varepsilon it \tag{2}$$

$$CCO2it{=}\alpha 0+\alpha 1GPRit+\alpha 2EPSit+\alpha 3GPRit*EPSit+\sum_{a=1}^{4}\beta aCCit+\varepsilon it \tag{3}$$

where: CCO_{2it} is the log term of CCO_2 emissions of country i at time t, GPR_{it} is the level of geopolitical risk of country i at time t, EPS_{it} is the environmental policy stringency of country i at time t, CC_{it} is the control variable of country i at time t, ε_{ijt} is the error term, Q_T is the conditional quantile, $_T$ represents the quantile.

Empirical results

Descriptive statistics

Table 2 presents the descriptive statistics of variables for all countries in the sample.

In terms of the dependent variable, the mean value of CCO_2 emissions was 5.88 with a standard deviation of 1.24. In the sample, the independent variable's mean value was 0.28. In the meantime, there was a significant range in both the maximum and minimum values of GPR, which reflects the diversity in GPR among nations. Significant fluctuations around the sample mean can also be observed for other control variables.

Table 3 presents Pearson's correlation matrix that displays coefficients between variables. Concerning the dependent variable, a negative correlation was found between CCO_2 emissions and FDI, Fiscal, ICT, EPS, and Renew. Conversely, there was a positive correlation between CCO_2 emissions and GPR. Additionally, the maximum correlation between the explanatory variables was found to be lower than 0.8, demonstrating that the regression estimation was not multicollinear. In a multivariate study, multicollinearity exists if the correlation coefficients with the explanatory variables are more than 0.8.

Variable	N	Mean	sd	Min	Max
CCO	824	5.88	1.24	3.75	9.21
GPR	837	0.28	0.49	0.01	4.35
FDI	837	3.34	6.45	-7.42	43.49
Fiscal	837	18.41	4.44	5.69	27.93
ICT	837	69.10	50.82	0.00	172.20
Renew	837	18.20	16.08	0.44	61.37
EPS	837	1.94	1.18	0.00	4.89

Table 2. Descriptive statistics for all countries.

	CCO	GPR	FDI	Fiscal	ICT	Renew	EPS
CCO	1						
GPR	0.604***	1					
FDI	− 0.168***	− 0.092***	1				
Fiscal	− 0.394***	− 0.139***	0.187***	1			
ICT	− 0.087**	− 0.017	0.131***	0.241***	1		
Renew	− 0.323***	− 0.289***	− 0.121***	− 0.052	− 0.019	1	
EPS	− 0.193***	− 0.036	0.091***	0.368***	0.726***	− 0.014	1

Table 3. Correlation matrix. *p < 0.1, **p < 0.05, ***p < 0.01.

The VIF value in Table 4 indicates that there was no significant multicollinearity among the variables in the regression model provided the maximum VIF value is 2.31.

The Pesaran CD[57], Pesaran scaled LM, and Breusch–Pagan LM tests[58] were used to test the cross-sectional dependence of data. Based on the results, there was no cross-sectional dependence, which confirmed the null hypothesis. All results demonstrated in Table 5 were statistically significant at the 1% level, suggesting a significant interdependence and cross-sectional correlation among the variables. The test's overall finding was that all variables were cross-sectionally dependent.

To explore the integration order of separate variables, the LLC[59], IPS[60], HT[61], ADF-Fisher[62], and PP-Fisher[63] tests were performed, and it was found that at the level form, not all variables were stationary, but when they reached their first difference, as shown in Table 6 they became stationary.

Basic results

In Table 7, GPR and control variables were included in the model. In the preliminary stage, the results from Table 7 show that the fixed effect model was most suitable to be used in this study as the p value of BP test and Chi-square of LM test was significant at 1% level or lower and the p value of the Hausman test was significant at 1% level or lower.

The FEM in Table 7 shows that GPR has a significant and positive effect on CCO_2 emissions. A 1% increase in GPR leads to an increase in CCO_2 emissions by 0.067%. The regression results indicate that GPR negatively impacts environmental sustainability in the sample countries. This confirms hypothesis H1. The above effect can be explained by the following reasons. Firstly, as the level of GPR increases, the risk premium of an investment rises. This means that investors may postpone or even reconsider the viability of the investment. For the private sector, there may also be concerns about the returns on investments in environmentally-friendly technologies and projects. In the case of the public sector, this can lead to a decrease in the investments in green technology, with the tendency to prioritise short-term financial gains over long-term sustainability projects. In addition, GPR can impact the sustainability of the international carbon reduction process. For example, when it comes to environmental challenges, tensions between countries can make international cooperation difficult. Cooperative efforts to combat climate change, preserve ecosystems, and exchange sustainable technologies may also face delays or encounter obstacles due to geopolitical conflicts. Additionally, geopolitical tensions have led nations

Variable	VIF	1/VIF
EPS	2.31	0.432
ICT	2.14	0.468
Fiscal	1.23	0.813
GPR	1.13	0.882
Renew	1.13	0.886
FDI	1.07	0.932
Mean/VIF	1.5	

Table 4. VIF.

Test	Statistics
Pesaran CD test	2.473**
Pesaran scaled LM test	2.526**
Breusch–Pagan LM test	8765.06***

Table 5. Results of cross-sectional dependence tests. *p < 0.1, **p < 0.05, ***p < 0.01.

	Variables	CCO	griska	FDI	Fiscal	ICT	Renew	EPS
Level form	LLC	–	− 6.568***	− 8.055***	− 2.201**	− 2.354***	1.207	− 0.402
	IPS	− 4.679***	− 8.710***	− 10.524***	− 2.539***	3.205	− 2.224**	− 3.591***
	HT	–	− 7.846***	− 13.556***	− 1.493*	5.479	− 1.037	0.770
	DF	124.614***	115.621***	161.108***	76.800**	35.269	44.099	56.875
	PP	92.845***	127.288***	246.851***	68.686*	8.635	66.258	74.177**
1st	LLC	–	− 8.059***	− 17.042***	− 6.980***	− 5.380***	− 7.304***	− 11.014***
	IPS	− 16.454***	− 18.193***	− 17.672***	− 13.498***	− 9.081***	− 15.518***	− 16.052***
	HT	–	− 34.747***	− 37.631***	− 23.652***	− 13.665***	− 24.473***	− 28.742***
	DF	375.489***	300.040***	587.072***	279.106***	129.924***	309.967***	341.171***
	PP	771.090***	909.330***	921.004***	444.839***	204.869***	681.162***	651.615***

Table 6. Stationarity test results. ***Indicates a 1% significance level. The Stata commands xtunitroot llc (for LLC), xtunitroot ips (for IPS), xtunitroot ht for (for HT), xtunitroot fisher dfuller (for ADF-Fisher), and xtunitroot fisher pperron (for PP-Fisher) were employed to estimate the results in this table. LLC and HT were not able to be performed in terms of CCO_2 emissions as strongly balanced data was needed.

	ols	fe	re
GPR	1.213*** (0.06)	0.067*** (0.02)	0.075*** (0.02)
FDI	− 0.017*** (0.00)	− 0.001 (0.00)	− 0.001 (0.00)
Fiscal	− 0.092*** (0.01)	0.015*** (0.00)	0.013*** (0.00)
ICT	0.000 (0.00)	0.002*** (0.00)	0.002*** (0.00)
Renew	− 0.018*** (0.00)	− 0.033*** (0.00)	− 0.033*** (0.00)
constant	7.576*** (0.14)	6.036*** (0.07)	6.054*** (0.16)
N	824	824	824
r2	0.510	0.685	
r2_a	0.507	0.672	
F	170.260***	343.829***	
BP LM	chibar2(01) = 8928.26***		
chi2			1629.747***
Hausman		chi2(5) = 49.73***	

Table 7. Basic regression result. Standard errors in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

to prioritise energy independence. Instead of relying on environmentally-friendly but highly import-dependent products, some nations may opt for more accessible yet carbon-intensive energy sources, potentially leading to an increase in carbon emissions. Finally, geopolitical disputes make it challenging to implement and maintain consistent environmental regulations due to political instability or weak governance[24]. This finding is consistent with a previous study[24] on the relationship between GPR and CO_2 emissions within the context of the OECD countries. It also aligns with another study[11] which confirmed that GPR escalates CO_2 emission in BRICS economics. Similar findings were also reported for BRICST countries[31] and for the transportation sector in the US[28].

Regarding the control variables, the regression results showed that renewable energy and FDI negatively contributed to CCO_2 emissions, while fiscal policy and ICT had a positive impact on CCO_2 emissions.

The results suggest a negative association between renewable energy and CCO_2 emissions. Renewable energy such as wind, solar, and hydroelectric can generate electricity without emitting any pollutants into the atmosphere[64]. It is worth noting that the findings confirm the conclusions in the works of several past research works[65,66]. Regarding the role of FDI, the regression results indicate that FDI can alleviate environmental pressure. This phenomenon can be attributed to the pollution halo hypothesis. According to this hypothesis, FDI brings advanced technologies and green practices from developed countries to the developing country, enabling these nations to produce in a more environmentally-friendly manner, which may be contradictory[67]. In terms of fiscal policy, the positive coefficient of fiscal policy indicates that fiscal policy, which increases government spending[68], aggravates CCO_2 emissions. Hence, this will greatly stimulate overall economic demand, thereby increasing CCO_2 emissions which is in line with the findings of previous researchers[69]. In addition, the use of ICT may contribute to increased CCO_2 emissions due to the high energy consumption associated with the large number of ICT devices[49].

Quantile regression

To attain a more robust result, the model was run by the panel quantile regression which offers a more thorough study for model estimation at multiple quantiles[70]. This method has two advantages. First, quantile regression is considered more reliable when the data is not normally distributed[71]. Secondly, quantile regression is a useful tool for estimating the significant impact of extreme values[24]. While the traditional econometric model provides the average effect of the independent variable, panel quantile regression not only provides results at different quantile and complies with the non-normality requirements, but also solves issues with variable slope coefficients and cross-sectional dependence[72]. This technique is widely used in the field of environmental economics. Hence, three kinds of quantiles were chosen based on past research[73], namely the lower (10th–30th), middle (40th–60th), upper quantiles (70th–90th) as depicted in Table 8 and Fig. 4. The magnitude supports the application of quantile regression because the impact of GPR on CCO_2 emissions is heterogeneous across quantiles.

The coefficients of GPR were found to be positive and significant across the distribution. As we transition from lower quantiles to middle quantiles, the magnitude also increases. Initially, a 1% rise in GPR leads to a 1.139% increase in CCO_2 emissions at the 10th percentile of CCO_2 emissions. However, the elasticity surges to 1.440% at the 60th percentile. In contrast, the magnitude decreases in upper quantiles, yet remains positive and statistically significant, which contradict findings from past research[31,32] which proposed that GPR deflates the environmental quality at lower quartiles while the effect is reverse at other quantiles. GPR has also been contradictorily been documented[32] to depress CO_2 emissions in Russia and South Africa and escalate emissions in other BRICS countries with the method of non-linear autoregressive distributed lag model. The varying positive association between GPR and CCO_2 emissions confirms hypothesis H1. This variation suggests that the impact of GPR is contingent upon the degree of environmental degradation. The increasing trend before the upper quantile can be explained by the following. First, in countries with higher CCO_2 emissions quantiles, technology is usually less advanced, which creates a gap between countries in higher and lower CCO_2 emissions quantiles. A wider technology gap will also result in a country holding a lower position in the global value chain and engage in less environmentally-friendly production[74]. The lower global value chain position also makes these countries more susceptible to disruptions caused by geopolitical events. Secondly, countries with higher CCO_2

	Lower			Middle			Upper		
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
GPR	1.139***	1.206***	1.285***	1.227***	1.308***	1.440***	1.428***	1.095***	1.107***
	(0.11)	(0.09)	(0.08)	(0.07)	(0.06)	(0.09)	(0.11)	(0.09)	(0.15)
FDI	− 0.007	− 0.019***	− 0.020***	− 0.015***	− 0.011**	− 0.011	− 0.012	− 0.017**	− 0.016
	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)
Fiscal	− 0.046***	− 0.079***	− 0.076***	− 0.080***	− 0.084***	− 0.093***	− 0.099***	− 0.135***	− 0.162***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
ICT	0.001	0.002**	0.001	0.001**	0.002***	0.001	− 0.000	0.001	0.001
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Renew	− 0.018***	− 0.025***	− 0.025***	− 0.023***	− 0.022***	− 0.019***	− 0.010***	− 0.012***	− 0.012***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
constant	5.476***	6.701***	6.939***	7.156***	7.266***	7.602***	7.963***	8.991***	9.845***
	(0.26)	(0.19)	(0.18)	(0.15)	(0.13)	(0.21)	(0.24)	(0.21)	(0.33)
N	824	824	824	824	824	824	824	824	824

Table 8. Quantile regression. Standard errors in parentheses. $^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$.

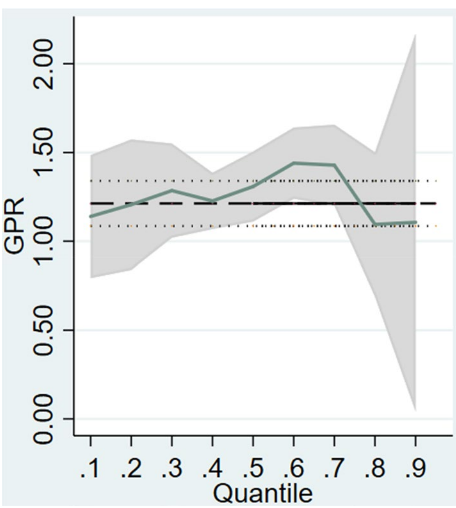

Figure 4. Graphical evaluation of coefficients of quantile regression.

emissions quantiles may have more resource-intensive industries and are more likely to be influenced by GPR that relate to resource and trade. Firms also tend to resort to polluting production methods due to concerns on GPR[11]. The diminishing effect in upper quantiles can be explained by market pressures and environment policy constrains. In terms of the former, industries in countries with higher CCO_2 emissions quantiles may experience pressure to adopt cleaner practices due to consumer and market demands for sustainability and environmental responsibility. In contrast, stringent environmental regulations are implemented by the government due to severe environmental pollution. This, to some extent, counteracts the dependence on polluting production methods and heavily-polluting energy sources caused by GPR.

In conclusion, as we progress from lower to higher quantiles, the coefficients exhibit an increasing trend. This suggests that GPR has a particularly notable impact in countries with higher CCO_2 emissions levels.

Moderating effect of EPS

Different exogenous shocks, such as global economic uncertainty and EPS, may impact the way GPR affects CCO_2 emissions. Various levels of EPS may produce different results. For instance, when EPS increases, the profit from using the polluting producing method and polluting energy may be halted or reduced. In line with the basic regression findings, the coefficient of GPR was found to be significantly positive at the 1% level. Furthermore, the interaction term (GPR* EPS) exhibited a significant negative coefficient, as demonstrated in Table 9. This signifies that the negative effects of GPR on environmental sustainability could be somewhat mitigated by an increase in EPS level. Hence, the negative coefficient confirms hypothesis H2. This can be explained by regulatory compliance. EPS backed by robust enforcement mechanisms can elevate the cost of polluting production and the use of non-clean energy sources, resulting in a mitigation effect on CCO_2 emissions. Furthermore, stringent regulations impose limits on emissions and encourage the adoption of greener practices and technologies. A similar carbon reduction effect of EPS has been documented[75] when analysing the moderating effect of EPS on the impact of financial development on environmental quality.

Robust test

In this section, four robustness tests were conducted to validate the basic findings. Initially, the independent variable was replaced. Then, the control variable was added to re-examine the underlying link. In addition, the dependent variable was replaced to assess the robustness of the basic regression model. Finally, the sample was segmented into pre- and post-Kyoto protocol periods to investigate the potential influence of external events on the nexus.

Robust test1: replacing independent variable

Following a method done in past literature[13], the annual GPR index calculated by the geometric mean method (GPR-G) was generated to test the robustness of the test. The results in Table 10 show that the main findings still hold.

Robust test2: add extra control variable

The absence of relevant variables was likely to decrease the validity of empirical findings and bring about estimation basis. Therefore, a factor was added to the model to see if the main findings change. FD (financial development) facilitates green projects in obtaining loans, thereby reducing CO_2 emissions[49]. Hence, the variable of FD was incorporated into the analysis following the method of past studies[49,76]. FD is proxied by domestic credit to private sector's percentage of GDP. Subsequently, this variable was introduced into the regression model.

	ols	fe	re
GPR	0.801*** (0.13)	0.118*** (0.03)	0.124*** (0.03)
EPS	− 0.191*** (0.04)	0.081*** (0.01)	0.080*** (0.01)
Interact	0.251*** (0.07)	− 0.041*** (0.01)	− 0.040*** (0.01)
FDI	− 0.017*** (0.00)	− 0.000 (0.00)	− 0.000 (0.00)
Fiscal	− 0.082*** (0.01)	0.010*** (0.00)	0.008** (0.00)
ICT	0.003*** (0.00)	0.001*** (0.00)	0.001*** (0.00)
Renew	− 0.017*** (0.00)	− 0.035*** (0.00)	− 0.035*** (0.00)
constant	7.596*** (0.14)	6.078*** (0.06)	6.092*** (0.16)
N	824	824	824
r2	0.524	0.710	
r2_a	0.520	0.698	
F	128.513***	276.802***	
BP LM	chibar2(01) = 8704.77***		
chi2			1843.699***
Hausman		chi2(7) = 47.47***	

Table 9. Moderating effect. Standard errors in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	ols	fe	re
GPR-G	1.330*** (0.07)	0.090*** (0.03)	0.101*** (0.03)
FDI	− 0.016*** (0.00)	− 0.001 (0.00)	− 0.001 (0.00)
Fiscal	− 0.092*** (0.01)	0.014*** (0.00)	0.012*** (0.00)
ICT	0.000 (0.00)	0.002*** (0.00)	0.002*** (0.00)
Renew	− 0.017*** (0.00)	− 0.033*** (0.00)	− 0.033*** (0.00)
constant	7.559*** (0.14)	6.036*** (0.07)	6.053*** (0.16)
N	824	824	824
r2	0.520	0.686	
r2_a	0.517	0.673	
F	177.240***	345.341***	
BP LM	chibar2(01) = 9149.93***		
chi2			1638.257***
Hausman		chi2(5) = 49.39***	

Table 10. Robust test1: replace independent variable. Standard errors in parentheses. *$p<0.1$, **$p<0.05$, ***$p<0.01$.

The corresponding outcomes are reported in Table 11. The regression outcomes validated the robustness of the fundamental regression analysis.

Robust test3: replace dependent variable
The model was re-estimated by replacing the dependent variable with CO_2 emissions metric tons per capita(log.) (CE). In line with past studies[49,77–81], CE was chosen as one indicator of the quality of the environment. The results are reported in Table 12. The regression results showed that the basic regression remains robust.

Robust test4: the impact of the Kyoto protocol's enforcement
All sample countries in this study were signatories to the Kyoto Protocol and were therefore influenced by it. In 2005, the Kyoto Protocol officially entered into force after being agreed upon in 2003. Therefore, the pre-Kyoto era was firstly examined, and unexpectedly, it was found that the GPR's sign was positive but not significant, indicating that earlier GPRs were wholly ineffective in escalating CO_2 emissions. However, when the post-Kyoto era was examined, similar signs were observed to the basic regression model as shown in Table 13, which confirmed the basic regression results.

Heterogeneity test

Based on the classification of United Nations (https://unstats.un.org/unsd/methodology/m49/historical-classification-of-developed-and-developing-regions.xlsx), this study divided the sample country into developed and developing countries as demonstrated in Table 14 and reperformed the regression model. For developing country samples, the REM was the most suitable while the FEM was the most suitable for developed countries according to Table 15. The impact of GPR on environmental sustainability was found to be smaller in developed countries

	ols	fe	re
GPR	1.190*** (0.07)	0.059*** (0.02)	0.066*** (0.02)
FDI	− 0.016*** (0.00)	0.000 (0.00)	− 0.000 (0.00)
Fiscal	− 0.093*** (0.01)	0.012*** (0.00)	0.011*** (0.00)
ICT	0.000 (0.00)	0.001*** (0.00)	0.001*** (0.00)
Renew	− 0.018*** (0.00)	− 0.034*** (0.00)	− 0.034*** (0.00)
FD	0.001 (0.00)	0.002*** (0.00)	0.002*** (0.00)
constant	7.531*** (0.15)	5.961*** (0.06)	5.975*** (0.16)
N	824	824	824
r2	0.511	0.713	
r2_a	0.507	0.702	
F	142.234***	327.863***	
BP LM	chibar2(01) = 8969.87***		
chi2			1872.294***
Hausman		chi2(6) = 47.51***	

Table 11. Robust test2: adding control variable FD. Standard errors in parentheses. *$p<0.1$, **$p<0.05$, ***$p<0.01$.

	CE		
	ols	fe	re
GPR	0.280*** (0.03)	0.067*** (0.02)	0.068*** (0.02)
FDI	− 0.006** (0.00)	− 0.000 (0.00)	− 0.000 (0.00)
Fiscal	0.065*** (0.00)	− 0.000 (0.00)	0.001 (0.00)
ICT	0.001** (0.00)	0.001*** (0.00)	0.001*** (0.00)
Renew	− 0.023*** (0.00)	− 0.033*** (0.00)	− 0.033*** (0.00)
constant	0.991*** (0.08)	2.420*** (0.05)	2.400*** (0.10)
N	837	837	837
r2	0.558	0.759	
r2_a	0.555	0.750	
F	209.462***	508.259***	
BP LM	chibar2(01) = 9975.67***		
chi2			2522.288***
Hausman		chi2(5) = 17.15***	

Table 12. Robust test3: replace dependent variable. Standard errors in parentheses. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

	Pre-Kyoto			Post-Kyoto		
	ols	fe	re	ols	fe	re
GPR	1.134*** (0.08)	0.031 (0.02)	0.039* (0.02)	1.312*** (0.10)	0.094** (0.04)	0.116** (0.05)
FDI	− 0.015 (0.01)	0.000 (0.00)	− 0.000 (0.00)	− 0.020*** (0.01)	0.001 (0.00)	0.001 (0.00)
Fiscal	− 0.068*** (0.01)	0.026*** (0.01)	0.023*** (0.01)	− 0.086*** (0.01)	0.006 (0.01)	0.004 (0.01)
ICT	− 0.005*** (0.00)	0.001*** (0.00)	0.001*** (0.00)	− 0.009*** (0.00)	0.002*** (0.00)	0.002*** (0.00)
Renew	− 0.011*** (0.00)	− 0.036*** (0.00)	− 0.034*** (0.00)	− 0.028*** (0.00)	− 0.032*** (0.00)	− 0.032*** (0.00)
constant	7.061*** (0.21)	5.889*** (0.10)	5.900*** (0.19)	8.772*** (0.23)	6.159*** (0.09)	6.199*** (0.18)
N	392	392	392	432	432	432
r2	0.477	0.433		0.617	0.603	
r2_a	0.470	0.384		0.612	0.572	
F	70.470***	55.042***		137.232***	121.582***	
BP LM	chibar2(01) = 1860.10***			chibar2(01) = 2318.16***		
chi2			243.780***			575.655***
Hausman		chi2(5) = 43.48***			chi2(5) = 35.66***	

Table 13. Robust test4: The impact of the Kyoto protocol's enforcement. Standard errors in parentheses. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Country	Type	Country	Type	Country	Type	Country	Type
Brazil	Developing	Australia	Developed	Hungary	Developed	Russia	Developed
China	Developing	Belgium	Developed	Italy	Developed	Spain	Developed
India	Developing	Canada	Developed	Japan	Developed	Sweden	Developed
Indonesia	Developing	Denmark	Developed	Netherlands	Developed	Switzerland	Developed
Korea	Developing	Finland	Developed	Norway	Developed	United Kingdom	Developed
South Africa	Developing	France	Developed	Poland	Developed	United States	Developed
Turkey	Developing	Germany	Developed	Portugal	Developed		

Table 14. Classification.

compared to developing countries. This may be because developed countries often have more advanced infrastructure and technology to support renewable energy development[82]. A well-established domestic renewable energy system enables a relatively independent energy supply. When facing GPRs, countries are less likely to heavily consume fuel energy. This results in smaller coefficients regarding developed countries.

	Developed			Developing		
	ols	fe	re	ols	fe	re
GPR	1.130*** (0.05)	0.036* (0.02)	0.047** (0.02)	3.935*** (0.29)	0.416*** (0.09)	0.425*** (0.09)
FDI	− 0.026*** (0.00)	0.000 (0.00)	− 0.000 (0.00)	0.285*** (0.03)	0.015* (0.01)	0.016* (0.01)
Fiscal	− 0.042*** (0.01)	0.010*** (0.00)	0.009** (0.00)	− 0.028** (0.01)	0.011 (0.01)	0.010 (0.01)
ICT	0.003*** (0.00)	0.001*** (0.00)	0.001*** (0.00)	0.002** (0.00)	0.003*** (0.00)	0.003*** (0.00)
Renew	− 0.042*** (0.00)	− 0.026*** (0.00)	− 0.026*** (0.00)	0.007** (0.00)	− 0.032*** (0.00)	− 0.032*** (0.00)
constant	6.694*** (0.18)	5.742*** (0.07)	5.752*** (0.16)	5.335*** (0.22)	6.860*** (0.13)	6.859*** (0.36)
N	607	607	607	217	217	217
r2	0.689	0.395		0.595	0.861	
r2_a	0.686	0.370		0.585	0.854	
F	266.001***	75.872***		62.010***	254.311***	
BP LM	chibar2(01) = 5549.82***			chibar2(01) = 756.79***		
chi2			376.316***			1242.266***
Hausman		chi2(5) = 43.24***			chi2(5) = 9.37*	

Table 15. Robust test4. Standard errors in parentheses. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Conclusion and policy recommendations

Conclusion

In the current modern era, GPR is a significant issue that has a strong environmental impact and economic impact on nations. Hence, this paper studies the impact of GPR on CCO_2 emissions based on the data collected from 27 countries ranging from 1990 to 2020. First, the GPR-CCO_2 emissions nexus was tested and then checked with regards to the heterogeneous impact of GPR at different quantiles of CCO_2 emissions. Furthermore, this study examined the moderating effect of EPS on the above nexus. Several robustness tests were used to check the basic results. Finally, a heterogeneity test was performed in developing countries and developed countries.

The results of the study suggest that GPR can significantly increase CCO_2 emissions and has a greater and more substantial impact on higher quantiles of CCO_2 emissions. Meanwhile, EPS can negatively moderate the nexus among GPR and CCO_2 emissions. In other words, the negative effects of GPS on environmental quality could be somewhat offset by improvements in EPS level. The robust tests confirm the basic regression results. Additionally, upon dividing the sample period into pre- and post-Kyoto periods, it was observed that the impact of GPR aligns with the basic regression model during the post-Kyoto periods. However, it is interesting to note that the effect of GPR in the pre- Kyoto period is positive but insignificant. The heterogeneity test indicates that the impact of GPR on CCO_2 emissions is greater in developing countries compared in developed countries.

Policy recommendations

This research has several implications for policy. First, the relationship between GPR and a country's environmental deregulation suggests that higher GPR may be detrimental to efforts aimed at improving environmental sustainability. To address this issue, the government should provide a stable political environment and a sound legal system, thereby attracting more investors to participate in environmental projects. Besides that, energy transition could be promoted by adopting policies to reduce reliance on high-carbon-emission energy sources and instead use cleaner and renewable energy sources. Finally, the government can strengthen environmental regulation to ensure the enforcement of environmental laws and enhance the effectiveness of environmental protection measures.

Second, the heterogeneous impact of GPR at different quantiles serve as a reminder that low- and middle-emissions countries should pay closer attention to reduce CCO_2 emissions, as the influence of GPR becomes stronger in higher level of CCO_2 emissions countries. Besides that, every country has different circumstances, thus, policies must be developed, put into practice, and be continuously improved to reflect those particulars.

Third, the government needs to make every effort to optimise the benefits of EPS. EPS weakens the negative impact of GPR by enforcing regulatory compliance and promoting green production. As a result, it may be more efficient to put strict measures into place, such extending the scope of environmental taxes and imposing different tax rates according to the degree of environmental harm. However, softer methods can also prove to be highly effective. It is imperative to make proactive investments in clean technology research and development. These technologies directly support source reduction of emissions by providing workable substitutes for high-emission processes. Promoting garbage recycling and sustainable consumption can also greatly increase public participation in the battle against environmental deterioration. By implementing these strategies, policymakers will be able to successfully manage the complex relationship between GPR, environmental quality, and EPS.

Limitations

First, this study's sample is constrained by data availability. It includes countries where the independent, dependent, and control variables intersect. In addition, data for only 27 countries and spanning from 1990 were used for this study.

Second, the empirical model only employed the techniques of OLS, FE, RE, and panel quantile regression.

Data availability

Data is provided within supplementary information files.

Received: 21 January 2024; Accepted: 26 April 2024
Published online: 10 May 2024

References

1. Smil, V. Decarbonization algebra: The COP26 calls for impossibly steep cuts in carbon emissions: Numbers don't lie. *IEEE Spectr.* **59**, 20–21 (2022).
2. Dai, S. & Du, X. Discovering the role of trade diversification, natural resources, and environmental policy stringency on ecological sustainability in the BRICST region. *Resour. Policy* **85**, 103868 (2023).
3. Gyamfi, B. A., Adedoyin, F. F., Bein, M. A., Bekun, F. V. & Agozie, D. Q. The anthropogenic consequences of energy consumption in E7 economies: Juxtaposing roles of renewable, coal, nuclear, oil and gas energy: Evidence from panel quantile method. *J. Clean. Prod.* **295**, 126373 (2021).
4. Zhuang, Y., Yang, S., Razzaq, A. & Khan, Z. Environmental impact of infrastructure-led Chinese outward FDI, tourism development and technology innovation: A regional country analysis. *J. Environ. Plan. Manag.* **66**, 367–399 (2022).
5. Li, S., Samour, A., Irfan, M. & Ali, M. Role of renewable energy and fiscal policy on trade adjusted carbon emissions: Evaluating the role of environmental policy stringency. *Renew. Energy* **205**, 156–165 (2023).
6. Meng, Y., Wu, H., Wang, Y. & Duan, Y. International trade diversification, green innovation, and consumption-based carbon emissions: The role of renewable energy for sustainable development in BRICST countries. *Renew. Energy* **198**, 1243–1253 (2022).
7. Wolde-Rufael, Y. & Mulat-Weldemeskel, E. Do environmental taxes and environmental stringency policies reduce CO_2 emissions? Evidence from 7 emerging economies. *Environ. Sci. Pollut. Res.* **28**, 22392–22408 (2021).
8. Albulescu, C. T., Boatca-Barabas, M.-E. & Diaconescu, A. The asymmetric effect of environmental policy stringency on CO_2 emissions in OECD countries. *Environ. Sci. Pollut. Res.* **29**, 27311–27327 (2022).
9. Hallegatte, S. Strategies to adapt to an uncertain climate change. *Glob. Environ. Change* **19**, 240–247 (2009).
10. Doğan, B., Shahbaz, M., Bashir, M. F., Abbas, S. & Ghosh, S. Formulating energy security strategies for a sustainable environment: Evidence from the newly industrialized economies. *Renew. Sustain. Energy Rev.* **184**, 113551 (2023).
11. Anser, M., Syed, Q. & Apergis, N. Does geopolitical risk escalate CO_2 emissions? Evidence from the BRICS countries. *Environ. Sci. Pollut. Res.* **28**, 1–11 (2021).
12. Anser, M. K., Syed, Q. R., Lean, H. H., Alola, A. A. & Ahmad, M. Do economic policy uncertainty and geopolitical risk lead to environmental degradation? Evidence from emerging economies. *Sustainability* **13**, 5866 (2021).
13. Wang, S., Wang, J. & Wang, W. Do geopolitical risks facilitate the global energy transition? Evidence from 39 countries in the world. *Resour. Policy* **85**, 103952 (2023).
14. Caldara, D. & Iacoviello, M. Measuring geopolitical risk. *Am. Econ. Rev.* **112**, 1194–1225 (2022).
15. Bildirici, M. E. Terrorism, environmental pollution, foreign direct investment (FDI), energy consumption, and economic growth: Evidences from China, India, Israel, and Turkey. *Energy Environ.* **32**, 75–95 (2021).
16. Sofuoğlu, E. & Ay, A. The relationship between climate change and political instability: the case of MENA countries (1985: 01–2016: 12). *Environ. Sci. Pollut. Res.* **27**, 14033–14043 (2020).
17. Wolde-Rufael, Y. & Mulat-weldemeskel, E. Effectiveness of environmental taxes and environmental stringent policies on CO_2 emissions: the European experience. *Environ. Dev. Sustain.* **25**, 5211–5239 (2023).
18. Wang, K.-H., Kan, J.-M., Jiang, C.-F. & Su, C.-W. Is geopolitical risk powerful enough to affect carbon dioxide emissions? Evidence from China. *Sustainability* **14**, 7867 (2022).
19. Li, H., Liu, Y. & Xu, B. Does target country's climate risk matter in cross-border M&A? The evidence in the presence of geopolitical risk. *J. Environ. Manag.* **344**, 118439 (2023).
20. Pata, U. K., Alola, A. A., Erdogan, S. & Kartal, M. T. The influence of income, economic policy uncertainty, geopolitical risk, and urbanization on renewable energy investments in G7 countries. *Energy Econ.* **128**, 107172 (2023).
21. Adams, S., Adedoyin, F., Olaniran, E. & Bekun, F. V. Energy consumption, economic policy uncertainty and carbon emissions; Causality evidence from resource rich economies. *Econ. Anal. Policy* **68**, 179–190 (2020).
22. Khan, A., Sun, C., Xu, Z. & Liu, Y. Geopolitical risk, economic uncertainty, and militarization: Significant agents of energy consumption and environmental quality. *Environ. Impact Assess. Rev.* **102**, 107166 (2023).
23. Umbach, F. *Global Energy Supply and Geopolitical Challenges* (IFRI, 2004).
24. Ding, T., Li, H., Tan, R. & Zhao, X. How does geopolitical risk affect carbon emissions? An empirical study from the perspective of mineral resources extraction in OECD countries. *Resour. Policy* **85**, 103983 (2023).
25. Chen, L., Gozgor, G., Mahalik, M. K., Pal, S. & Rather, K. N. How does geopolitical risk affect CO_2 emissions? The role of natural resource rents. *Resour. Policy* **87**, 104321 (2023).
26. Li, Z. Do geopolitical risk, green finance, and the rule of law affect the sustainable environment in China? Findings from the BARDL approach. *Resour. Policy* **81**, 103403 (2023).
27. Chu, L. K., Doğan, B., Abakah, E. J. A., Ghosh, S. & Albeni, M. Impact of economic policy uncertainty, geopolitical risk, and economic complexity on carbon emissions and ecological footprint: An investigation of the E7 countries. *Environ. Sci. Pollut. Res.* **30**, 34406–34427 (2022).
28. Pata, U. K., Kartal, M. T. & Zafar, M. W. Environmental reverberations of geopolitical risk and economic policy uncertainty resulting from the Russia–Ukraine conflict: A wavelet based approach for sectoral CO_2 emissions. *Environ. Res.* **231**, 116034 (2023).
29. Kiliç Depren, S., Erdogan, S., Tevfik Kartal, M. & Pata, U. K. Effect of political stability, geopolitical risk and R&D investments on environmental sustainability: Evidence from European countries by novel quantile models. *Polit. Ekon.* (2024).
30. Pata, U. K. & Ertugrul, H. M. Do the Kyoto Protocol, geopolitical risks, human capital and natural resources affect the sustainability limit? A new environmental approach based on the LCC hypothesis. *Resour. Policy* **81**, 103352 (2023).
31. Syed, Q. R., Bhowmik, R., Adedoyin, F. F., Alola, A. A. & Khalid, N. Do economic policy uncertainty and geopolitical risk surge CO_2 emissions? New insights from panel quantile regression approach. *Environ. Sci. Pollut. Res.* **29**, 27845–27861 (2022).
32. Zhao, W., Zhong, R., Sohail, S., Majeed, M. T. & Ullah, S. Geopolitical risks, energy consumption, and CO_2 emissions in BRICS: An asymmetric analysis. *Environ. Sci. Pollut. Res.* **28**, 39668–39679 (2021).
33. Cohen, M. A. & Tubb, A. The impact of environmental regulation on firm and country competitiveness: A meta-analysis of the porter hypothesis. *J. Assoc. Environ. Resour. Econ.* **5**, 371–399 (2018).
34. Neves, S. A., Marques, A. C. & Patrício, M. Determinants of CO_2 emissions in European Union countries: does environmental regulation reduce environmental pollution?. *Econ. Anal. Policy* **68**, 114–125 (2020).
35. Porter, M. E. & van der Linde, C. Toward a new conception of the environment-competitiveness relationship. *J. Econ. Perspect.* **9**, 97–118 (1995).
36. Jaffe, A. B. & Palmer, K. Environmental regulation and innovation: A panel data study. *Rev. Econ. Stat.* **79**, 610–619 (1997).
37. Mulatu, A. Environmental regulation and international competitiveness: A critical review. *Int. J. Glob. Environ. Issues* **17**, 41–63 (2018).

38. Sinn, H.-W. Introductory comment—the green paradox: A supply-side view of the climate problem. *Rev. Environ. Econ. Policy* https://doi.org/10.1093/reep/rev011 (2015).
39. Hao, Y. U., Deng, Y., Lu, Z.-N. & Chen, H. Is environmental regulation effective in China? Evidence from city-level panel data. *J. Clean. Prod.* **188**, 966–976 (2018).
40. Phan, C. *et al.* Controlling environmental pollution: Dynamic role of fiscal decentralization in CO_2 emission in Asian economies. *Environ. Sci. Pollut. Res.* **28**, 65150–65159 (2021).
41. Wang, H. & Wei, W. Coordinating technological progress and environmental regulation in CO_2 mitigation: The optimal levels for OECD countries & emerging economies. *Energy Econ.* **87**, 104510 (2020).
42. Husnain, M. I., Syed, Q. R., Bashir, A. & Khan, M. A. Do geopolitical risk and energy consumption contribute to environmental degradation? Evidence from E7 countries. *Environ. Sci. Pollut. Res.* **29**, 41640–41652 (2022).
43. Ulussever, T., Kartal, M. T. & Kılıç Depren, S. Effect of income, energy consumption, energy prices, political stability, and geopolitical risk on the environment: Evidence from GCC countries by novel quantile-based methods. *Energy Environ.* https://doi.org/10.1177/0958305X231190351 (2023).
44. Chen, Y., Cheng, L. & Lee, C.-C. How does the use of industrial robots affect the ecological footprint? International evidence. *Ecol. Econ.* **198**, 107483 (2022).
45. Bouoiyour, J., Selmi, R., Hammoudeh, S. & Wohar, M. E. What are the categories of geopolitical risks that could drive oil prices higher? Acts or threats?. *Energy Econ.* **84**, 104523 (2019).
46. Dogan, E., Majeed, M. T. & Luni, T. Analyzing the impacts of geopolitical risk and economic uncertainty on natural resources rents. *Resour. Policy* **72**, 102056 (2021).
47. Shekhawat, K. K., Yadav, A. K., Sanu, M. S. & Kumar, P. Key drivers of consumption-based carbon emissions: Empirical evidence from SAARC countries. *Environ. Sci. Pollut. Res.* **29**, 23206–23224 (2022).
48. Yilanci, V. & Pata, U. K. On the interaction between fiscal policy and CO_2 emissions in G7 countries: 1875–2016. *J. Environ. Econ. Policy* **11**, 196–217 (2022).
49. Danish Khan, N., Baloch, M. A., Saud, S. & Fatima, T. The effect of ICT on CO_2 emissions in emerging economies: Does the level of income matters?. *Environ. Sci. Pollut. Res.* **25**, 22850–22860 (2018).
50. Khan, Z., Ali, S., Umar, M., Kirikkaleli, D. & Jiao, Z. Consumption-based carbon emissions and international trade in G7 countries: The role of environmental innovation and renewable energy. *Sci. Total Environ.* **730**, 138945 (2020).
51. Adebayo, T. S. & Samour, A. Renewable energy, fiscal policy and load capacity factor in BRICS countries: Novel findings from panel nonlinear ARDL model. *Environ. Dev. Sustain.* **26**, 4365–4389 (2024).
52. Pata, U. K. & Samour, A. Assessing the role of the insurance market and renewable energy in the load capacity factor of OECD countries. *Environ. Sci. Pollut. Res.* **30**, 48604–48616 (2023).
53. Zhao, W.-X., Samour, A., Yi, K. & Al-Faryan, M. A. S. Do technological innovation, natural resources and stock market development promote environmental sustainability? Novel evidence based on the load capacity factor. *Resour. Policy* **82**, 103397 (2023).
54. Samour, A., Adebayo, T. S., Agyekum, E. B., Khan, B. & Kamel, S. Insights from BRICS-T economies on the impact of human capital and renewable electricity consumption on environmental quality. *Sci. Rep.* **13**, 5245 (2023).
55. Jiang, Y. *et al.* Does green growth in E-7 countries depend on economic policy uncertainty, institutional quality, and renewable energy? Evidence from quantile-based regression. *Geosci. Front.* **14**, 101652 (2023).
56. Lang, Q., Khaskheli, A., Raza, S. A., Khan, K. A. & Puah, C.-H. Nonlinear and nonparametric causal relationship between financial inclusion, energy efficiency, and sustainable environment in developed economies. *J. Knowl. Econ.* 1–30 (2023).
57. Pesaran, M. H. General diagnostic tests for cross section dependence in panels. *Available SSRN 572504* (2004).
58. Breusch, T. S. & Pagan, A. R. The Lagrange multiplier test and its applications to model specification in econometrics. *Rev. Econ. Stud.* **47**, 239–253 (1980).
59. Levin, A., Lin, C.-F. & James Chu, C.-S. Unit root tests in panel data: Asymptotic and finite-sample properties. *J. Econ.* **108**, 1–24 (2002).
60. Im, K. S., Pesaran, M. H. & Shin, Y. Testing for unit roots in heterogeneous panels. *J. Econ.* **115**, 53–74 (2003).
61. Harris, R. D. & Tzavalis, E. Inference for unit roots in dynamic panels where the time dimension is fixed. *J. Econ.* **91**, 201–226 (1999).
62. Maddala, G. S. & Wu, S. A comparative study of unit root tests with panel data and a new simple test. *Oxf. Bull. Econ. Stat.* **61**, 631–652 (1999).
63. Choi, I. Unit root tests for panel data. *J. Int. Money Finance* **20**, 249–272 (2001).
64. Abbasi, K. R., Shahbaz, M., Zhang, J., Irfan, M. & Alvarado, R. Analyze the environmental sustainability factors of China: The role of fossil fuel energy and renewable energy. *Renew. Energy* **187**, 390–402 (2022).
65. Ibrahim, R. L., Al-mulali, U., Ozturk, I., Bello, A. K. & Raimi, L. On the criticality of renewable energy to sustainable development: Do green financial development, technological innovation, and economic complexity matter for China?. *Renew. Energy* **199**, 262–277 (2022).
66. Ibrahim, R. L. & Ajide, K. B. Nonrenewable and renewable energy consumption, trade openness, and environmental quality in G-7 countries: the conditional role of technological progress. *Environ. Sci. Pollut. Res.* **28**, 45212–45229 (2021).
67. Udemba, E. N. Mitigating environmental degradation with institutional quality and foreign direct investment (FDI): New evidence from asymmetric approach. *Environ. Sci. Pollut. Res.* **28**, 43669–43683 (2021).
68. Mahmood, H. *et al.* The Fiscal and monetary policies and environment in GCC countries: Analysis of territory and consumption-based CO_2 emissions. *Sustainability* **14**, 1225 (2022).
69. Ike, G. N., Usman, O. & Sarkodie, S. A. Fiscal policy and CO_2 emissions from heterogeneous fuel sources in Thailand: Evidence from multiple structural breaks cointegration test. *Sci. Total Environ.* **702**, 134711 (2020).
70. Koenker, R. Quantile regression for longitudinal data. *J. Multivar. Anal.* **91**, 74–89 (2004).
71. Powell, D. Quantile regression with nonadditive fixed effects. *Empir. Econ.* **63**, 2675–2691 (2022).
72. Ullah, S., Luo, R., Adebayo, T. S. & Kartal, M. T. Dynamics between environmental taxes and ecological sustainability: Evidence from top-seven green economies by novel quantile approaches. *Sustain. Dev.* **31**, 825–839 (2023).
73. Hoang, D. P., Chu, L. K. & To, T. T. How do economic policy uncertainty, geopolitical risk, and natural resources rents affect economic complexity? Evidence from advanced and emerging market economies. *Resour. Policy* **85**, 103856 (2023).
74. Ye, C., Ye, Q., Shi, X. & Sun, Y. Technology gap, global value chain and carbon intensity: Evidence from global manufacturing industries. *Energy Policy* **137**, 111094 (2020).
75. Balsalobre-Lorente, D., Topaloglu, E. E., Nur, T. & Evcimen, C. Exploring the linkage between financial development and ecological footprint in APEC countries: A novel view under corruption perception and environmental policy stringency. *J. Clean. Prod.* https://doi.org/10.1016/j.jclepro.2023.137686 (2023).
76. Saidi, K. & Mbarek, M. B. The impact of income, trade, urbanization, and financial development on CO_2 emissions in 19 emerging economies. *Environ. Sci. Pollut. Res.* **24**, 12748–12757 (2017).
77. Adedoyin, F. F. & Zakari, A. Energy consumption, economic expansion, and CO_2 emission in the UK: The role of economic policy uncertainty. *Sci. Total Environ.* **738**, 140014 (2020).
78. Ben Lahouel, B., Taleb, L., Ben Zaied, Y. & Managi, S. Does ICT change the relationship between total factor productivity and CO_2 emissions? Evidence based on a nonlinear model. *Energy Econ.* **101**, 105406 (2021).

79. Durani, F., Bhowmik, R., Sharif, A., Anwar, A. & Syed, Q. R. Role of economic uncertainty, financial development, natural resources, technology, and renewable energy in the environmental Phillips curve framework. *J. Clean. Prod.* **420**, 138334 (2023).
80. Jahanger, A., Zaman, U., Razib Hossain, M. & Awan, A. Articulating CO_2 emissions limiting roles of nuclear energy and ICT under the EKC hypothesis: An application of non-parametric MMQR approach. *Geosci. Front.* https://doi.org/10.1016/j.gsf.2023.101589 (2023).
81. Nan, S., Huang, J., Wu, J. & Li, C. Does globalization change the renewable energy consumption and CO_2 emissions nexus for OECD countries? New evidence based on the nonlinear PSTR model. *Energy Strategy Rev.* **44**, 100995 (2022).
82. Zhu, X., Ding, Q. & Chen, J. How does critical mineral trade pattern affect renewable energy development? The mediating role of renewable energy technological progress. *Energy Econ.* **112**, 106164 (2022).

Author contributions
HENG LUO: conceptualization, methodology, formal analysis, investigation, data curation, writing—original draft, YING SUN: conceptualization, methodology, resources, writing—review and editing, supervision. All authors have read, reviewed, and agreed to the published version of the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-024-60773-5.

Correspondence and requests for materials should be addressed to Y.S.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.