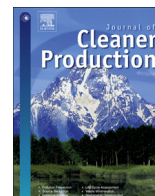




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# The effects of trade openness on decoupling carbon emissions from economic growth – Evidence from 182 countries

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## ABSTRACT

The current rise of protectionism has become the main uncertainty associated with global energy, economy, and the environment. Furthermore, the decoupling carbon emissions from economic growth is crucial for implementing Intended Nationally Determined Contributions (INDCs). These INDCs would be discounted if decreasing carbon emissions would require sacrificing economic growth. This study explored the effect of protectionism (by measuring trade openness based on available data) on the decoupling carbon emissions from economic growth. For this, the heterogeneous effects of trade openness on carbon emissions were investigated using in data of 182 countries from 1990 to 2015. The results show that trade openness decreased carbon emissions in high-income and upper-middle-income countries, while having no significant impact on carbon emissions of lower-middle-income countries; even worse, for low-income countries, trade openness increased carbon emissions. The heterogeneous effects of trade openness on carbon emissions indicate that trade openness positively impacts the decoupling economic growth from carbon emission in rich countries, but negatively impacts poor countries. In addition, increasing individual incomes and population distort the decoupling economic growth from carbon emissions. Renewable energy and high oil prices contributed to the decoupling economic growth from carbon emissions. These effects are similar in all countries. Targeted policy implications are presented that enable the decoupling economic growth from carbon emissions for countries with different income levels.

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## 1. Introduction

The Kyoto Protocol relied on a top-down approach, while the Paris Agreement relied on a bottom-up approach. Under its new governance, the core of the Paris Agreement are the Intended Nationally Determined Contributions (INDCs), according to which, countries make their own commitments to decrease carbon emissions. However, one problematic issue is that if mitigating carbon emissions requires to sacrifice economic growth, the motivation and efforts of countries to commit to INDCs will greatly decrease. It is thus imperative to decouple economic growth from carbon emissions, so that more countries are stimulated to make every effort to curtail their carbon emissions.

Recently, to decrease Public Health Emergency of International Concern (PHEIC) COVID-19 transmission, numerous countries have

implemented trade restrictions, which negatively impacted international trade. Undoubtedly, the current rise of protectionism has induced a new challenge for the carbon reduction for both developing and developed countries. Considering the strong inclination of countries to achieve the goals of the Paris Agreement, investigations regarding the impact of trade openness on the decoupling of economic growth and carbon emissions is necessary to develop more effective carbon reduction policies.

In this context, the present study is dedicated to solving three key issues based on panel data between the annual periods of 1990–2015 for 182 selected countries: (1) Is economic growth globally decoupled from carbon emissions? (2) What is the effect of trade openness on carbon emissions? (3) Is this effect heterogeneous for countries at different income levels?

To address these three issues, first, the Tapio decoupling model

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was applied to ascertain the decoupling between economic growth and carbon emissions. Then, the effect of trade openness on decoupling of economic growth and carbon emissions was investigated with the carbon functions. Unit root tests, cointegration tests, OLS and FMOLS estimates for panel models were adopted in carbon functions. This study established global panel and four income level panels, the results report the heterogeneous effect of trade openness on the decoupling of economic growth and carbon emissions. Effective policy implications can be drawn toward decoupling economic growth from carbon emissions, especially for countries with different income levels.

This article consists of five sections, which are organized as follows: Section 2 reviews and summarizes the relevant literature. Section 3 provides methods and data descriptions. Section 4 shows the results and discussion and Section 5 summarizes the main results and provides both conclusions and policy implications.

## 2. Literature review

### 2.1. Review of the decoupling process

The ideal state of decoupling indicates that economic growth does not depend on the growth of carbon emissions. To accurately understand the relationship between carbon emissions and economic growth, an indicator is required that reflects the relationship between both. The concept of decoupling was first proposed by Von in 1989 and was used to describe the relationship between carbon emissions and the economy. In 2002, the OECD first used the decoupling theory to study the relationship between economic growth and carbon emissions. Thus, the decoupling model gradually emerged. Subsequently, the concepts of primary decoupling and secondary decoupling were developed (Moldan et al., 2012). In 2005, the Tapio decoupling model began to use decoupling elasticity to describe the decoupling state (Tapio, 2005). In the following, for research level, the Tapio decoupling model was increasingly used in departmental and national research. At the departmental level, a deep understanding of the decoupling of industrial growth and carbon emissions was achieved (Wang and Jiang, 2019). In addition, decoupling process of soil erosion and human activities was investigated for the Loess Plateau of China using the concept of decoupling (Wei et al., 2006). In the tourism department, it has been suggested that China's tourism economy experienced negative and weak decoupling (Tang et al., 2014). Moreover, many scholars also focused on the national level, and investigated relevant issues in specific countries, e.g., China (Yang et al., 2018), the United States (Datta, 2019), the OECD (Chen et al., 2018), Pakistan (Raza and Lin, 2020), and India (Wang et al., 2019). In short, the Tapio decoupling model has been widely used, which indicates the maturity and adaptability of this model. This study thus used the Tapio decoupling model to identify the decoupling status of economic growth and carbon emissions. Moreover, such a comparison between countries with different income levels can help to formulate targeted carbon emission reduction policies. Therefore, further empirical research is needed at the global level.

### 2.2. Review of trade openness and carbon emissions

The literature on factors affecting carbon emissions is quite rich (Al-mulali, 2011; Wang and Zhang, 2020; Zhang and Da, 2015). The linear econometric model is the most commonly used model to study the factors affecting carbon emissions (Jalil and Feridun, 2011), and has been applied to time series data and panel data (Bhattacharya et al., 2017). As research increases, the existing research in this field can be divided into three categories. The first

category investigated the relationship between economic development and carbon emissions (Galeotti et al., 2009; Saboori et al., 2012; Selden and Song, 1994). The second category incorporated population and energy into the research framework of economic development and carbon emissions (Lehmann and Gawel, 2013; O'Neill and Chen, 2002; Weber and Perrels, 2000). Age structure (Fan et al., 2006), urbanization (Martínez-Zarzoso and Maruotti, 2011), the size of households (Poumanyong and Kaneko, 2010), energy prices (Rout et al., 2008), and energy consumption (Fortes et al., 2008) were specifically investigated. The third category not only includes population and energy but also control variables such as trade and foreign direct investment (Dasgupta et al., 2001; Tamazian et al., 2009; Zhang, 2011).

The present research is part of the third category and presents in-depth research on the impact of trade openness on carbon emissions, including individual incomes, population, oil prices, and renewable energy. Free trade helps the global economy to grow faster by increasing the trade volume and income, both in developed and developing countries. However, this growth trend is accompanied by specific environmental consequences (Shahbaz et al., 2017b).

In general, the impact of trade openness can mainly be divided into two theories in the environmental field. The first theory assumes that the impact of trade openness on pollution is vague and can be divided into scale effect, technology effect and composition effect (Farhani et al., 2014a). The second theory is the Pollution Haven Hypothesis (Copeland and Taylor, 2004). Trade openness introduces foreign direct investment. Since different countries set different environmental standards, polluting enterprises will choose to produce in countries with comparatively low environmental standards, which thus become "pollution haven". Therefore, the impact of trade openness on the environment needs to be considered for specific countries.

Based on these two theories, conclusions from the literature formed four hypotheses: (1) trade openness promotes carbon emissions; (2) carbon emissions promote trade openness; (3) feedback hypothesis: Trade openness and carbon emissions interact; (4) neutral hypothesis: Trade openness is independent of carbon emissions. In the evidence supporting hypothesis (1), at the national level, it has been found that trade openness positively affects carbon emissions in the long run for Pakistan by using the vector error correction model (VECM) (Nasir and Ur Rehman, 2011). Moreover, it has been observed that increased trade openness will increase pollution. This has been corroborated by applying the panel vector error correction model (PVECM), the fully modified ordinary least squares (PFMOLS) model, and the panel dynamic ordinary least squares (PDOLS) (Farhani et al., 2014b). With regard to hypothesis (2), China has been studied in the context of globalization using VECM causality as well as the ARDL bounds test (Shahbaz et al., 2017a). The causal test proved the unidirectional Granger causality of carbon emissions to trade openness. Besides, several international organizations also suggested that environmental regulations exert a serious impact on international trade. Hypothesis (3) refers to the bidirectional causality between trade openness and carbon emissions. At the transnational level, a study of 105 countries identified bidirectional causality between the global group and the middle-income group by using the panel regression model (Shahbaz et al., 2017b). While trade openness is affected by carbon emissions, it also affects carbon emissions. Hypothesis (4) does not support the link between trade openness and carbon emissions; however, relatively little literature supporting this hypothesis. At the national level, it has been argued that it is difficult to find a causal relationship between trade and the environment by using a linear econometric model (Frankel and Romer, 1999). At the transnational level, in the panel regression model,

trade openness has been found to be not generally correlated with increased emissions when studying the effects of trade on environmental Kuznets curve (EKC) (Kearsley and Riddel, 2010). Clearly, the results of different studies support different hypotheses. Consequently, the relationship between trade openness and carbon emissions still merits further investigation.

Although the existing literature covers a similar scope than the present work, this study contributes to previous literature in a number of notable aspects. First, this study extends the literature by incorporating of trade openness into the existing economic growth-carbon emission research framework. Renewable energy and population are used as additional variables, and a systematic study was conducted. The conclusions also provide comprehensive policy recommendations toward the achieving decoupling of economic growth from carbon emissions. Second, this study not only includes a similarities analysis at the global level, but more importantly, investigates the differences of four income sub-panels (high-income, upper-middle-income, lower-middle-income, and low-income) on the effect of trade openness in the decoupling of economic growth from carbon emissions. Such an analysis of differences can help more countries to find effective ways to embark on the path of decoupling economic growth from carbon emissions.

### 3. Method and data

#### 3.1. Decoupling index model

This study uses Tapio decoupling model, with the following equation:

$$e(C) = \frac{\Delta C / C_0}{\Delta G / G_0} \tag{1}$$

where  $e(C)$  represents the decoupling elasticity coefficient between economic activities and carbon emissions,  $\Delta C$  represents the total carbon emission change from the base period to the end period,  $C_0$  represents the carbon emissions at the base period.  $\Delta G$  represents the total GDP change from the base period to the end, and  $G_0$  represents the base period GDP. The Tapio model subdivides the decoupling state into eight states according to the decoupling elasticity value (Fig. 1).

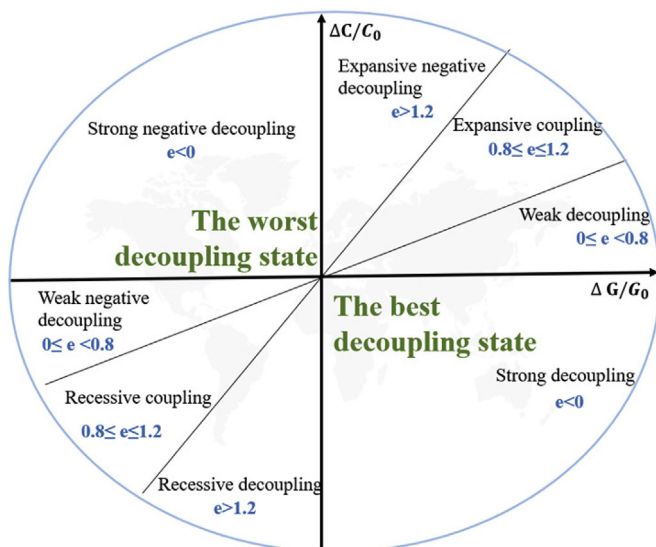


Fig. 1. Schematic diagram of decoupling states.

#### 3.2. Empirical model

Based on previous research (Dong et al., 2018) (Dogan and Turkekul, 2016), the following models were established:

$$C_{nt} = f(OPEN_{nt}, X_{nt}) \tag{2}$$

In Eq. (2),  $n$  ( $n = 1, 2, \dots, 182$ ) represents the sample country,  $t$  represents the year,  $OPEN$  represents trade openness, and  $C$  represents carbon emissions per capita. The estimation model is converted into a log linear econometric model:

$$\ln C_{nt} = \alpha_0 + \alpha_1 \ln OPEN_{nt} + \beta X_{nt} + \varepsilon_{nt} \tag{3}$$

In Eq. (3),  $X$  represents control variables, including oil prices, renewable energy consumption, individual incomes and population. Among these,  $\alpha_0$  and  $\varepsilon_{nt}$  represent the intercept and error terms, respectively, and  $\alpha_1$  and  $\beta$  represent the estimated coefficients of different variables. In Model 1, the only independent variable is  $\ln OPEN$ , and in Models 2 and 3,  $\ln OP$ ,  $\ln GDP$ ,  $\ln RE$ , and  $\ln POP$  are added as control variables.

#### 3.3. Estimation techniques

The study of the relationship between  $C$ ,  $OPEN$ ,  $OP$ ,  $GDP$ ,  $RE$ , and  $POP$  was divided into three steps. First, the panel unit root test was used to test the stability of each variable. Second, the panel cointegration test was used to determine the long-term cointegration relationship between variables. Next, the fixed-effect OLS and FMOLS cointegration estimates were used to analyze the long-term cointegration relationship between variables.

##### 3.3.1. Panel unit root tests

This study used four panel unit root tests: LLC, IPS, Fisher-ADF and Fisher-PP. These four tests include the same root test and the different root test. The unit root test was used to test the stability of the variable (Wang and Su, 2019). The null hypothesis of this test is that the variable has a unit root. If the result shows that the null hypothesis can be accepted, then the variable is not stationary; otherwise, the variable is stationary.

The formula of LLC test is as follows (Levin et al., 2002):

$$\Delta F_{it} = a_i Y_{it-1} + \sum_{L=1}^{mn} b_{ip} \Delta Y_{it-L} + c_{pi} d_{pt} + e_{it}, \quad p = 1, 2, 3 \tag{4}$$

where  $a_i$ ,  $c_{pi}$ ,  $d_{pt}$ , and  $e_{it}$  represent the autoregression coefficients of the model, and the corresponding vectors of the regression parameters were  $p = 1, 2, 3$ .

The formula of the IPS test (Im et al., 2003) is similar to that of the LLC test. In addition, the unit root test of the Fisher-PP panel, as developed by Phillips and Perron is a different unit root test (Phillips and Perron, 1988), the expression of which is as follows:

$$Fisher - ADF = -2 \sum_m^p \log(X_m) \rightarrow P \tag{5}$$

$$Choi - ADF = \frac{1}{\sqrt{T_{m-1}}} \sum_{m-1}^K \gamma^{-1}(X_m) \rightarrow K(0, 1) \tag{6}$$

where  $m$ ,  $\gamma^{-1}$  represents the reciprocal of the normal distribution function, and  $X_m$  represents the P-value of the ADF unit root test. The null hypothesis is  $a_i = 0$ , which indicates that there is a unit root; if  $a_i < 0$ , there is no unit root.

3.3.2. Panel cointegration tests

The cointegration test can determine whether variables that are stable at a specific level or of the same order have a long-term stable cointegration relationship. In this study, the panel Kao test (Kao, 1999) and the panel Pedroni test (Pedroni, 2001) were used, both of which are part of the Engle-Granger method. The Pedroni cointegration test includes two alternative hypotheses: panel statistical hypotheses and outlier statistical hypotheses. The specific statistical formula is as follows:

A. Panel-ρ

$$F\sqrt{AB_{\rho A,F-1}} \equiv F\sqrt{A \left( \sum_{\alpha=1}^A \sum_{\beta=1}^F \tilde{L}_{11\alpha}^{-2} \varepsilon_{\alpha,\beta-1}^2 \right)^{-1} \sum_{\alpha=1}^A \sum_{\beta=1}^F \tilde{L}_{11\alpha}^{-2} (\hat{\varepsilon}_{\alpha,\beta-1} \Delta \hat{\varepsilon}_{\alpha,\beta} - \hat{\theta}_{\alpha})} \quad (7)$$

B. Panel-β

$$B_{\alpha A,F}^* \equiv \left( S_{A,F}^{*2} \sum_{\alpha=1}^A \sum_{\beta=1}^F \tilde{L}_{11\alpha}^{-2} \varepsilon_{\alpha,\beta-1}^2 \right)^{-\frac{1}{2}} \sum_{\alpha=1}^A \sum_{\beta=1}^F \tilde{L}_{11\alpha}^{-2} \varepsilon_{\alpha,\beta-1} \Delta \hat{\varepsilon}_{\alpha,\beta} \quad (8)$$

C. Group-ρ

$$F\tilde{B}_{\rho A,F-1} \equiv FA^{-\frac{1}{2}} \sum_{\alpha=1}^A \left( \sum_{\beta=1}^F \varepsilon_{\alpha,\beta-1}^2 \right)^{-\frac{1}{2}} \sum_{\beta=1}^F (\hat{\varepsilon}_{\alpha,\beta-1} \Delta \hat{\varepsilon}_{\alpha,\beta} - \hat{\theta}_{\alpha}) \quad (9)$$

D. Group-β

$$A^{-\frac{1}{2}} \tilde{B}_{\rho A,F} \equiv A^{-\frac{1}{2}} \sum_{\alpha=1}^A \left( \sum_{\beta=1}^F S_{\alpha,F}^{*2} \varepsilon_{\alpha,\beta-1}^2 \right)^{-\frac{1}{2}} \sum_{\beta=1}^F \hat{\varepsilon}_{\alpha,\beta-1} \Delta \hat{\varepsilon}_{\alpha,\beta} \quad (10)$$

where

$$\hat{\theta}_{\alpha} = \frac{1}{2} (\hat{\mu}_{\alpha}^2 - \hat{S}_{\alpha}^2); S_{A,F}^{*2} = \frac{1}{A} \sum_{\alpha} S_{\alpha}^{*2} \quad (11)$$

3.3.3. Panel cointegration estimates

The second step of the long-term cointegration relationship is a cointegration estimation. This study used the ordinary least squares (OLS) method to perform regression on Model 2, and fully modified ordinary least squares (FMOLS) to perform regression on Models 1 and 3. FMOLS is widely used for regressions (Liu et al., 2019). Compared with OLS estimation, FMOLS estimation can correct sequence correlation and prevent pseudo regression, thus, it is a robust panel econometrics technology. In the FMOLS cointegration system, Pedroni (2000) proposed the following equation.

$$y_{\alpha\beta} = l_{\alpha} + \alpha x_{\alpha\beta} + \sum_{p=-P_{\alpha}}^{P_{\alpha}} \mu_{\alpha p} \Delta x_{\alpha\beta-p} + \theta_{\alpha\beta} \quad (12)$$

where  $\rho_{\alpha\beta} = (\hat{\theta}_{\alpha\beta}, \Delta x_{\alpha\beta})$ ,  $\delta_{\alpha\beta} = \lim_{D \rightarrow \infty} E \left[ \frac{1}{D(\sum_{d=1}^D \rho_{\alpha\beta})(\sum_{d=1}^D \rho_{\alpha\beta})} \right]$ ,  $\delta_{\alpha\beta}$  is the long-term covariance. In Equation (12),  $x$  and  $y_{\alpha\beta}$  have a cointegration relationship. The long-term covariance can be decomposed into  $\delta_{\alpha} = \delta_{\alpha}^o = \omega_{\alpha} = \omega_{\alpha}'$ , where  $\omega_{\alpha}$  represents the automatic covariance and  $\delta_{\alpha}^o$  represents the weighted sum of the covariance and  $\omega_{\alpha}$ . The FMOLS criteria are as follows:

$$\hat{\alpha}_{FMOLS} = \frac{1}{B} \sum_{\alpha}^B \left[ \frac{1}{\left( \sum_{d=1}^D x_{\alpha\beta} - \bar{x}_{\alpha} \right)^2} \left( \sum_{d=1}^D (x_{\alpha\beta} - \bar{x}_{\alpha}) y_{\alpha\beta}^* - \omega_{\mu_{\alpha}} \right) \right] \quad (13)$$

where  $y_{\alpha\beta}^* = y_{\alpha\beta} - \bar{y}_{\alpha} - (\hat{\delta}_{2,1,\alpha} \hat{\delta}_{2,2,\alpha}) \Delta x_{\alpha\beta}$ ,  $\hat{\gamma}_{\alpha} = \hat{\omega}_{2,1,\alpha} + \hat{\delta}_{2,1,\alpha}^o - (\hat{\omega}_{2,1,\alpha} / \hat{\omega}_{2,2,\alpha})(\hat{\omega}_{2,2,\alpha} + \hat{\delta}_{2,2,\alpha}^o)$

3.4. Data

Based data availability, unbalanced panel data was obtained for 182 countries from 1990 to 2015. Compared with many previous studies, this sample offers greater coverage in terms of country and year. First, a global panel composed of 182 countries was used. Second, the estimated sample was divided into four income sub-panels based on the 2020 World Bank's country classification: low-income (LI), lower-middle-income (LMI), upper-middle-income (UMI) and high-income (HI). Among these, the LI group is composed of 27 countries, the LMI and UMI groups are composed of 45 and 56 countries respectively, and the HI group is composed of 54 countries (see Table A1 in Appendix A). The variable definitions are shown in Table 1 and Table 2 shows the descriptive statistics of variables.

4. Results and discussion

4.1. Analysis of decoupling status of carbon emissions and economic growth

4.1.1. Decoupling status of each income group

Five decoupling states were identified in HI countries over the investigated period (Fig. 2): recessive decoupling (4%), expansive coupling (17%), strong decoupling (25%), weak decoupling (50%), and expansive negative decoupling (4%). Strong decoupling and weak decoupling totaled 75% in HI countries, identifying these as the highest among the four income groups. This suggests that decoupling of economic growth and carbon emissions is relatively common in HI countries. In addition, strong decoupling was maintained over the last five years of this dataset (2010–2014). This indicates that HI countries have gradually acquired the ability to decrease their carbon emissions without sacrificing economic growth. However, the expansion coupling state and the negative expansion decoupling state still appeared in individual years. The economic crisis in 2008 caused negative growth of both carbon emissions and GDP in HI countries, which leads to the emergence of weak negative decoupling. Later, as the economy recovered, carbon emission reductions were successful. The decoupling state improved to strong decoupling (2010–2011) in HI countries.

With regard to UMI countries, four decoupling states were identified: expansive coupling (29%), strong decoupling (12.5%), weak decoupling (37.5%), and expansive negative decoupling (21%). Overall, the year 2000 can be regarded as a turning point. Before 2000, strong and weak decoupling of economic growth from carbon emissions dominated. From 2000 to 2011, UMI countries entered a period of high-speed industrialization. The prevailing rapid economic development has caused excessive carbon emissions. In this context, expansion coupling has become the main performance of the relationship between economic growth and carbon emissions in 2000–2011. To overcome this dilemma, UMI countries strive to develop the tertiary industry and transform their economic development mode. In addition, many countries strive to increase the proportion of clean energy to adjust their energy

**Table 1**  
Definitions and sources of data in the model.

Symbol	Definition	Source
C	CO <sub>2</sub> emissions (metric tons per capita)	World Bank
OP	Brent Spot crude prices (US dollars per barrel)	BP Statistical Review of World
RE	Renewable energy consumption (% of total final energy consumption)	World Bank
GDP	GDP per capita (constant 2010 US\$)	World Bank
POP	Population, total (Ten thousand)	World Bank
OPEN	Trade (% of GDP)	World Bank

**Table 2**  
Descriptive statistics of variables.

Statistics	LNC	LNTRADE	LNOP	LNGDP	LNPOP	LNRE
<b>Mean</b>	0.4927	4.2817	3.6128	8.3513	8.1262	2.7443
<b>Std. Dev</b>	1.6531	0.6276	0.7128	1.5074	4.4497	1.7258
<b>Max</b>	3.5812	6.0927	4.7155	11.6260	20.9934	4.5885
<b>Min</b>	-4.5356	-3.8633	2.5428	5.1019	-0.0508	-6.3399

structure (Wang and Wang, 2020). For example, China, which uses coal as its main energy source, showed a clear trend of improving its energy structure. Ultimately, the continuous weak decoupling appeared in 2011–2014, indicating that the efforts of the UMI countries have yielded results.

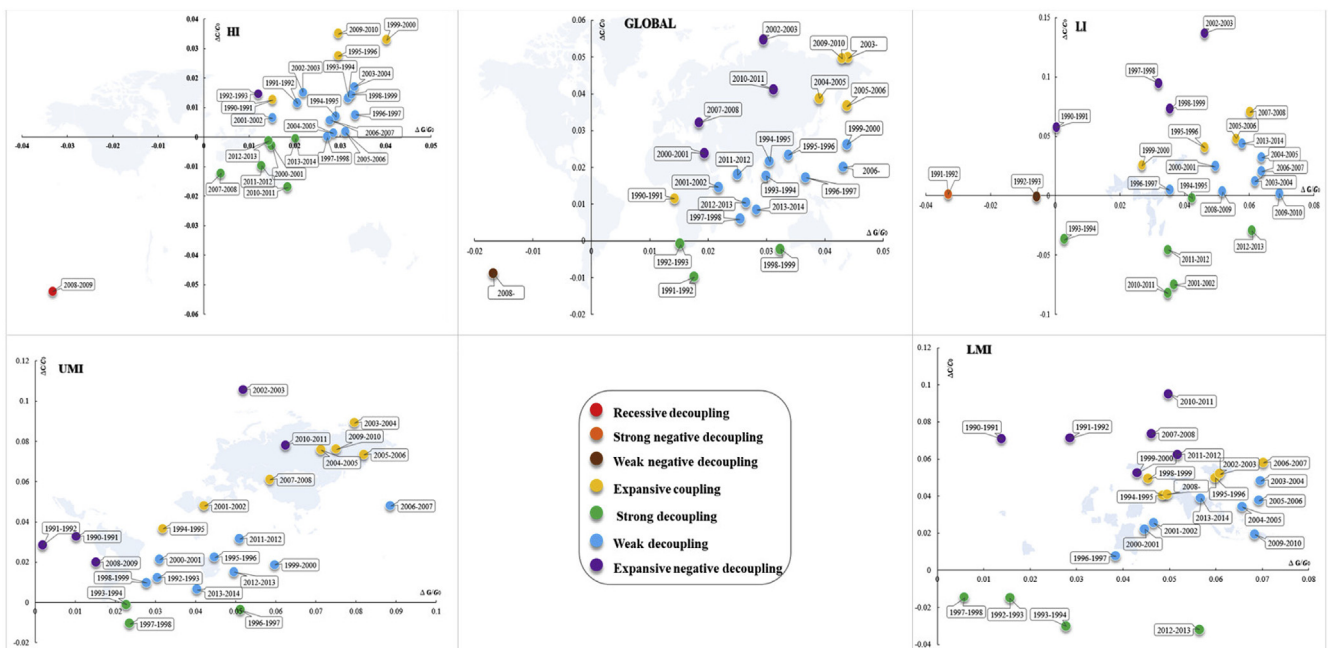
Four decoupling states were identified in LMI countries in 1990–2014, expansive coupling (25%), strong decoupling (17%), weak decoupling (33%), and expansive negative decoupling (25%). The decoupling of economic growth and carbon emissions has fluctuated state in LMI (1990–2014). The fluctuation was obvious compared with UMI over the same period. The reason may be that because of the desire to improve the economy, LMI countries focus more on economic development than environmental quality. However, the dependence of economic growth on energy will further stimulate carbon emissions, which is not conducive to their reduction (Wang and Su, 2020). In addition, developed countries export industrial production to LMI. The decrease of carbon emissions in HI countries is thus, in fact, paid for by developing

countries (Schaltegger and Csutora, 2012). Hence, it is difficult for LMI countries to achieve a long-term decoupling of economic growth and carbon emissions.

The decoupling status of LI countries is quite rich, and the following six states were identified: expansive coupling (17%), strong decoupling (25%), weak decoupling (33%), expansive negative decoupling (17%), strong negative decoupling (4%), and weak negative decoupling (4%). This may be related to the ability of LI countries to resist risks. The economic development of LI countries was very difficult in 1991–1992. The negative economic growth and low carbon emissions led to the appearance of strong negative decoupling and weak negative decoupling. Overall, with improving economic conditions, the decoupling status gradually improves.

**4.1.2. Global decoupling status**

Five decoupling states appeared in the global sample over the considered period: strong decoupling (12%), weak decoupling (46%), expansive coupling (21%), expansive negative decoupling (17%), and weak negative decoupling (4%). Among these, weak decoupling occurred most frequently. Consequently, the world has been in a state where economic output and carbon emissions have simultaneously increased for most of the time. The lethargic economy of 2008 has decreased carbon emissions compared with the previous year. Therefore, weak negative decoupling occurred in 2008–2009. Judging from the overall decoupling evolution trend, the decoupling of global economic growth and carbon emissions was subject to an iterative process. First, weak decoupling was the



**Fig. 2.** Decoupling trend of economic growth and carbon emissions.

**Table 3**  
Panel data unit root test results high-income (HI) countries.

variable	Test method	At level		At 1st difference	
		t-Statistic	Prob.	t-Statistic	Prob.
lnC	LLC	0.3303	0.6294	-25.3482***	0.0000
	IPS	-0.5472	0.2921	-24.7075***	0.0000
	ADF	157.8240***	0.0013	745.0330***	0.0000
	PP-Fisher	119.4290	0.2128	945.6830***	0.0000
lnOP	LLC	0.0565	0.5225	-14.4233***	0.0000
	IPS	4.7687	1.0000	-18.5345***	0.0000
	ADF	29.7437	1.0000	512.7750***	0.0000
	PP-Fisher	30.0693	1.0000	472.4640***	0.0000
lnRE	LLC	-0.1487	0.4409	-26.5624***	0.0000
	IPS	2.9442	0.9984	-25.5011***	0.0000
	ADF	126.9620	0.1027	805.7770***	0.0000
	PP-Fisher	142.2660**	0.0151	829.9100***	0.0000
lnGDP	LLC	-5.9370***	0.0000	-16.6356***	0.0000
	IPS	2.0601	0.9803	-16.1460***	0.0000
	ADF	81.7711	0.9612	456.0830***	0.0000
	PP-Fisher	98.0067	0.6975	457.5450***	0.0000
lnPOP	LLC	-2.5610***	0.0052	-0.9226	0.1781
	IPS	5.2753	1.0000	-5.4887***	0.0000
	ADF	120.0550	0.1658	240.4860***	0.0000
	PP-Fisher	229.1550***	0.0000	227.2430***	0.0000
lnOPEN	LLC	-3.2272***	0.0006	-27.3984***	0.0000
	IPS	-0.7895	0.2149	-25.1925***	0.0000
	ADF	114.0190	0.3273	705.8020***	0.0000
	PP-Fisher	116.7810	0.2653	789.7430***	0.0000

Note: \*\*\*, \*\*, \* represent significant at 1%, 5%, and 10% inspection levels, respectively.

**Table 4**  
Panel data unit root test results upper-middle-income (UMI) countries.

variable	Test method	At level		At 1st difference	
		t-Statistic	Prob.	t-Statistic	Prob.
lnC	LLC	-5.8321***	0.0000	-33.1267***	0.0000
	IPS	-3.8975***	0.0000	-30.1645***	0.0000
	ADF	200.2090***	0.0000	1028.3200***	0.0000
	PP-Fisher	239.9240***	0.0000	1935.3500***	0.0000
lnOP	LLC	0.0575	0.5229	-14.6880***	0.0000
	IPS	4.8562	1.0000	-18.8746***	0.0000
	ADF	30.8453	1.0000	531.7670***	0.0000
	PP-Fisher	31.1830	1.0000	489.9630***	0.0000
lnRE	LLC	-8.6057***	0.0000	-27.8186***	0.0000
	IPS	-5.8853***	0.0000	-26.8433***	0.0000
	ADF	265.1480***	0.0000	798.1670***	0.0000
	PP-Fisher	221.9790***	0.0000	823.3950***	0.0000
lnGDP	LLC	-2.0807**	0.0187	-21.7528***	0.0000
	IPS	4.4646	1.0000	-20.5271***	0.0000
	ADF	87.1641	0.9604	601.7010***	0.0000
	PP-Fisher	90.8616	0.9288	620.9370***	0.0000
lnPOP	LLC	-4.2406***	0.0000	-5.9177***	0.0000
	IPS	-1.1059	0.1344	-4.8509***	0.0000
	ADF	244.5330***	0.0000	231.6940***	0.0000
	PP-Fisher	445.9320***	0.0000	178.8140***	0.0001
lnOPEN	LLC	-4.3522***	0.0000	-28.9283***	0.0000
	IPS	-5.6305***	0.0000	-29.3186***	0.0000
	ADF	213.7520***	0.0000	810.5830***	0.0000
	PP-Fisher	211.8550***	0.0000	976.9980***	0.0000

Note: \*\*\*, \*\*, \* represent significant at 1%, 5%, and 10% inspection levels, respectively.

dominant state of decoupling before 2000. Over the next decade, environmental protection was ignored as countries sought to accelerate their economic growth. This allowed decoupling to evolve into expansive coupling. Finally, climate change has induced countries to take practical action to control their carbon emissions. In fact, many practical actions were already taken before 2011, but only developed countries actively participated before 2011. With the participation of more developing countries, UMI (2011–2012) and LMI (2012–2013) gradually entered a weak decoupling state. This led to the emergence of weak decoupling at a global level in 2011–2014.

#### 4.2. Unit root test results

All variables passed the four panel unit root tests, and the results are shown in Tables 3–7. Independent of the income group, the stationarity of the variables remains stable after the first-order difference. This prompted the next cointegration analysis. Specifically, since the test results of the four panel unit roots are sometimes inconsistent, the majority of the test results was selected.

#### 4.3. Panel cointegration test results

The results of the panel cointegration test are shown in Table B1–B5 (see Appendix B). To study the long-term relationship between trade openness, oil prices, individual incomes, population, renewable energy and carbon emissions, all variables were included in the panel cointegration test. The results of the Pedroni cointegration test and the Kao cointegration test were consistent. Independent of the income group results, the null hypothesis was rejected, i.e., a long-term co-integration relationship was identified between 182 countries and regions, trade openness, oil prices, individual incomes, population, renewable energy consumption and carbon emissions from 1990 to 2015. To further study this long-term stable relationship, OLS and FMOLS cointegration estimation were used in the next step.

**Table 5**  
Panel data unit root test results lower-middle-income (LMI) countries.

variable	Test method	At level		At 1st difference	
		t-Statistic	Prob.	t-Statistic	Prob.
lnC	LLC	-3.7109***	0.0001	-26.1813***	0.0000
	IPS	-1.6884**	0.0457	-24.0032***	0.0000
	ADF	147.4100***	0.0001	644.9100***	0.0000
	PP-Fisher	124.3340***	0.0097	857.0880***	0.0000
lnOP	LLC	0.0515	0.5206	-13.1666***	0.0000
	IPS	4.3532	1.0000	-16.9196***	0.0000
	ADF	24.7864	1.0000	427.3130***	0.0000
	PP-Fisher	25.0578	1.0000	393.7200***	0.0000
lnRE	LLC	2.0742	0.9810	-27.1339***	0.0000
	IPS	4.9360	1.0000	-26.2791***	0.0000
	ADF	62.5797	0.9877	693.2200***	0.0000
	PP-Fisher	61.3183	0.9911	688.8040***	0.0000
lnGDP	LLC	5.2366	1.0000	-19.2367***	0.0000
	IPS	10.1081	1.0000	-17.4271***	0.0000
	ADF	45.9966	1.0000	589.2890***	0.0000
	PP-Fisher	34.9186	1.0000	497.2910***	0.0000
lnPOP	LLC	-0.3006	0.3819	-1.7484**	0.0402
	IPS	4.0095	1.0000	-4.5529***	0.0000
	ADF	79.3686	0.4989	183.4000***	0.0000
	PP-Fisher	415.3820***	0.0000	109.4880*	0.0795
lnOPEN	LLC	-5.9406***	0.0000	-39.1776***	0.0000
	IPS	-4.0791***	0.0000	-31.4556***	0.0000
	ADF	166.7420***	0.0000	662.1240***	0.0000
	PP-Fisher	140.6720***	0.0005	729.1150***	0.0000

Note: \*\*\*, \*\*, \* represent significant at 1%, 5%, and 10% inspection levels, respectively.

#### 4.4. Panel cointegration regression results

In light of the evidence of the long-term cointegration relationship among variables, regression estimates were calculated to identify reasonable environmental policies. This identification can be achieved by understanding the linear nexus between carbon emissions, trade openness, oil price, individual incomes, population and renewable energy. The OLS and FMOLS regression results are

**Table 6**  
Panel data unit root test results low-income (LI) countries.

variable	Test method	At level		At 1st difference	
		t-Statistic	Prob.	t-Statistic	Prob.
lnC	LLC	-1.7353**	0.0413	-15.2650***	0.0000
	IPS	0.8792	0.8103	-15.2674***	0.0000
	ADF	66.7183*	0.0823	308.1050***	0.0000
lnOP	PP-Fisher	41.5566	0.8498	357.0010***	0.0000
	LLC	0.0399	0.5159	-10.1988***	0.0000
	IPS	3.3720	0.9996	-13.1059***	0.0000
lnRE	ADF	14.8718	1.0000	256.3880***	0.0000
	PP-Fisher	15.0347	1.0000	236.2320***	0.0000
	LLC	2.4478	0.9928	-15.8517***	0.0000
lnGDP	IPS	2.6257	0.9957	-15.6843***	0.0000
	ADF	44.2898	0.8243	313.8250***	0.0000
	PP-Fisher	48.4476	0.6876	346.8300***	0.0000
lnPOP	LLC	0.9599	0.8315	-14.3983***	0.0000
	IPS	2.6465	0.9959	-15.8866***	0.0000
	ADF	51.3827	0.5760	337.3760***	0.0000
lnOPEN	PP-Fisher	54.6054	0.4514	347.8860***	0.0000
	LLC	-0.5092	0.3053	-2.0899**	0.0183
	IPS	1.5108	0.9346	-6.7961***	0.0000
lnPOP	ADF	91.1887***	0.0001	245.7320***	0.0000
	PP-Fisher	96.2146***	0.0000	75.3192**	0.0292
	LLC	-3.4066***	0.0003	-20.3063***	0.0000
lnOPEN	IPS	-2.2479**	0.0123	-19.9645***	0.0000
	ADF	98.1022***	0.0002	408.3280***	0.0000
	PP-Fisher	95.6248***	0.0004	492.3560***	0.0000

Note: \*\*\*, \*\*, \* represent significant at 1%, 5%, and 10% inspection levels, respectively.

**Table 7**  
Panel data unit root test results all countries (Global).

variable	Test method	At level		At 1st difference	
		t-Statistic	Prob.	t-Statistic	Prob.
lnC	LLC	-6.4189***	0.0000	-51.6412***	0.0000
	IPS	-2.9896***	0.0014	-48.0612***	0.0000
	ADF	572.1610***	0.0000	2726.3700***	0.0000
lnOP	PP-Fisher	525.2430***	0.0000	4095.1200***	0.0000
	LLC	0.1037	0.5413	-26.4791***	0.0000
	IPS	8.7546	1.0000	-34.0267***	0.0000
lnRE	ADF	100.2470	1.0000	1728.2400***	0.0000
	PP-Fisher	101.3450	1.0000	1592.3800***	0.0000
	LLC	-2.6812***	0.0037	-49.8834***	0.0000
lnGDP	IPS	1.7832	0.9627	-47.8708***	0.0000
	ADF	498.9790***	0.0000	2610.9900***	0.0000
	PP-Fisher	474.0110***	0.0001	2688.9400***	0.0000
lnPOP	LLC	0.4248	0.6645	-36.7636***	0.0000
	IPS	9.6816	1.0000	-35.0305***	0.0000
	ADF	266.3150	1.0000	1984.4500***	0.0000
lnOPEN	PP-Fisher	278.3920	0.9996	1923.6600***	0.0000
	LLC	-3.2912***	0.0005	-5.5718***	0.0000
	IPS	4.7683	1.0000	-10.5915***	0.0000
lnPOP	ADF	535.1450***	0.0000	901.3130***	0.0000
	PP-Fisher	1186.6800***	0.0000	590.8650***	0.0000
	LLC	-8.2820***	0.0000	-59.3767***	0.0000
lnOPEN	IPS	-6.4467***	0.0000	-53.3991***	0.0000
	ADF	592.6160***	0.0000	2586.8400***	0.0000
	PP-Fisher	564.9330***	0.0000	2988.2100***	0.0000

Note: \*\*\*, \*\*, \* represent significant at 1%, 5%, and 10% inspection levels, respectively.

reported in Table B6 (see Appendix B). This analysis focuses on the FMOLS estimation results.

4.4.1. Regression results for the global group

Fig. 3 shows the importance of each factor for 182 countries. The following section analyzes the results of the global group. In this study, Model 1 investigates the effect of trade openness on carbon emissions without interference of other factors. In Model 1, a 1%

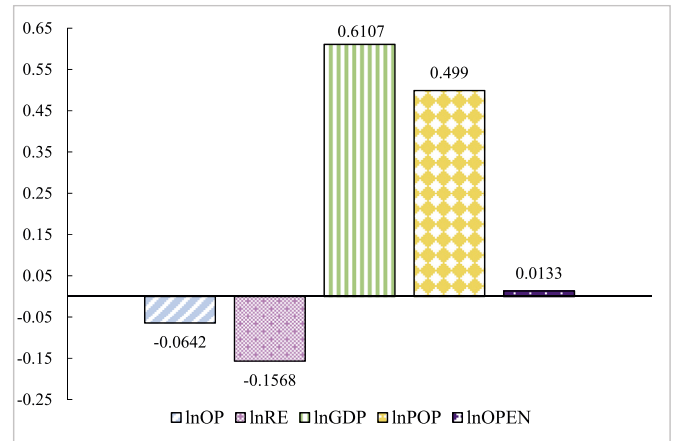


Fig. 3. Summary of regression coefficients on global carbon emissions influencing factors.

increase in trade openness leads to a 0.1279% increase of global carbon emissions in the long run. Additionally, Model 3 investigates the effect of trade openness on carbon emissions considering oil prices, individual incomes, population, and renewable energy. In Model 3, a 1% increase in trade openness leads to a 0.0133% increase of global carbon emission in the long run. The regression coefficient of trade openness is positive in all models. Therefore, regardless of have interference from other factors, trade openness significantly promotes global carbon emissions, which is in line with previous publications (Cole and Elliott, 2005; Grossman and Krueger, 1994; Jalil and Feridun, 2011).

For individual incomes and population, this study traces that individual incomes and population positively affect carbon emissions in global group. In Model 3, a 1% increase in individual incomes and population leads to 0.6107% and 0.499% decrease of global carbon emission in the long run, respectively. These results match those reported by Mensah et al. (2019), who argued that carbon emissions are likely highly correlated with individual incomes because they are by-products of industrial processes, energy consumption (direct consumption of fossil fuels and electricity), and car use. Although a number of advanced economies have decoupled their economic growth from carbon emissions in recent years (Andreoni and Galmarini, 2012), this is not common.

The increasing population drives carbon emissions, however, this driving effect is less than that of individual incomes. This is desirable, as certain human behavior customs may directly trigger excessive energy consumption and subsequently influence environmental change. The ensuing increase of the number of private cars and construction operations has also increased energy consumption, which may be the main reason why increasing population leads to increased carbon emissions (Wong et al., 2015).

In contrast, higher oil prices and renewable energy hinder global carbon emission regardless of the income group, and the effect of renewable energy generation is stronger. Regarding renewable energy, a statistical inverse relationship exists with carbon emissions. In Model 3, a 1% increase in the proportion of renewable energy consumption yields a corresponding 0.1568% decrease in global carbon emissions over the considered period. These results confirm that the consumption of renewable energy effectively decreases carbon emissions (Cai et al., 2018).

A 1% increase in international crude oil prices leads to a 0.0642% decrease of global carbon emissions in the long run, which is supported in by previous research (Winchester and Ledvina, 2017). Changes in oil prices affect energy consumption since oil is an



important component of the global energy consumption structure, and oil is also the main source of carbon dioxide. It should be noted that the turmoil in the financial market caused by the decline in oil prices has negatively impacted the economies of many crude oil producing countries. In the long run, this decline will accelerate the carbon dioxide emissions of these countries, which will undoubtedly bring difficulties to the global carbon emission reduction work.

#### 4.4.2. Regression results for different income groups

This study also investigated four income groups. Comparative analysis of the results between different income groups has practical significance for many countries when formulating targeted emission reduction policies. Four carbon functions of different income groups were obtained from Model 3, as shown in Table 8. Fig. 4 shows the distribution of the effects for different income levels. The effects of oil prices, individual incomes, population, and renewable energy on carbon emissions are consistent among all four income groups, however, the effect of trade openness is clearly inconsistent. Therefore, this section discusses the heterogeneous effects of trade openness on carbon emissions across four income groups.

Model 1 investigates the impact of trade openness on carbon emissions without interference from any other factors. For the HI group, the long-term coefficients of trade openness are negatively linked to carbon emission and the coefficients are also statistically significant at the 1% level. A 1% increase in trade openness will decrease carbon emission by 0.1276%. However, the result for the LI group is the complete opposite, showing that trade openness is positively linked to carbon emissions and the coefficients are also statistically significant at the 1% level. A 1% increase in trade openness will create 0.4942% additional carbon emissions. In addition, for UMI and LMI groups, the long-term coefficients of trade openness to carbon emissions are not statistically significant.

Importantly, Model 3 provides powerful evidence that trade openness exerts a heterogeneous effect on carbon emissions considering the roles of oil prices, individual incomes, population and renewable energy in the carbon function of the investigation of trade openness. Specifically, the outcome of Model 3 implies that the trade openness of HI and UMI groups increased by 1%, and carbon emissions decreased by 0.1674% and 0.0478% over in the long run, respectively. Regarding the LMI group, a linear positive relationship is indicated between trade openness and carbon emissions, however, this relationship is not significant. For the LI group, as a 1% increase in trade openness yields a corresponding 0.3567% increase in carbon emissions in the long run, which contrasts with the results of HI and UMI groups.

This is insightful, as it indicates that trade openness has a positive impact on carbon emission reduction in both the HI and UMI countries, but not significant on carbon emissions in LMI countries, and even a negative impact on LI countries. This indicates that with increasing income level, the impact of trade openness on carbon emissions also changes. This supports a previously reported the view (Shahbaz et al., 2017b), where trade openness contributes to carbon emissions at all income levels but exerts with varying influence on different panels. The heterogeneous effects of trade

openness on carbon emission suggest that trade openness improves the environment of rich countries, but aggravates the environmental pollution of poor countries. This is in line with the recognized phenomenon of carbon transfer in the process of international trade (Essandoh et al., 2020). Environmental standards in LI countries are generally lower than in other countries with higher income levels, and the environmental management system is deficient. Therefore, with the formation of global supply chains, developed countries either transfer or outsource high-carbon emission industries to LI countries (Baumert et al., 2019). This supports the views of Grossman and Krueger (1994) who pointed out that dirty industries in developing countries tend to cause a heavy share of pollutants. Most developing countries are LI countries. The ‘‘Pollution Refuge Hypothesis’’ was verified (Zhang et al., 2017) and trade implied carbon emissions were also assumed as a key way to transfer pollution (Rafindadi et al., 2018). Hence, with decreasing income levels, the impact of trade openness on the environment changes from positive to negative.

## 5. Conclusions and policy implications

### 5.1. Conclusions

This study investigated the effect of trade openness on the decoupling of economic growth from carbon emissions. Combining the Tapio decoupling model with the log linear econometric model, differences of decoupling status and the heterogeneity effect of trade openness on carbon emissions were found in different income groups. The main findings are summarized in the following:

- > Although global decoupling economic growth from carbon emissions converges on weak decoupling, obvious differences were found between countries with different income levels. Specifically, HI countries have the best decoupling status, followed by UMI and LI countries, which show a stable improvement trend. LMI countries are the worst because of their unstable decoupling status and lack of improvement trend.
- > For the world as a whole, trade openness increases carbon emissions. For individual countries, trade openness decreases carbon emissions in HI and UMI countries, and does not significantly impact carbon emissions in LMI countries. However, for LI countries, trade openness increases carbon emissions. The heterogeneous effects of trade openness on carbon emissions indicates that trade openness has a positive impact on the decoupling of economic growth from carbon emissions in rich countries, but a negative impact in poor countries.
- > Increasing individual incomes and population distort the decoupling of economic growth from carbon emissions, and the distortion of individual incomes is stronger than population growth. In contrast, renewable energy consumption and high oil prices contributed to the decoupling of economic growth from carbon emission, and the contribution of renewable energy is stronger than that of high oil prices. Moreover, these effects are similar in all countries independent of income levels.

**Table 8**  
Equations based on FMOLS regression results.

Panel	Logarithmic panel model	R-squared
HI	$LnC_{nt} = -0.1674LnOPEN_{nt} - 0.0498 LnOP_{nt} + 0.3086 LnGDP_{nt} + 0.0129 LnPOP_{nt} - 0.1432 LnRE_{nt}$	0.4291
UMI	$LnC_{nt} = -0.0478LnOPEN_{nt} - 0.0359 LnOP_{nt} + 0.6289 LnGDP_{nt} + 1.1016 LnPOP_{nt} - 0.1068 LnRE_{nt}$	0.9812
LMI	$LnC_{nt} = -0.0126LnOPEN_{nt} - 0.0357 LnOP_{nt} + 0.7046 LnGDP_{nt} + 0.3312 LnPOP_{nt} - 0.5378 LnRE_{nt}$	0.9561
LI	$LnC_{nt} = 0.3567LnOPEN_{nt} - 0.0569 LnOP_{nt} + 0.6378 LnGDP_{nt} + 0.1834 LnPOP_{nt} - 1.6065 LnRE_{nt}$	0.9432

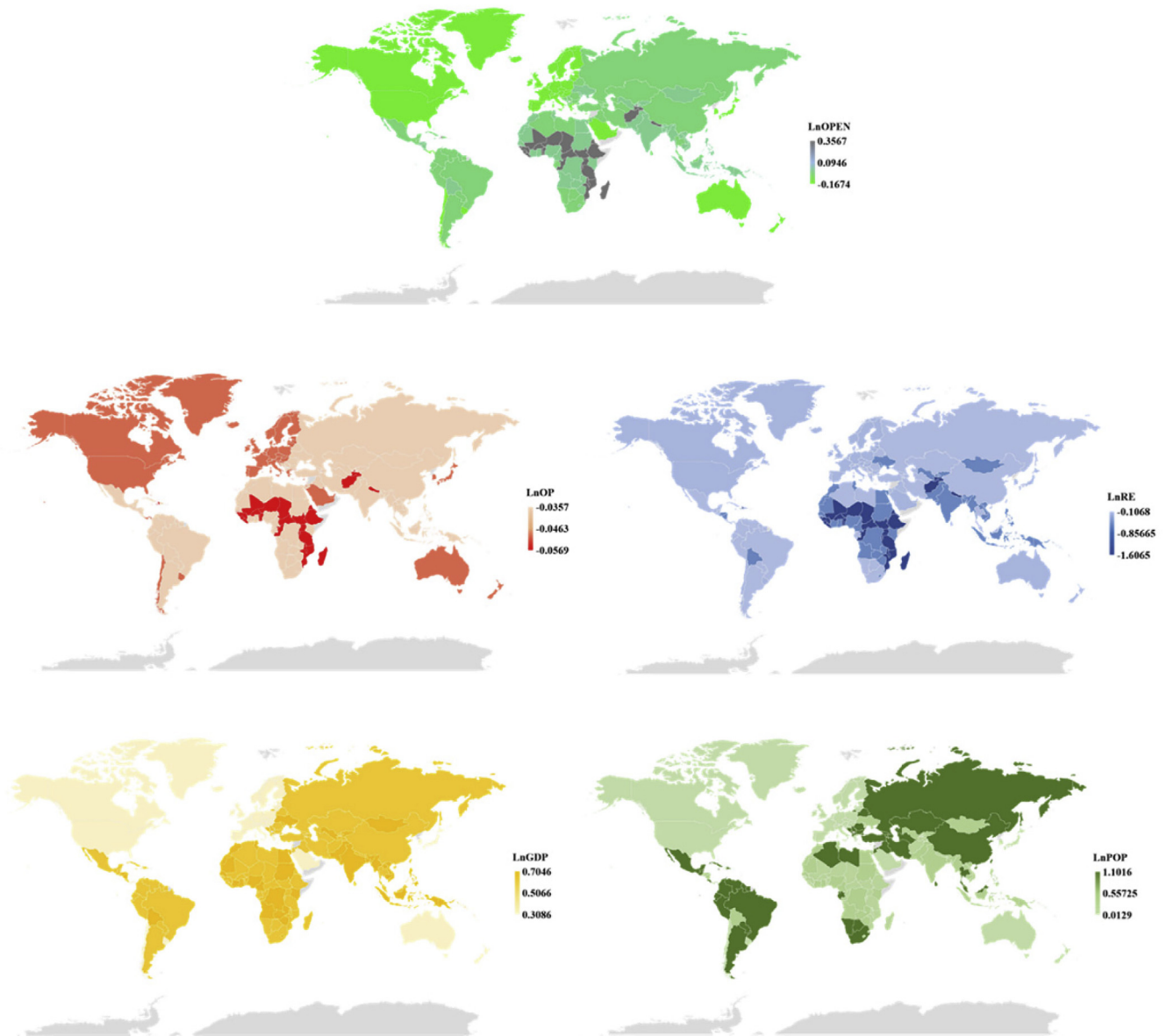


Fig. 4. Spatial characteristics of elastic coefficients across the global.

## 5.2. Policy implications

Targeted policy implications are needed toward achieving a complete decoupling of economic growth from carbon emissions.

- HI countries already have the ability to decrease their carbon emissions without sacrificing economic growth. This is a sign for HI countries to strengthen their commitment to the Paris Agreement. Consequently, more developed countries should sign the Paris Agreement. Moreover, developed countries should consciously make more aggressive and efficient efforts with regard to INDCs.
- For LI countries, trade openness has led to more pollution because of the less stringent environmental regulations. Imposing environmental regulations on trade-related gas emissions and without hindering the improvement of production levels is difficult in these countries. Thus, developing countries should use clean and environmentally friendly technologies when producing trade goods. Furthermore, increasing

the share of the tertiary industry in foreign direct investment is a feasible way to help decrease environmental pollution along the path of liberalizing of international trade.

- For the world, to contribute to the decoupling of economic growth from carbon emissions, increasing the share of renewable energy in the energy portfolio is a sensible option. This can also enhance the ability to resist energy risks, such as oil price fluctuations. Governments can attract further investors to explore and implement renewable energy technologies by developing further renewable energy policies and relevant institutions. This in turn, will promote the use of renewable energy.

## CRedit authorship contribution statement

**Qiang Wang:** Conceptualization, Methodology, Software, Data curation, Writing - original draft, Supervision, Writing - review & editing. **Fuyu Zhang:** Methodology, Data curation, Investigation, Writing - original draft, Writing - review & editing.

## Declaration of competing interest

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

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## Appendix A

**Table A1**

List of sample countries.

High-income	Upper-middle-income	Lower-middle-income	Low-income
Aruba	Albania	Angola	Afghanistan
United Arab Emirates	Argentina	Bangladesh	Burundi
Australia	Armenia	Bolivia	Benin
Austria	Azerbaijan	Bhutan	Burkina Faso
Belgium	Bulgaria	Cote d'Ivoire	Central African Republic
Bahamas, The	Bosnia and Herzegovina	Cameroon	Congo, Dem. Rep.
Bermuda	Belarus	Congo, Rep.	Eritrea
Barbados	Belize	Comoros	Ethiopia
Brunei Darussalam	Brazil	Cabo Verde	Guinea
Canada	Botswana	Egypt, Arab Rep.	Gambia, The
Switzerland	China	Micronesia, Fed. Sts.	Guinea-Bissau
Chile	Colombia	Ghana	Haiti
Cyprus	Costa Rica	Honduras	Liberia
Czech Republic	Cuba	Indonesia	Madagascar
Germany	Dominica	India	Mali
Denmark	Dominican Republic	Kenya	Mozambique
Spain	Algeria	Kyrgyz Republic	Malawi
Estonia	Ecuador	Cambodia	Niger
Finland	Gabon	Kiribati	Nepal
France	Georgia	Lao PDR	Rwanda
Faroe Islands	Equatorial Guinea	Lesotho	Sierra Leone
United Kingdom	Grenada	Morocco	South Sudan
Greece	Guatemala	Moldova	Chad
Greenland	Guyana	Myanmar	Togo
Hong Kong SAR, China	Iran, Islamic Rep.	Mongolia	Tajikistan
Croatia	Iraq	Mauritania	Tanzania
Hungary	Jamaica	Nigeria	Uganda
Ireland	Jordan	Nicaragua	
Iceland	Kazakhstan	Pakistan	
Israel	Lebanon	Philippines	
Italy	Libya	Papua New Guinea	
Japan	St. Lucia	West Bank and Gaza	
St. Kitts and Nevis	Sri Lanka	Sudan	
Korea, Rep.	Maldives	Senegal	
Kuwait	Mexico	Solomon Islands	
Lithuania	Marshall Islands	El Salvador	
Luxembourg	North Macedonia	Eswatini	
Latvia	Montenegro	Timor-Leste	
Macao SAR, China	Mauritius	Tunisia	
Malta	Malaysia	Ukraine	
Netherlands	Namibia	Uzbekistan	
Norway	Nauru	Vietnam	
New Zealand	Peru	Vanuatu	
Panama	Paraguay	Zambia	
Poland	Romania	Zimbabwe	
Portugal	Russian Federation		
Saudi Arabia	Serbia		
Singapore	Suriname		
Slovak Republic	Thailand		
Slovenia	Turkmenistan		
Sweden	Tonga		
Seychelles	Turkey		
Uruguay	St. Vincent and the Grenadines		
United States	Venezuela, RB		
	Samoa		
	South Africa		

## Appendix B

**Table B1**  
Cointegration Test results (HI)

Pedroni Cointegration Test	Value	P-value
Panel v-Statistic	-2.6582	0.9961
Panel rho-statistic	4.4629	1.0000
Panel PP-statistic	-8.6343***	0.0000
Panel ADF-statistic	-7.7463***	0.0000
Group rho-statistic	6.0033	1.0000
Group PP-statistic	-19.5805***	0.0000
Group ADF-Statistic	-12.8081***	0.0000
<b>Kao Cointegration Test</b>		
	<b>Statistic</b>	<b>P-value</b>
ADF	-3.6300***	0.0001
Residual variance	0.0086	
HAC variance	0.0079	

Note: \*\*\*, \*\*, \* represent significant at 1%, 5%, and 10% inspection levels, respectively.

**Table B2**  
Cointegration Test results (UMI)

Pedroni Cointegration Test	Value	P-value
Panel v-Statistic	-4.6528	1.0000
Panel rho-statistic	3.2684	0.9995
Panel PP-statistic	-13.5374***	0.0000
Panel ADF-statistic	-11.2282***	0.0000
Group rho-statistic	6.0220	1.0000
Group PP-statistic	-18.6456***	0.0000
Group ADF-Statistic	-13.3144***	0.0000
<b>Kao Cointegration Test</b>		
	<b>Statistic</b>	<b>P-value</b>
ADF	-7.059443***	0.0000
Residual variance	0.009924	
HAC variance	0.008044	

**Table B3**  
Cointegration Test results (LMI)

Pedroni Cointegration Test	Value	P-value
Panel v-Statistic	-3.7130	0.9999
Panel rho-statistic	2.7149	0.9967
Panel PP-statistic	-8.8684***	0.0000
Panel ADF-statistic	-8.3578***	0.0000
Group rho-statistic	5.4183	1.0000
Group PP-statistic	-17.2533***	0.0000
Group ADF-Statistic	-11.3124***	0.0000
<b>Kao Cointegration Test</b>		
	<b>Statistic</b>	<b>P-value</b>
ADF	-7.3790***	0.0000
Residual variance	0.0206	
HAC variance	0.0172	

Note: \*\*\*, \*\*, \* represent significant at 1%, 5%, and 10% inspection levels, respectively.

**Table B4**  
Cointegration Test results (LI)

Pedroni Cointegration Test	Value	P-value
Panel v-Statistic	-0.8150	0.7925
Panel rho-statistic	1.9785	0.9761
Panel PP-statistic	-6.4175***	0.0000
Panel ADF-statistic	-6.5357***	0.0000
Group rho-statistic	4.5462	1.0000
Group PP-statistic	-5.3402***	0.0000
Group ADF-Statistic	-4.6913***	0.0000
<b>Kao Cointegration Test</b>		
	<b>Statistic</b>	<b>P-value</b>
ADF	-4.9352***	0.0000
Residual variance	0.0157	
HAC variance	0.0137	

Note: \*\*\*, \*\*, \* represent significant at 1%, 5%, and 10% inspection levels, respectively.

**Table B5**  
Cointegration Test results (Global)

Pedroni Cointegration Test	Value	P-value
Panel v-Statistic	-6.2813	1.0000
Panel rho-statistic	5.9589	1.0000
Panel PP-statistic	-18.3646***	0.0000
Panel ADF-statistic	-16.9298***	0.0000
Group rho-statistic	11.0537	1.0000
Group PP-statistic	-31.6636***	0.0000
Group ADF-Statistic	-21.8000***	0.0000
<b>Kao Cointegration Test</b>		
	<b>Statistic</b>	<b>P-value</b>
ADF	-8.7903***	0.0000
Residual variance	0.0147	
HAC variance	0.0133	

Note: \*\*\*, \*\*, \* represent significant at 1%, 5%, and 10% inspection levels, respectively.

**Table B6**  
Estimation results for carbon emissions

Group	Model	LnOPEN	LnOP	LnGDP	LnPOP	lnRE	C
<b>HI</b>	Model 1	-0.1276*** (-10.4146)					
	Model 2	0.1476*** (4.9805)	-0.0722*** (-6.8266)	0.2938*** (8.9418)	0.0798 (1.4157)	-0.0974*** (-15.9682)	-1.6808*** (-3.4841)
	Model 3	-0.1674*** (-37.8510)	-0.0498*** (-14.1915)	0.3086*** (122.8840)	0.0129*** (9.1165)	-0.1432*** (-103.9827)	
<b>UMI</b>	Model 1	-0.0125 (-0.7720)					
	Model 2	-0.0231** (-2.0908)	-0.0031 (-0.2659)	0.5349*** (19.8765)	0.0789 (1.3705)	-0.1889*** (-14.3439)	-3.4723*** (-7.9495)
	Model 3	-0.0478*** (-3.9945)	-0.0359** (-2.2256)	0.6289*** (12.4641)	1.1016*** (3.6288)	-0.1068*** (-5.9398)	
<b>LMI</b>	Model 1	0.0314 (0.9501)					
	Model 2	-0.0057 (-0.2852)	-0.0341** (-1.9789)	0.6838*** (16.8478)	0.3248*** (4.0718)	-0.5600*** (-15.9217)	-7.8678*** (-6.7930)
	Model 3	-0.0126 (-1.1105)	-0.0357*** (-3.4798)	0.7046*** (29.3625)	0.3312*** (6.6319)	-0.5378*** (-26.4482)	
<b>LI</b>	Model 1	0.4942*** (8.3112)					
	Model 2	0.3374*** (10.5980)	-0.0615** (-2.4107)	0.6426*** (11.4468)	0.1976* (1.9377)	-1.6291*** (-18.8988)	-1.5394*
	Model 3	0.3567*** (23.6731)	-0.0569*** (-4.4696)	0.6378*** (23.6562)	0.1834*** (3.4174)	-1.6065*** (-38.8503)	
<b>GLOBAL</b>	Model 1	0.1279*** (9.0018)					
	Model 2	0.0154 (1.5672)	-0.0633*** (-8.3419)	0.6123*** (31.2870)	0.4834*** (13.9385)	-0.1606*** (-22.5117)	-8.0481*** (-24.7188)
	Model 3	0.0133*** (3.1040)	-0.0642*** (-18.7342)	0.6107*** (67.8722)	0.4990*** (30.5800)	-0.1568*** (-49.5702)	

Note: The data in brackets are the t-statistics. \*\*\*, \*\*, \* represent significant at 1%, 5%, and 10% inspection levels, respectively.

## Appendix C. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2020.123838>.

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