



International Trade as a Double-Edged Sword: The Perspective of Carbon Emissions

Jialin Gao¹, Fengfeng Gao², Bo Yin³ and Mengwan Zhang^{2*}

¹Postdoctoral Research Station of China Banking and Insurance Regulatory Commission, School of Economics and Management, Tsinghua University, Beijing, China, ²School of Economics and Management, Beijing University of Technology, Beijing, China, ³Europe Office of Global Energy Interconnection Development and Cooperation Organization, Brussels, Belgium

OPEN ACCESS

Edited by:

Kangyin Dong,
University of International Business
and Economics, China

Reviewed by:

Zewen Ge,
Shanghai Jiao Tong University, China
Pengfei Zhang,
Shandong University, China
Mingkun Jiang,
East China University of Science and
Technology, China

*Correspondence:

Mengwan Zhang
alicezmw@163.com

Specialty section:

This article was submitted to
Sustainable Energy Systems and
Policies,
a section of the journal
Frontiers in Energy Research

Received: 26 August 2021

Accepted: 08 October 2021

Published: 26 October 2021

Citation:

Gao J, Gao F, Yin B and Zhang M
(2021) International Trade as a Double-
Edged Sword: The Perspective of
Carbon Emissions.
Front. Energy Res. 9:764914.
doi: 10.3389/fenrg.2021.764914

Due to the rapid growth of fossil energy consumption, countries worldwide have paid considerable attention to reducing carbon emissions. Moreover, with economic globalization and trade liberalization, exploring the relationship between foreign trade and carbon emission reduction has become increasingly critical. Exploring this relationship can aid in establishing suitable recommendations for global carbon emission reductions. This paper uses a spatial econometric model and a dynamic panel threshold model to empirically test the spatial effect, nonlinear effect, and heterogeneous effect of foreign trade on global carbon emissions. All the above models are based on the construction of the economic weight matrix of different countries. The results reveal that 1) carbon emissions in various countries exhibit with significant spatial spillover in the overall spatial context; 2) foreign trade has a significant role in promoting carbon emissions in local and similar economic areas, but it has an apparent dual-threshold effect on economic development; and 3) there are significant differences in the impact of foreign trade on carbon emissions in different regions and different periods. Therefore, in the process of global economic integration, based on their development stages and comparative advantages, countries can focus on overall planning and coordination to promote the optimal allocation of resources and reduce carbon emissions.

Keywords: international trade, carbon emission reduction, space econometric, dynamic panel, heterogeneous test

INTRODUCTION

An urgent focus must be placed on reducing greenhouse gas emissions and controlling climate change. The rapid development of industrialization has dramatically improved people's living standards. However, the consumption of a large amount of fossil energy has led to a dramatic increase in CO₂ emissions. According to the assessment report of the Intergovernmental Panel on Climate Change, over the past 50 years, global warming has largely been related to greenhouse gas emissions. The global average temperature is approximately 1.2°C higher than that before industrialization, and the six years between 2015 and 2020 were the warmest recorded in the history of meteorological observation. All countries, whether developed or developing, must assume responsibilities and obligations related to global climate change. At present, 126 countries and organizations around the world have promised to achieve the goal of "carbon neutrality". Twenty-two countries and regions have set the goal of carbon neutrality in the form of legislation and policies. In addition, carbon emission reduction has become a common research focus and an urgent issue in

current global development (Li, et al., 2020). Moreover, in the process of industrialization, international trade has effectively promoted the growth of the world economy and enabled countries to realize comparative advantages, but it has also led to an international trade pattern with a centre-periphery structure, which has led to regionally varying carbon emissions.

There are two main problems in global carbon emissions and international trade. First, the transfer of products through trade may lead to disputes regarding carbon emission reduction responsibilities. In global supply and production chains, carbon emissions embedded in traded products are transferred through international trade. For example, developing countries usually export products associated with high energy consumption and high pollution and import low-pollution and high value-added products from developed countries. This process amplifies the carbon emission intensity through trade and leads to an imbalance in the carbon emission reduction burden between exporting and importing countries, leading to potential conflicts (Zhang, et al., 2020). Second, additional green barriers and carbon tax competition may impact the free trade system. After years of industrial development, most developed countries have achieved a carbon peak, and their carbon neutralization strategies were implemented at various points in the past. However, the application of low-carbon technology and equipment renewal have increased the production costs of enterprises. To protect domestic enterprises, developed countries may introduce carbon tariffs or raise environmental protection standards to set obstacles to international trade. For example, the European Union has introduced the “carbon border adjustment mechanism”, which levies taxes on countries’ goods in a slow emission reduction process, thus forming *de facto* trade barriers and increasing the costs to exporting countries (Chu, et al., 2021).

International trade and energy economics have been identified among the top-ten research topics of current economic studies (Luo, et al., 2021). With the acceleration of global carbon neutrality, developing export-oriented economies face heavy pressure to reduce emissions, and exporting countries may require importing countries to assume more carbon emission responsibilities, which may increase international carbon emission responsibility disputes and trade frictions. Moreover, the increase in green barriers may create obstacles for the international trading system. In addition, under the condition of noncooperative emission reduction, the phenomenon of free riding occasionally occurs, causing a “tragedy of the commons”.

Hence, this paper focuses on clarifying the impact of international trade on carbon emissions. There are several issues that need to be addressed, such as the effect of international trade on carbon emissions, whether international trade can be an opportunity for countries to reach their carbon emission reduction goals, and whether countries with different regional economic development levels have the same carbon emission reduction level. This paper systematically investigates the carbon emission reduction effect of foreign trade from different perspectives to provide theoretical and empirical support for countries worldwide to better cope with energy development. In the next section, a literature review is

conducted to analyse the existing research and identify research gaps.

LITERATURE REVIEW

Reducing carbon emissions and addressing global climate change have become unified goals worldwide (Chang, et al., 2019). However, agreement about how international trade influences carbon emissions has not been reached. Some scholars have suggested that the rapid growth of international trade has led to carbon emission issues. For example, Zhong et al. (2021) analysed the impact of international trade on carbon emission reductions based on the global value chain. With evidence from 39 major economies, they found that the development of international trade has led to a 5% increase in the interregional flow of carbon emissions, on average. Wang et al. (2021) found that China’s energy consumption increased due to the expansion of the international trade scale. Shi et al. (2020) focused on countries from the Belt and Road region using a threshold model and discovered a nonlinear relation between international trade and carbon emissions. Wang W et al. (2019) discovered that the ratio of embodied carbon per unit value-added exports to embodied carbon per unit value-added imports is much lower in developed countries than in developing countries, indicating that developed countries have obtained higher trade benefits at relatively low environmental costs. This finding suggests that developed countries are in an advantageous position in relation to embodied carbon flows in global trade. Wang L et al. (2020) found that with the development of international trade, environmental quality is threatened by an increasing energy demand, which has also led to an increase in carbon emissions.

Some scholars have reported that international trade can reduce carbon emissions. For instance, Kerui et al. (2020), using approximately 116 panel datasets from 1986 to 2014, indicated that international trade could improve carbon emission reductions and increase income, and the greater the increase in income is, the higher the carbon emission reduction. Li et al. (2019) showed the positive effects of international trade on carbon emission reduction. China’s high level of technological development has led to reduced carbon emissions in the context of international trade. Wang et al. (2018) found that improving the level of economic expansion and enhanced foreign trade are conducive to improving environmental effects. Khan et al. (2020) analysed international trade in G7 countries and identified the relationship among international trade, carbon emission reduction, and renewable energy, thereby discovering a sustainable environment for G7 countries. Misak et al. (2018) also studied international trade, carbon emissions and other factors, such as model choice and international transport. The results indicated that establishing international transport laws can help reduce carbon emissions within international trade. Sun et al. (2019) also considered international trade and carbon emission reduction in conjunction with green innovation and energy efficiency.

In the research on international trade and carbon emissions, several methods have been applied. For example, Wang S et al. (2020) used a stochastic regression model to determine the best path to reach a carbon emission reduction target. Carbon emissions can also be calculated through an accounting framework with investment-based methods (Zhang, et al., 2020). Moreover, intertemporal mechanisms were provided by Bednar et al. (2021) to encourage countries to take responsibility for carbon emissions in the international trade market. Adnan et al. (2021) used second- and third-panel cointegration methods, and the results indicated that cross-sectional dependency and heterogeneity confirm the correlations among panels in the study. Moreover, technological innovation can reduce carbon emissions in international trade. Baloch et al. (2018) used the autoregressive distributed lag (ARDL) model, vector error correction (VEC) model and regressive threshold model to estimate carbon emission reductions and identify financial instability within an international trade background.

RESEARCH GAPS

The literature review indicated that many scholars have examined international trade and carbon emissions, but research gaps still exist. First, few researchers have systematically investigated the impact of foreign trade on carbon emission reduction in countries worldwide from a spatial perspective based on economic geography. Second, few studies have considered the overall context of international trade and carbon emissions. Through heterogeneity analysis, this paper examines the heterogeneous effects of international trade on carbon emissions in different countries and at different times and refines the research on the impact of international trade on carbon emissions. The marginal contribution of this paper is three-fold. First, the spatial spillover effect of foreign trade and carbon emissions are studied by using dynamic spatial models, including the Durbin model and a spatial autoregression model, thus expanding upon the existing research. Second, a dynamic threshold panel model is used to discuss the dynamic relationship between foreign trade and carbon emissions and obtain scientifically valid estimation results.

METHODS

Research Hypotheses

Countries can meet their own consumption needs by importing products while avoiding the responsibility of reducing the emission of carbon dioxide and other greenhouse gases. Therefore, international trade and industrial transfer generally increase the total carbon emissions of the host country. To a certain extent, international trade forces a country to optimize and upgrade its industrial structure, which is conducive to energy efficiency improvement. However, carbon emission reduction is characterised by global externalities. Different countries have different emission reduction capabilities, historical

responsibilities, environmental protection strategies, and free-riding problems, which may cause cross-border transfers of carbon emissions through international investment and trade, resulting in “carbon leakage”. Therefore, we formulate research Hypothesis 1 as follows.

Research Hypothesis 1: International Trade has a Spatial Spillover Effect on the Carbon Emission

Antweiler et al. (2001) believed that technological level improvements can reduce the pollution caused by trade and that international trade is beneficial to the environment. Therefore, developing international trade is conducive to improving the environment and reducing carbon emissions. However, with regional development, the introduction of advanced technology, the optimization and upgrading of the industrial structure and the elimination of backward production capacity, the allocation of carbon resources tends to be optimized, and carbon emissions are reduced. In addition, economic improvements increase the environmental protection requirements of products, which result in the development of high-tech and low-polluting products and help reduce carbon emissions. Therefore, we formulate research Hypothesis 2 as follows.

Research Hypothesis 2: The impact of international trade on carbon emissions exhibits nonlinear changes due to different levels of economic development, with a certain threshold effect.

Model Setting

The Dynamic Spatial Model

To explore the impact of international trade on carbon emissions, we establish a dynamic spatial model as follows:

$$\begin{aligned} \ln Carr_{i,t} = & \alpha + \beta_1 WLN Carr_{2i,t} + \beta_2 WLN Carr_{2i,t-1} + \rho_1 open_{i,t} \\ & + \rho_1 Wopen_{i,t} + \delta X_{i,t} + \mu_i + \mu_t + \varepsilon_{i,t} \end{aligned} \quad (1)$$

In Eq. 1, i stands for the country; t is time; $LNCarr$ represents the log of carbon emission intensity; $open$ stands for foreign trade; X is a series of control variables; $\beta_1, \beta_2, \rho_1, \rho_2$ and δ represent the estimation coefficients of the respective variables; μ_i and μ_t are spatial and temporal effects; $\varepsilon_{i,t}$ is the residual term; W is a spatial weight matrix; and α is a constant term.

The Dynamic Threshold Model

The effect of international trade on carbon emissions varies in different countries. Therefore, a dynamic threshold model is necessary and can be expressed as follows:

$$\begin{aligned} \ln Carr_{2i,t} = & \mu_1 + \ln Carr_{2i,t-1} + \beta open_{i,t} + \delta X_{i,t} + \lambda WLN CO_{2i,t} \\ & + \lambda_1 \ln open_{i,t} * I(LNPGDP_{i,t} \leq \gamma_1) \\ & + \lambda_2 \ln open_{i,t} * I(LNPGDP_{i,t} \leq \gamma_2) \\ & + \lambda_3 \ln open_{i,t} * I(LNPGDP_{i,t} \leq \gamma_3) + \varepsilon_{i,t} \end{aligned} \quad (2)$$

In Eq. 2, λ_1, λ_2 , and λ_3 are the coefficients of the influence of the foreign trade level on carbon emissions at different threshold intervals based on the economic development level; $LNPGDP_{i,t}$ is

a threshold variable; γ is the threshold estimate; γ_1 and γ_2 represent the first threshold value and the second threshold value, respectively; $I(\cdot)$ is an indicator function; and the other variables are set as described above.

Moran's Index Model

To perform a spatial correlation test, Moran's index was used to test foreign trade and carbon emissions based on the corresponding autocorrelation. According to Moran's theory, when the Moran's index varies from 0–1, a positive relation exists. The formula for the Moran's index is as follows:

$$M = \frac{q}{T_0} \frac{\sum_{i=1}^q \sum_{k=1}^q A_{i,k} B_i B_k}{\sum_{i=1}^q B_i^2} \quad (3)$$

In Eq. 3, B_i is the deviation between the attribute value for sector i and the average value ($O_i - \bar{O}$); $A_{i,k}$ represents the spatial weights between sectors i and k ; q refers to the total number of sectors; and T_0 is the sum of all the spatial weights. When Moran's $M > 0$, a positive spatial correlation exists, and a high value indicates a high correlation. When Moran's $M < 0$, a negative spatial correlation exists, and a low value represents a large spatial difference. When Moran's $M = 0$, the spatial correlation is random.

VARIABLE DESCRIPTIONS AND DATA SOURCES

Explained Variable

This paper selects the carbon emission intensity ($LNcarr_{2i,t}$) as the explained variable; it is calculated based on the CO₂ emissions per unit Gross Domestic Product (GDP).

Core Explanatory Variable

This paper selects foreign trade (Open) as the core explanatory variable. This variable is equal to the ratio of import and export trade to the GDP and is used to express the foreign trade level of a country or region.

Control Variables

There are six control variables in this paper: PGDP, Urban, Industry, People, Foreign Direct Investment (FDI) and GDPdeflator.

PGDP refers to the per capita GDP, which is the GDP divided by the population of the country. Urban refers to the proportion

of the urban population to the total population of the country. Industry refers to the ratio of the added value of secondary industry to GDP. People refers to the number of people per unit area. FDI refers to the ratio of FDI stock to the GDP of a country. The GDPdeflator measures inflation based on the GDP in the current year divided by the GDP in the previous year.

Data Sources

To investigate the effect of international trade on carbon emissions, this paper empirically examines the corresponding trade-emissions relationship using a spatial measurement model and a dynamic threshold model. In total, 17 of the G20 countries were selected as the sample in this paper based on the availability of data (Refer to **Appendix Table A1**). The explained variable "LNcarr" is the log of the carbon emission intensity, with a unit of million tons, and the corresponding data source is the BP database. The core explanatory variable "Open" refers to the ratio of import and export trade to the GDP, with a unit of United States dollars, and the corresponding data source is the World Integrated Trade Solution (WITS) database. The control variable "PGDP" is from the World Bank database, with a unit of United States dollars. "Urban", with a unit of people per square kilometre, is derived from the World Bank. "Industry" refers to the proportion of industrial output value in the GDP, with a unit of United States dollars, and the corresponding data source is the World Bank. "People" refers to the population density, with a unit of people per square kilometre, and the data source is the World Bank. "FDI" refers to the proportion of foreign direct investment stock in the GDP, with a unit of %, and the corresponding data source is the United Nations Conference on Trade and Development (UNCTAD) database. "GDPdeflator", in %, is derived from the World Bank. The above data were obtained from 1996 to 2018, and the corresponding descriptive statistics (e.g., mean, SD, minimum value and maximum value) are shown in **Table 1**.

EMPIRICAL RESULTS

Results of Moran's Index Calculations

The Moran's index calculation results are listed in **Table 2**. The results show that Moran's $M > 0$ in all years except 2015. The results also indicate that the Moran's index for carbon emissions and foreign trade fluctuated between approximately 0.22 and 0.559 from 1996 to 2018, exhibiting significant positive spatial

TABLE 1 | Descriptive statistics for the considered variables.

	Variables	Obs	Mean	SD	Min	Max
Explained	LNcarr	391	6.251494	0.8504613	4.660,028	8.90654
	Open	391	0.396318	0.143,606	0.1186059	0.8613456
Core explanatory	PGDP	391	21,533.68	17,588.19	399.95	68,150.11
	Urban	391	70.63276	15.84259	26.82	91.62
	Industry	391	28.54	7.40	17.07	48.06
Control	People	391	151.75	146.99	2.38	529.19
	FDI	391	34.51	56.51	0.61	425.37
	GDPdeflator	391	1.058579	0.1269025	0.4424	1.5176

SD, Min and Max denote the standard deviation, minimum and maximum, respectively.

TABLE 2 | Moran's index results regarding the effect of foreign trade on carbon emissions.

Year	Moran's M	Year	Moran's M
1996	0.336	2008	0.366
1997	0.433	2009	0.33
1998	0.496	2010	0.328
1999	0.415	2011	0.325
2000	0.379	2012	0.401
2001	0.412	2013	0.559
2002	0.517	2014	0
2003	0.446	2015	0.271
2004	0.484	2016	0.22
2005	0.576	2017	0.352
2006	0.356	2018	0.362
2007	0.391		

TABLE 3 | Empirical analysis results regarding the effect of foreign trade on carbon emissions.

VARIABLES	LNCARR			
	(1)	(2)	(3)	(4)
	SAR	SDM	GMM	OLS
L.LNCarr			0.825*** (32.86)	
Open	0.351*** (5.27)	0.495*** (6.47)	0.241*** (6.28)	0.443*** (5.92)
Urban	0.030*** (18.46)	0.025*** (12.97)	0.004*** (3.20)	0.032*** (17.57)
FDI	0.000 (0.22)	0.000 (0.88)	0.000 (0.93)	0.000 (0.44)
People	0.004*** (10.06)	0.005*** (10.66)	0.000* (1.70)	0.004*** (8.64)
PGDP	-0.690*** (-43.41)	-0.672*** (-40.40)	-0.097*** (-5.03)	-0.669*** (-37.43)
Industry	0.017*** (7.28)	0.015*** (6.66)	0.004*** (3.07)	0.020*** (7.53)
GDPdeflator	-0.139*** (-4.17)	-0.117*** (-3.81)	-0.797*** (-28.87)	-0.133*** (-3.50)
Constant			2.301*** (9.95)	9.330*** (50.91)
ρ	-0.236*** (-7.51)	-0.288*** (-3.72)		
sigma2_e	0.004*** (13.93)	0.003*** (14.06)		
Observations	391	391	391	391
R-squared	0.8134	0.6425	0.9934	0.9718
Number of IDs	17	17	17	17

Note: z-statistics in parentheses: ***p < 0.01, **p < 0.05, and *p < 0.1. SAR, SDM, GMM, and OLS denote the spatial lag regression model, spatial Durbin model, Gaussian mixture model, and ordinary least squares model, respectively.

dependence. This finding indicates that from the perspective of spatial correlation, an increase in international trade leads to an increase in carbon emissions. This result verifies research Hypothesis 1.

SAR, SDM, GMM and OLS Results

The robustness of the spatial econometric results for the panel dual fixed-effect model, GMM, SAR model, and SDM was

assessed. The results are shown in **Table 3**. The trend and magnitude of the core explanatory variable coefficients are consistent, and the results pass the significance test, reflecting good model robustness.

Table 3 lists the empirical analysis results regarding the effect of foreign trade on carbon emissions. The first column in **Table 3** lists the variables, the second column gives the SAR results, the third column gives the SDM results, the fourth column gives the GMM results, and the fifth column gives the OLS results. First, the regression coefficient of carbon emissions with one-stage lag (L.LNCarr) is significantly positive, which indicates that there is a significant “temporal inertia” related to carbon emissions in various countries, with a specific “snowball effect”. Second, the coefficients of ρ are -0.236 and -0.288 , which are significantly negative. This result indicates that an increase in carbon emissions in a region has a significant negative impact in areas with a similar per capita GDP; that is, carbon emission reductions are transferred among regions through trade. The coefficient of foreign trade (open) is significantly positively related to the core explanatory variables, indicating that an increase in foreign trade in this region is positively correlated with the intensity of carbon emissions. This finding shows that foreign trade has a positive spatial spillover effect on carbon emissions. In addition, the degree of urbanization, population density, and the proportion of industrial output value are all positively correlated with the carbon emission intensity, which is in line with expectations. The SAR, SDM, GMM and OLS results all validate research Hypothesis 1.

Analysis of the Regression Results for Threshold Effects

The single and dual thresholds in **Table 4** pass the significance test, but the triple threshold fails, which means there is a dual-threshold effect. In addition, **Table 5** shows that the threshold values in the 95% confidence interval are 8.5345 and 10.4494. To intuitively express this results, further delogarithmic processing is performed. The values after delogarithmic processing correspond to the regional per capita GDP, with threshold values of 5,087.29 United States dollars and 34,523.65 United States dollars. Therefore, the global economic development stage can be divided into three threshold intervals. The first threshold interval is GDP per capita values less than 4,337.27 United States dollars. The second threshold interval is GDP per capita values between 4,337.27 United States dollars and 34,523.65 United States dollars. The third threshold interval is GDP per capita values above 34,523.65 United States dollars. Thus, research Hypothesis 2 in this paper is validated.

Based on **Table 6**, a high level of foreign trade significantly inhibits carbon emissions. Specifically, if a region is in the first threshold range and the regional economy is underdeveloped, foreign trade positively promotes regional carbon emissions. To catch up with economically developed areas, financially underdeveloped areas consume many natural resources at the expense of the environment. This process increases carbon emissions. When the regional economic development level passes the second threshold, there is a gradual shift from a state of underdevelopment to a moderate development level.

TABLE 4 | Threshold estimation and test results.

Model	F- statistic	Prob	Bootstrap time	Critical value		
				10%	5%	1%
Single threshold	109.57	0.09	300	106.2615	122.2793	171.7156
Double threshold	166.79	0.000	300	68.8225	78.3972	119.7082
Triple threshold	61.53	0.7133	300	159.836	187.1816	272.5536

TABLE 5 | Threshold estimation and confidence intervals.

	Threshold	95%
Threshold 1	8.3193	[8.2599, 8.3227]
Threshold 2-1	8.5345	[8.4532, 8.5499]
Threshold 2-2	10.4494	[10.4245, 10.4521]

TABLE 6 | Results of the threshold effect model.

Interpreted variable	Elasticity coefficient	t-statistic	Prob
λ_1	0.3768076	6.56	0.000
λ_2	0.114,673	3.48	0.001
λ_3	0.057255	1.73	0.085

The promoting effect of foreign trade on carbon emissions disappears and gradually changes to inhibition. When the economic development level passes the third threshold, the economy becomes relatively developed, and foreign trade significantly inhibits carbon emissions. Notably, economically developed areas can introduce advanced technology and achieve a high resource utilization efficiency; therefore, increasing trade helps allocate resources to achieve a comparative advantage, reduce the consumption of ecological resources and restrain carbon emissions. Hypothesis 2 is confirmed, which suggests that the impact of foreign trade on carbon emissions nonlinearly varies according to different levels of economic development.

HETEROGENEITY TEST

To investigate the heterogeneity in the relationship between international trade and carbon emissions, this paper conducts extensive tests on regional and temporal heterogeneity.

Regional Heterogeneity Tests

The results regarding regional heterogeneity indicate that countries with high economic development levels focus on the introduction of clean technologies when developing foreign trade, which can restrain carbon emissions. The foreign trade coefficient is significantly negative in non-BRICS G20 countries but highly positive in BRICS countries. BRICS countries are characterised by relatively backward economic development. In the early period of

development, rapid economic growth is achieved at the expense of environmental damage, thus increasing carbon emissions. The above results suggest that the impact of international trade on carbon emissions varies across G20 countries. Therefore, different countries will choose different strategies to reduce carbon emissions in the future.

Temporal Heterogeneity Tests

The results of temporal heterogeneity tests are analysed over two periods: from 1996 to 2000 and from 2000 to 2018. According to the results shown in **Table 7**, the coefficient of foreign trade is positive. Between 1996 and 2000, which was part of the early stage of economic development, economic growth mainly involved a large amount of energy consumption. In comparison, between 2000 and 2018, the coefficient of foreign trade was significantly negative. This trend reveals that with the rapid economic development achieved by increased foreign trade, environmental protection was enhanced, and advanced technology was introduced. Most countries have recognized the importance of reducing carbon emissions. To a certain extent, pollution prevention and control were thus improved, and carbon emission reductions were achieved. These changes are associated with certain stages, dynamics, and continuity characteristics of the impact of foreign trade on carbon emissions.

Finally, based on the results of the regional heterogeneity tests and temporal heterogeneity tests, international trade can affect carbon emissions, and this relationship exhibits periodic features and dynamic characteristics.

ROBUSTNESS TEST

The above results and tables show that international trade generally promotes carbon emissions. To assess the robustness of the above results, this section presents a robustness test, and the results are listed in **Table 8**. Specifically, a variable substitution method is used in this assessment. The logarithm of the carbon emission intensity is replaced by the logarithm of the carbon emissions of a country. As shown in **Table 8**, the OLS and GMM trends reflect the moderate effect of international trade on carbon emission reductions. For the core explanatory variable Open, the OLS, GMM, SDM and SAR results are all significant, and the core explanatory variables are highly robust. For the control variables PGDP, Urban, Industry, People, and FDI, the OLS, GMM, SDM and SAR results are all significant. Although the OLS, SDM, and

TABLE 7 | Results of the heterogeneity tests.

Variables	LNCARR			
	(1)	(2)	(3)	(4)
	Non-BRICS	BRICS	Years 1996–2000	Years 2000–2018
Open	−0.312*** (−3.17)	0.766*** (3.30)	0.125 (1.03)	−0.457*** (−3.95)
Urban	0.017*** (4.70)	0.034*** (10.45)	0.020*** (3.08)	0.021*** (5.09)
FDI	0.000 (1.56)	0.006* (1.99)	−0.000 (−0.15)	−0.001** (−2.14)
People	0.003** (2.33)	0.003*** (4.55)	0.001 (1.06)	0.004*** (4.93)
PGDP	−0.960*** (−35.56)	−0.697*** (−13.90)	−0.924*** (−26.44)	−0.904*** (−38.66)
Industry	0.037*** (9.02)	0.011 (1.60)	0.003 (0.66)	0.034*** (7.06)
GDPdeflator	0.053 (0.93)	0.081 (0.91)	0.015 (0.55)	0.006 (0.11)
Constant	12.688*** (38.43)	9.866*** (20.21)	13.231*** (24.12)	11.883*** (38.70)
Observations	276	115	85	306
Number of IDs	12	5	17	17
R-squared	0.917	0.982	0.967	0.914

Notice: z-statistics in parentheses: ***p < 0.01, **p < 0.05, and *p < 0.1.

TABLE 8 | Results of the robustness test.

Variables	LNcarbon			
	OLS	GMM	SDM	SAR
L.LNCarbon		0.888*** (41.57)		
Open	0.272*** (3.08)	0.145*** (3.96)	0.320*** (3.64)	0.169** (2.07)
Urban	0.034*** (15.66)	0.002** (2.04)	0.026*** (11.67)	0.032*** (16.54)
FDI	0.000** (2.20)	0.000** (1.98)	0.001*** (2.80)	0.000*** (2.70)
People	0.005*** (10.26)	0.000* (1.81)	0.005*** (10.63)	0.004*** (9.44)
PGDP	0.315*** (14.97)	0.060*** (5.51)	0.286*** (14.50)	0.258*** (11.80)
Industry	0.025*** (7.96)	0.004*** (2.90)	0.019*** (7.34)	0.026*** (8.94)
GDPdeflator	−0.167*** (−3.72)	0.034* (1.85)	−0.136*** (−3.88)	−0.142*** (−3.47)
Constant	−0.086 (−0.40)	−0.230** (−2.53)		
rho			−0.296*** (−3.85)	0.240*** (5.35)
sigma2_e			0.004*** (13.80)	0.006*** (13.92)
Observations	391	374	391	391
Number of IDs	17	17	17	17
R-squared	0.8347	0.9723	0.6155	0.6695

Notice: t-statistics in parentheses: ***p < 0.01, **p < 0.05, and *p < 0.1.

OLS, GMM, SDM and SAR denote the ordinary least squares model, generalized method of moments model, spatial Durbin model, and spatial autoregression model, respectively.

SAR results for GDPdeflator are below 0, the GMM result is 1.85. The overall results are significant; therefore, they verify the previous results. Moreover, the robustness test shows that the

measurement of the explained variables does not influence the core conclusions of this paper.

CONCLUSION AND POLICY IMPLICATIONS

Conclusion

Based on the above results, the conclusions of this paper are as follows: 1) The spatial correlation indicates significant positive spatial dependence between international trade and carbon emissions. 2) The spatial econometric model results indicate that foreign trade has a positive spatial spillover effect on the carbon emissions of countries with similar local development levels. The growth of foreign trade promotes carbon emissions to a certain extent. 3) The regression results for the threshold effect indicate that the impact of foreign trade on carbon emissions in various countries has a noticeable dual-threshold effect on the economic development level, with threshold values of GDP per capita of 5,087.29 United States dollars and 34,523.65 United States dollars. Thus, three threshold intervals are delineated to indicate the different stages of economic development. 4) The heterogeneity test results indicate that foreign trade impacts carbon emissions differently in different regions and different periods and that the spatial spillover effect is characterised by regional and temporal heterogeneity, with certain stages, dynamics, and continuity.

International trade is important for a country's economic development, but carbon emission reduction is also necessary. Hence, research on the relationship between international trade and economic development and the corresponding effects has significant value for long-term development. For instance, the international trade war between China and the United States has

led to a reduction in current carbon emissions. China has reduced its carbon emissions by 3,621.11–4,031.52 ten thousand tons, and the United States has reduced its carbon emissions by 214.6–314.59 ten thousand tons. However, the international trade war may also lead to a carbon increase in other countries (Zhang, et al., 2021).

In current research, the relationship between international trade and carbon emissions is still mainly viewed from two perspectives. One view posits that international trade increases carbon emissions, and the other posits that international trade reduces carbon emissions. The results of studies adopting different perspectives, variables, and research methods can contradict each other. For example, international trade between China and the United States has led to emissions issues because global shipping generates 938 million tons of carbon emissions per year (Lin, et al., 2014; Liu, et al., 2019; Zhang, et al., 2017). Kazakhstan can develop green energy to reach the goal of a green economy (Wang X, et al., 2019), and China can improve agricultural technology to mitigate poor energy use (Jiang et al., 2020). Dietzenbacher et al., 2020 proposed accounting methods to encourage countries to develop an effective energy policy in relation to international trade and establish a reward and punishment system as a useful way to reach the established goals. In addition to benefiting from low-carbon industries, high-income countries develop leading low-carbon technologies and management modes based on their advantages in technology, talent, capital, and awareness of environmental protection, thus contributing to carbon reduction (Qin, 2020). According to above literatures, international trade as a double-edged sword impacts the carbon emissions. Therefore, in future research, more scholars need to study the relationship between international trade and carbon emissions.

Policy Implications

The results of this paper highlights several policy implications for further development, and they are listed below.

- 1) Promote the low-carbon transformation of foreign trade strategies according to the conditions in different countries. While maintaining the current development trend, countries can formulate differentiation strategies according to the threshold effect of economic development. They should also strengthen environmental supervision while expanding foreign trade. For instance, mandatory corporate social responsibility information disclosure, which is conducive to corporate green technological innovation, can be supported to finally achieve a win-win situation between the economy and environment. For instance, countries in threshold 1 should improve their particular strengths to increase the GDP rather than rely on international trade because in threshold 1, international trade increases carbon emissions. Countries with a threshold of 2–1 should balance industrial development to prevent carbon emissions. For countries with a threshold of 2–2, although international trade can reduce carbon emissions, they should identify green development methods for the future.
- 2) Strengthen international coordination and urge developed countries to assume more responsibilities in trade. The impact of carbon dioxide on climate is the same everywhere. Due to the gap between output and energy efficiency, the carbon emissions of the same products produced in different countries vary. The international trade mode of production in low-income countries and consumption in high-income countries is associated with high carbon emissions. Therefore, developed countries should provide financial and technical support to developing countries to help them improve their overall energy efficiency and reduce emissions.
- 3) Monitor the different relationships between international trade and carbon emission reductions and adjust the relationships considering the associated dynamics. This approach requires relevant departments to understand the development trends of international trade and carbon emissions. Moreover, different countries can adopt certain methods to reduce carbon emissions without restricting international trade. For example, to reduce carbon emissions, China has focused on establishing new transitional policies.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

JG: Thesis Writing; FG and BY: Data processing; MZ: Data analysis, thesis writing and correction. All authors contributed to the paper and approved the submitted version.

FUNDING

This article supported by Beijing Postdoctoral Research Foundation (Q6011019202101), the Key Projects of the National Social Science Foundation (19AZD004).

ACKNOWLEDGMENTS

Thankful for the comments and suggestions that given by the reviewers. They have improved the content of this paper and pointed out research directions of particular interest.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenrg.2021.764914/full#supplementary-material>

REFERENCES

- Antweiler, W., Copeland, B. R., and Taylor, M. S. (2001). Is Free Trade Good for the Environment. *Am. Econ. Rev.* 91 (4), 877–908. doi:10.1257/aer.91.4.877
- Avetisyan, M. (2018). Impacts of Global Carbon Pricing on International Trade, Modal Choice and Emissions from International Transport. *Energ. Econ.* 76, 532–548. doi:10.1016/j.eneco.2018.10.020
- Baloch, M. A., DanishMeng, F., Zhang, J., and Xu, Z. (2018). Financial Instability and CO2 Emissions: the Case of Saudi Arabia. *Environ. Sci. Pollut. Res.* 25 (26), 26030–26045. doi:10.1007/s11356-018-2654-2
- Bednar, J., Obersteiner, M., Baklanov, A., Thomson, M., Wagner, F., Geden, O., et al. (2021). Operationalizing the Net-Negative Carbon Economy. *Nature* 596, 377–383. doi:10.1038/s41586-021-03723-9
- Chang, C.-P., Dong, M., Sui, B., and Chu, Y. (2019). Driving Forces of Global Carbon Emissions: From Time- and Spatial-Dynamic Perspectives. *Econ. Model.* 77, 70–80. doi:10.1016/j.econmod.2019.01.021
- Chu, J., Shao, C., Emrouznejad, A., Wu, J., and Yuan, Z. (2021) Performance Evaluation of Organizations Considering Economic Incentives for Emission Reduction: A Carbon Emission Permit Trading Approach. *Energ. Econ.*, 101, 105398. doi:10.1016/j.eneco.2021.105398
- Dietzenbacher, E., Cazcarro, I., and Arto, I. (2020). Towards a more effective climate policy on international trade. *Nat Commun* 11, 1130. doi:10.1016/j.eneco.2021.105398
- Du, K., Yu, Y., and Li, J. (2020). Does International Trade Promote CO2 Emission Performance? an Empirical Analysis Based on a Partially Linear Functional-Coefficient Panel Data Model. *Energ. Econ.* 92, 104983. doi:10.1016/j.eneco.2020.104983
- Jiang, S. J., Deng, X. Z., Xiao-xue, Z., and Guo-feng, W. (2020). Quantitative Predictions of Impacts of Trade Friction between China and the US on Wheat Trade and its Embodied Carbon Emissions[J]. *J. Agro-Environment Sci.* 39 (4), 762–773.
- Khan, Z., Ali, S., Umar, M., Kirikkaleli, D., and Jiao, Z. (2020). Consumption-based Carbon Emissions and International Trade in G7 Countries: The Role of Environmental Innovation and Renewable Energy. *Sci. Total Environ.* 730, 138945. doi:10.1016/j.scitotenv.2020.138945
- Li, S., and Wang, S. (2019). Examining the Effects of Socioeconomic Development on China's Carbon Productivity: A Panel Data Analysis. *Sci. Total Environ.* 659, 681–690. doi:10.1016/j.scitotenv.2018.12.409
- Lin, J., Pan, D., Davis, S. J., Zhang, Q., He, K., Wang, C., et al. (2014). China's International Trade and Air Pollution in the United States. *Proc. Natl. Acad. Sci. USA* 111, 1736–1741. doi:10.1073/pnas.1312860111
- Liu, H., Meng, Z.-H., Lv, Z.-F., Wang, X.-T., Deng, F.-Y., Liu, Y., et al. (2019). Emissions and Health Impacts from Global Shipping Embodied in US-China Bilateral Trade. *Nat. Sustain.* 2, 1027–1033. doi:10.1038/s41893-019-0414-z
- Lu, Q., Fang, K., Heijungs, R., Feng, K., Li, J., Wen, Q., et al. (2020). Imbalance and Drivers of Carbon Emissions Embodied in Trade along the Belt and Road Initiative. *Appl. Energy* 280, 115934. doi:10.1016/j.apenergy.2020.115934
- Luo, R., Li, Q., and Xie, X. (2021) Analysis of Hot Spots of Chinese Economics Research in 2020. *Econ. Dyn.*, 38–57.
- Safi, A., Chen, Y., Wahab, S., Ali, S., Yi, X., and Imran, M. (2021). Financial Instability and Consumption-Based Carbon Emission in E-7 Countries: The Role of Trade and Economic Growth. *Sustainable Prod. Consumption* 27, 383–391. doi:10.1016/j.spc.2020.10.034
- Shi, Z., and Trigkas, V. (2020). Reconstructing Geography, Power and Politics in the Belt and Road Initiative. *Investment Res.* (06), 67–92. doi:10.1007/978-3-030-53153-9_4
- Sun, H., Edziah, B. K., Sun, C., and Kporsu, A. K., and (2019). Institutional Quality, green Innovation and Energy Efficiency. *Energy Policy* 135, 111002. doi:10.1016/j.enpol.2019.111002
- Wang, Di., Liu, X., Yang, X., Zhang, Z., Wen, X., and Zhao, Y. (2021). China's Energy Transition Policy Expectation and its CO2 Emission Reduction Effect Assessment. *Front. Energ. Res.* 8, P410. doi:10.3389/fenrg.2020.627096
- Wang, L., Chang, H. L., Sari, A., Rizvi, S. K. A., and Sari, A. (2020). Are Eco-Innovation and export Diversification Mutually Exclusive to Control Carbon Emissions in G-7 Countries. *J. Environ. Manage.* 270, 110829. doi:10.1016/j.jenvman.2020.110829
- Wang, p., Du, G., and Jiang, X.(2018). Study on the Structural Decomposition of Implied Carbon Emissions in China's export Trade — Based on the Comparative Analysis of Industrial Trade Carbon Emissions Data between China and its Trading Partners [J]. *Price Theor. Pract.*,
- Wang, S., Yun, T., Zehua, D., and Malin, S. (2020). Export Trade, Embodied Carbon Emissions, and Environmental Pollution: An Empirical Analysis of China's High- and New-Technology Industries. *J. Environ. Manage.* 276, 111371. doi:10.1016/j.jenvman.2020.111371
- Wang, W., Yang, S., and Wang, Y. (2019). Shared Responsibility for Embodied Carbon in Global Trade and its Cross-Regional Compensation[J]. *Environ. Econ. Res.*, (3): 30–47.
- Wang, X., Heran, Z., Zhenyu, W., Yuli, S., Jing, M., Xi, L., et al. (2019). Kazakhstan's CO2 Emissions in the post-Kyoto Protocol Era: Production- and Consumption-Based Analysis. *J. Environ. Manage.*, 249, 109393, 2019, ISSN 0301-4797, doi:10.1016/j.jenvman.2019.109393
- Xiang, L., Theodoros, D., Stadler, Z., Stefano, M., Meier, B., Markus, F., et al. (2020). Decarbonization in Complex Energy Systems: A Study on the Feasibility of Carbon Neutrality for Switzerland in 2050. *Front. Energ. Res.* 8, 274. doi:10.3389/fenrg.2020.549615
- Zhang, Q., Jiang, X., Tong, D., Davis, S. J., Zhao, H., Geng, G., et al. (2017). Transboundary Health Impacts of Transported Global Air Pollution and International Trade. *Nature* 543, 705–709. doi:10.1038/nature21712
- Zhang, Z., Guan, D., Wang, R., Meng, J., Zheng, H., Zhu, K., et al. (2020). Embodied Carbon Emissions in the Supply Chains of Multinational Enterprises. *Nat. Clim. Chang.* 10, 1096–1101. doi:10.1038/s41558-020-0895-9
- Zhong, Z., Zhifang, G., and Jianwu, Z. (2021). Does Participation in Global Value Chains Promote Interregional Carbon Emissions Transferring via Trade? Evidence from 39 Major Economies. *Technol. Forecast. Soc. Change* 169, 120806. doi:10.1016/j.techfore.2021.120806

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Copyright © 2021 Gao, Gao, Yin and Zhang. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

APPENDIX

TABLE A1 | The 17 countries of this paper.

17 Countries	Australia, Brazil, Germany, Russia, France, South Korea, Canada, United States, Mexico, South Africa, Japan, Turkey, Italy, India, Indonesia, United Kingdom, China
--------------	---
