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Study on the synergistic effect of foreign trade, technological progress, and carbon emissions

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A primary development plan for a country is to attain carbon neutrality and high-quality international commerce development. This study uses panel data from 30 provinces in mainland China to analyze the dynamic interplay between international trade, technological innovation, and carbon emissions. The findings show that foreign trade, technological progress, and carbon emissions all have their own "economic inertia" that can be self-motivated and self-reinforcing. Foreign commerce and carbon emissions are mutually inhibiting, but technical progress and carbon emissions are mutually reinforcing. This illustrates that achieving a positive cycle of international trade, technological improvement, and carbon emissions necessitates a significant baseline need. Overcoming carbon trade barriers is currently the most difficult challenge for Chinese enterprises involved in foreign commerce. Low-carbon technology advancements are a critical part in this process. Our research strengthens the positive connections between international trade and carbon emissions as a result of technological improvement and proposes a feasible plan for international trade to achieve carbon peaking and carbon neutrality.

KEYWORDS

foreign trade, technological progress, carbon emission reduction, carbon neutrality, PVAR model

Introduction

As the global greenhouse effect worsens, carbon emissions have become a global issue that affects production, life, and economic development. To actively address climate change, the "double carbon" target of achieving peak carbon by 2030 and carbon neutrality by 2060 was first proposed by China in September 2020 and has been regularly highlighted at important meetings and press conferences. This framework takes green development to a new level. More than 130 countries have set net-zero emission targets in laws, regulations, official documents, and statements (Zhao et al., 2022), but the uncertainty of economic policy makes carbon-trading a bad gamble from the investor's point of view (Li X. et al., 2022), which increases the difficulty in achieving low-cost carbon reductions. Foreign trade, the most basic and important aspect of a country's foreign economic linkages, incurs a large amount of carbon emissions while driving economic development (Wu et al., 2016). From 2010 to 2018, emissions produced the services sector grew at an average rate of +1.34% per year, accounting for nearly 30% of total global trade emissions (Huo et al., 2021). Therefore, there is still a long road of green trade development to go before reaching peak carbon and then realizing carbon neutrality.

The responsibility for carbon emissions is mostly attributed to the production side rather than to consumers, which raises the questions of the flow and measurement of so-called "implied carbon" produced in international trade (Meng et al., 2018). Developed countries have achieved economic leapfrogging through trade activities, which has led to the phenomena of pollution havens and carbon displacement (Lin et al., 2017; Lin and Xu, 2019; Wang et al., 2019; Wen and Wang, 2019; Su et al., 2021). In the context of trade liberalization, countries around the world are also lowering their environmental standards as a sacrifice to maintain their international competitiveness. The "race to the bottom" phenomenon has emerged. The environmental problems caused by trade activities cannot be underestimated. The strong environmental controls imposed by governments have also had a negative impact on foreign trade. On the one hand, environmental regulation has given rise to a new technological innovations and promoted dynamic competition in international technology trade and technology transfer. On the other hand, the potential conflict between unilateral trade measures and multilateral trade rules for a low-carbon economy is increasingly exposed. Carbon labeling (Xu and Lin, 2021; Lohmann et al., 2022) and carbon tariffs (Fang et al., 2020; Zhu et al., 2020) have become new trade barriers and have a huge impact on trade structure. This study attempts to resolve the contradiction between carbon emissions and foreign trade. We will explore the realistic path of the systematic green trade system in China.

Technology is widely recognized as the key to addressing global climate change and achieving carbon emission reduction. Technological progress is essential to reducing carbon emissions (Erdogan, 2021). However, the effect of technological progress is not simple and straightforward to achieve. Sometimes, the siphoning effect of technological progress is accompanied by increased environmental pollution (Liu et al., 2022). Therefore, it is of great practical significance to clarify the role of technological progress in achieving carbon emissions reduction.

Most of the existing literature examining the impact of foreign trade on carbon emissions is based on input–output models (Chen and Chen, 2011; Kim and Tromp, 2021), the general equilibrium model (Guo et al., 2021), the dynamic panel data model (Sharma, 2011), and time series models (Kanjilal and Ghosh, 2013). Most researchers focused only on the unidirectional effect of foreign trade on carbon emissions while neglecting the effect of carbon emission reduction on foreign trade. Few studies in the literature have focused on technological progress in the context of the relationship between foreign trade and carbon emissions. In this paper, the researcher will first review the existing literature to sort out the interactions between foreign trade and carbon emissions and consider the lagged effect of carbon emissions. Second, the researcher will introduce an overall technological progress indicator to better explore the inherent synergy between foreign trade in the process of technological progress and carbon emissions. Third, the researcher will construct a panel vector autoregressive model (PVAR), which can effectively circumvent the overly complicated endogeneity and theoretical discussions between foreign trade and carbon emissions and analyze the two-way causality between them, unlike the unidirectional impact of foreign trade on carbon emissions or the impact of carbon emissions on foreign trade.

Literature review

The study of foreign trade and carbon emissions has been an issue of academic interest in recent years. From an ex-ante perspective, some researchers have modeled the potential impact of international trade policies on carbon emissions. The carbon reduction effect varies with the difference of trade policy. Excessive export tax rebate policies can cause overproduction in highly polluting industries, but biased policy support for low-carbon enterprises will significantly reduce carbon emissions (Song et al., 2015). From an ex-post perspective, the effect of foreign trade on carbon emissions reduction is specifically summarized as three types: positive, negative, and uncertain. Some researchers have argued that foreign trade has shown strong momentum in the development of a low-carbon economy. Renewable energy plays an important role in reducing greenhouse gas emissions (Yuan et al., 2022). Trade liberalization occurs to promote the use of renewable energy in the long or short terms through technological effects rather than scale and structural effects (Zhou and Li, 2022). Carbon emissions trading has a certain promotion effect on carbon emissions reduction (Li and Wang, 2022). Carbon-trading schemes can significantly improve a city's single-factor and total-factor energy efficiency through green innovation and resource allocation channels, which leads to a low-carbon transition to the developing countries (Hong et al., 2022). Although carbon trading can also increase the price of carbon trading through the crowding-out effect on firms' R&D investments, which in turn discourages green technology innovation, it can still significantly reduce carbon emissions and carbon intensity (Zhang et al., 2022). Whether from a city perspective (Yu et al., 2017), a provincial perspective (Zhang et al., 2021), or a national perspective (Wu et al., 2022), the evidence of the decoupling effects of economic growth and environmental issues all further confirms the positive effect of foreign trade on the environment. Pu et al. (2020) argued that total trade is the main factor driving the growth of carbon emissions. Trade openness (Ertugrul et al., 2016) and trade liberalization (Yang, 2001; Lu et al., 2022; Zhou and Li, 2022) have both led to an increase in CO_2 emissions. Especially in the context of growing international trade conflicts, countries are facing greater challenges in how to address environmental issues. Take Sino–United States trade as an example. The Sino–United States trade conflict not only hinders the volume of international trade but also increases the transportation distance of international trade in goods, which will adversely affect the control of carbon emissions of international shipping (Pu et al., 2020). The trade triple effect theory suggests that the impact of foreign trade on the environment depends on the combined effects of scale, structure, and technology effects (Grossman and Krueger, 1995). By comparing import and export data from seven ASEAN countries, the researchers found that higher population correlated with increased carbon emissions but that technological innovation significantly reduced them through increased energy efficiency (Salman et al., 2019). The same conclusion is reached through decomposing the environmental Kuznets curve into size, technology, and composition while incorporating the role of trade openness and foreign direct investment (FDI) effects into the United States carbon emissions function (Shahbaz et al., 2019). Studies on developed and less-developed countries also differ. Some of the literature has suggested that trade openness reduces carbon emissions in high- and upper-middle-income countries, but trade openness increases carbon emissions in low-income countries (Wang and Zhang, 2021). Some researchers have also made opposite arguments by breaking down trade into exports and imports. They argued that imports have a negative effect on the intensity of CO_2 emissions in African countries, whereas exports have the opposite effect (Huang et al., 2022). However, both exports (i.e., production-side emissions) and imports (i.e., consumption-side emissions) are driving the increase in emissions in South Korea (Kim and Tromp, 2021). Carbon transfer in developed countries has been criticized by other countries, but its contribution to carbon reduction seems to be underestimated. The study found that without Germany, global embodied CO2 emissions would increase by an average of 1.53%, its participation in international trade has contributed to carbon reductions in developing countries, particularly China and Russia (Li R. et al., 2022).

The importance of technological progress in alleviating environmental pressures cannot be overstated. The dominant technology progress contributes to the reduction of CO_2 (Leitão et al., 2022). Eco-friendly technologies can mitigate or even eliminate the harmful effects of environmental quality (Erdoğan et al., 2022), especially carbon capture and storage technology (Wilberforce et al., 2021; Vaz et al., 2022). Studies on technology spillover effects also confirmed that technological progress in neighboring regions plays an important role in reducing carbon emissions (Huang et al., 2020). Technological progress does not simply exhibit a facilitating effect on carbon emissions reduction. It also increases carbon emissions, which is the rebound effect of carbon emissions. The rebound effect tends to reduce the marginal effect of carbon emissions reduction. Thus, the impact of technological progress on carbon emission reduction becomes confounded (Zhang et al., 2020). Most of the existing literature has developed a detailed analysis of regional carbon emissions from different technological pathways. Some studies have broken down technological progress into domestic innovation, foreign technology introduction, and regional technology transfer (Lin and Ma, 2022). One study used a panel data model to investigate the carbon reduction effects of technological progress at four levels: energy technology, carbon emission technology, neutral technology, and capital-embodied technology (You and Zhang, 2022). Another study deconstructed technological change into environmental technological change and production technological change and found that the relationship between technological progress and carbon emissions is complex and depends on both environmental technological change and production technological change (Chen et al., 2020). Further studies have considered carbon emissions in agriculture, industry, construction, transportation, wholesale production, and residential building from three technology channels: R&D investments, FDI-related technology spillovers, and technology spillover (Yang et al., 2021).

A large body of literature has examined only the relationship between foreign trade and carbon emissions or only the relationship between technological progress and carbon emissions. However, the literature lacks studies on the synergistic effects of foreign trade, technological progress, and carbon emissions. There is still room to expand its depth and breadth. In this paper, based on the existing literature, the researcher will introduce the overall technological progress index to explore the mechanism of synergistic effect between foreign trade, technological progress, and carbon emissions. The researcher will also explore realistic pathways to low-carbon living alongside economic growth and technological progress.

Empirical design

Model construction

Love and Zicchino (2006) and Lian and Chung (2008) extended the PVAR model after its first creation. It has, since then, become widely adopted. The model combines panel data based on the benefits of the typical VAR model without any pre-existing limits on the relationship between variables.

The lagged value of each explanatory variable is used to read the equation identically and more appropriately reflect the dynamic interactions between endogenous variables. This research develops a PVAR model to investigate the relationship among international trade, technological progress and a low-carbon economy. The model is constructed as follows.

$$G_{i,t} = \Gamma_0 + \sum_{j=1}^{k} \Gamma_j G_{i,t-j} + \varphi_i + \eta_t + \varepsilon_{i,t} \quad (1)$$

where i is an individual, indicating different provinces; t is time, indicating different years; $G_{i,t}$ is a vector of three observable random variables for individual i at time t (i.e., three different vectors of carbon emissions, foreign trade and technological progress); Γ denotes a matrix of lagged effects of variables; k is the number of lags; φ_i is an individual fixed-effect reflecting individual heterogeneity, η_t is a time-fixed-effect term indicating the trend characteristics of the system variables; ε_{it} denotes a random disturbance term.

Selection of indicators

The two basic international trade indicators are net exports to GDP and external dependency. Foreign trade growth shows that there are different structural characteristics at different stages of economic development. Both foreign trade dependence and net exports as a share of GDP can more appropriately and scientifically depict the degree of international economic development at the appropriate stage of development. In the early days of reform and opening-up, China's economy was primarily boosted by exports. Imports appear to be minor in contrast to exports. The ratio of net exports to GDP accurately reflected international trade at that time. However, as China's economy enters a phase of rapid development, particularly during the current stage of high-quality development, imports of high-quality products, especially high-quality intermediate products, are increasing. Imports and exports are roughly equal in general. As a result, the ratio of net exports to GDP cannot adequately reflect the volume of international trade. Using the ratio of net exports to GDP as a measure of international trade is erroneous. The two indicators used to assess the extent of international trade are exports and imports. Considering the current development of import and export, this paper selects the degree of foreign dependence as the measure of international trade level.

To assess technical progress, there are three commonly used measures: output, input, and total factor productivity. Although the number of issued patents in the output method as an indicator of development has some limitations, the patent output directly reflects the degree of technological innovation. The Patent Office selects the granted patents strictly and objectively according to the criteria, so the statistics are unambiguous. Therefore, using the number of three domestic patent applications in this study as a barometer of technological improvement is well supported.

Carbon emission intensity and carbon emission efficiency are the two most important indicators of low-carbon economy. Carbon intensity refers to the ratio of CO_2 emissions to gross domestic product. It is a more accurate indication of economic health than carbon emission efficiency in the low-carbon economy. Therefore, carbon emission intensity is chosen as a measure indicator to evaluate the relationship between economic growth and carbon emissions in this study. If the province's economy expands when CO_2 emissions decreases, it indicates that the province has successfully implemented a low-carbon development strategy.

Data sources and description

Due to data availability, panel data from 30 mainland Chinese provinces from 2007 to 2019 (excluding Tibet, Hong Kong, Macao, and Taiwan) were chosen for empirical analysis. The import and export of each province, as well as GDPat provincial level, is calculated using the China Statistical Yearbook. The unit of export trade is converted to RMB by using the average exchange rate of the year. The number of three domestic patent applications can be found in the China Statistical Yearbook of Science and Technology. Due to a lack of credible data on CO_2 emissions at provincial level, the IPCC's accounting approach is adopted to calculate CO_2 emissions for each province. In this paper, eight representative energy sources, including coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, and natural gas, were selected. The carbon emissions of each province are calculated from Equation 2 by using the energy consumption of each province in the China Energy Statistics Yearbook and the relevant reference coefficients.

$$TCO_2 = \sum_{i=1}^{8} CO_2 = \sum_{i=1}^{8} E_i \times LCV_i \times CC_i \times COR_i \times (14/12) \quad (2)$$

Where TCO_2 represents the amount of carbon dioxide released by the consumption of various fossil energy sources; E_i represents the consumption of the i-th energy source in each province; LCV_i refers to the average low level heating value of the i-th energy source; CC_i refers to the carbon content per unit calorific value of the i-th energy source; COR_i refers to the carbon oxidation rate when the i-th energy source is burned; 44/12 refers to the ratio of carbon dioxide to carbon molecular weight.

Because there was a considerable variance in values between each variable's data, the data for all variables were dimensionless. Stata 15.0 software is utilized in the article for the required econometric study. The descriptive statistics for the variables are shown in Table 1.

TABLE 1 Descriptive statistics of variables.

Variable	Observations	Mean	Standard error	Min	Max
CO_2	390	0.338	0.219	0.1	1
tra	390	0.299	0.247	0.1	1
tec	390	0.254	0.221	0.1	1

Results of empirical analysis

The panel data should be evaluated for smoothness to ensure the validity of the further study. Following the smoothness test, Granger causality analysis is performed to further filter the interrelationship between variables. The ideal lag order of the PVAR model is then determined. The stability and estimate of PVAR model were then tested. 300 Monte Carlo simulations were finally done to determine the impulse response and variance decomposition of the model. The detailed analysis is as follows.

Smoothness test

The pseudo-regression problem may develop if non-stationary data is directly modeled. The smoothness of the variables is thus the foundation for the following study. Currently, six unit root testing approaches are frequently used: the HT, LLC, Breitung, IPS, Fisher, and HadriLM tests. Except for Breitung, the other five tests only consider perturbation term serial correlation. HT tests can be used for short panel data tests but sample size requirements are strict. Considering the numerous limitations, we use the IPS and Breitung tests of distinct unit root tests in this investigation. The test results are shown in **Table 2**.

The *P*-values for CO_2 and tec were less than 0.05 in the original value test of the variables, indicating that the initial data were stationary. Both the non-stationary IPS and Breitun tests yield *P*-values for *tra* greater than 0.05. Hence, all variables must go through first-order differencing. **Table 2** reveals that the *P*-values after first-order differencing are all less than 0.05, which reject the original hypothesis of non-stationarity of international trade, technological advancement, and carbon emission intensity. Every variable is consistent.

TABLE 2 Unit root test results of panel data.

	Original data		First difference	
	Breitun test	IPS test	Breitun test	IPS test
CO_2	−3.9930***	−2.2651*	−3.9206***	−9.9586***
tra	−0.5010	0.8734	−2.9426***	−4.8858***
tec	−1.8450*	−4.1179***	−3.7798***	−6.8421***

* and *** indicate significance at the significant levels of 0.05, 0.01 and 0.001 respectively.

Determination of the lag order

Before performing PVAR regression, we must determine the optimal lag order. Andrews and Lu's Consistent Moment and Model Selection Criteria (CMMSC) Andrews and Lu's (2001) are employed to determine the lag order of the PVAR model in this work. When the minima are at different lag orders, the order with the most minima is picked as the best lag order. According to **Table 3**, the first lag order is the best lag order since the MBIC, MQIC, and MAIC values are the smallest, although the second lag order has the smallest MAIC value.

Granger causality test

The Granger causality test can determine whether there is a two-way or one-way causal relationship among international trade, carbon emissions intensity, and technological progress in each province. The test results are shown in **Table 4**. The test results reveal a two-way causal link between carbon emissions and technological progress, refuting the null hypothesis. Both test results of international trade and carbon emissions refute the null hypothesis, and confirm a two-way Granger causal link. As the initial hypothesis is accepted, there is no Granger causation between international trade and technical growth.

PVAR model estimation and model stability test

Based on the findings of the panel data smoothness test, the first-order difference series of variables are chosen for PVAR

TABLE 3 Optimal lag order.

Lag	MBIC	MAIC	MQIC
1	−105.7099*	−15.33803	−51.87204*
2	−82.59853	−22.35059*	−46.7066
3	−40.26801	−10.14404	−22.32204

* indicates the optimal lag order selected by this criterion.

TABLE 4 Granger causality test.

Variable	Test item	chi^2	df	p
dCO_2	dtra	3.846	1	0.050
	dtec	6.127	1	0.013
Dtra	dCO_2	4.826	1	0.028
	dtec	1.990	1	0.158
Dtec	dCO_2	7.385	1	0.007
	dtra	0.242	1	0.622

TABLE 5 GMM estimation results of PVAR model.

Explained variable	Explaining variable		
	L1.h_dCO_2	L1.h_dtra	L1.h_dtec
h_dCO_2	0.2096036***	−0.1143221*	0.0401404**
	(0.0297051)	(0.0642055)	(0.0170286)
h_dtra	−0.0214356*	0.1703102	−0.0916079
	(0.0120691)	(0.1116111)	(0.0690461)
h_dtec	−0.0374844***	−0.0991669	0.6124269***
	(0.0135616)	(0.1115857)	(0.1518649)

The value in bracket is standard error; *, ** and *** indicate significance at the significant levels of 1%, 5% and 10% respectively; h_ indicates that the variable has undergone Helmert transformation; L1h_ indicates the first-order lag of the variable.

model estimation in this study. In order to minimize the time fixed effects and individual fixed effects of the sample and avoid biased estimation, we further orthogonalize the variables by using the Helmert method. The variables that have been transformed are, respectively, *h-d*CO_2, *h-dtra*, and *h-dtec*.

Table 5 shows that when *h-d*CO_2 is the explanatory variable, the levels of significance for carbon emission, technical advancement, and international trade are 1%, 5%, and 10%, respectively. Carbon emissions are significant at 10% trade level when *h-dtrade* being the explanatory variable, and the coefficient of the first-order lagged term being negative. It demonstrates that technological progress has no effect on the volume of international trade and that carbon emissions have a detrimental impact on its growth. When *h-dtec* is used as the explanatory variable, carbon emissions are substantial at the 1% level of significance and technological progress also has some self-motivating benefits. The lag period has made a significant and constructive contribution to the technological progress for the current period. However, there is scant evidence that international trade influences technological progress.

The stability of the PVAR model supports the subsequent impulse response analysis and variance decomposition. As seen in Figure 1, all unit roots have eigenvalues smaller than one, and all three estimation sites are within the circle. It implies that both the established PVAR model and the connection between the variables are long-term stable.

Impulse response and variance decomposition

Although PVAR model is a dynamic model, the GMM estimation of PVAR only illustrates the static interaction of variables. Therefore, it is particularly important to perform impulse response analysis between variables. The analysis keeps other variables constant when displaying the dynamic interaction between two variables. The impulse response function is a useful tool to understand the long-run equilibrium

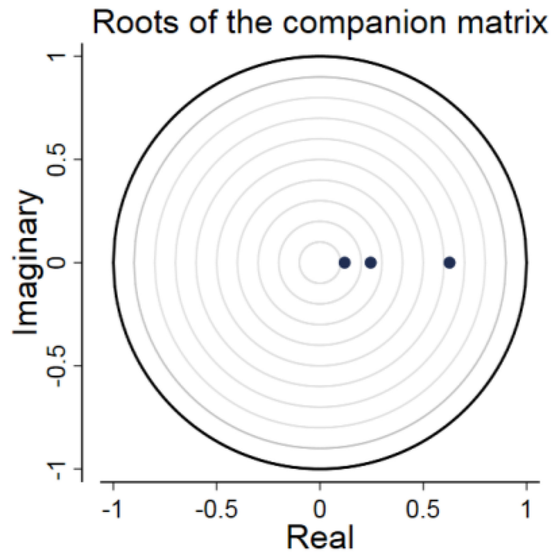

FIGURE 1
Stability test of the model.

relationship between variables. Because not all variables exhibit Granger causality, this work exclusively performs impulse response analysis on endogenous variables with one-way or two-way Granger causality. The impulse response plot in Figure 2 is produced by 300 iterations of Monte Carlo simulation in this work, which intuitively depicts the relationship between carbon emissions, international trade, and technological advancement. The vertical axis depicts how the variables behave to the shocks, while the dashed lines on either side depict the 95 percent confidence intervals. The horizontal axis indicates the number of response periods.

Figure 2 depicts the general patterns of technological progress and carbon emissions. Both have excellent reactions to their own shocks. The reactions to their own informational shocks peak in the present and last longer (especially for technological progress). It is clear that the reactions have some economic "inertia." Both current period carbon emissions and technological progress are anticipated to boost the subsequent carbon emissions and technological progress. They inspire and support one another. However, this reinforcing mechanism lessens as time passes. Consequently, to establish a positive cycle of low carbon and high technology, both carbon emission reduction and technological advancement must have a stable base. This foundation can be built by supporting low-carbon lifestyles, reducing carbon consumption, and usage and boosting investment in technological research and development. When confronted with initial shocks, international trade responds quickly and favorably. This boosting effect quickly goes away to nothing. It demonstrates that foreign trade shocks have relatively mild long-term implications, and the effect on itself is rather short-lived.

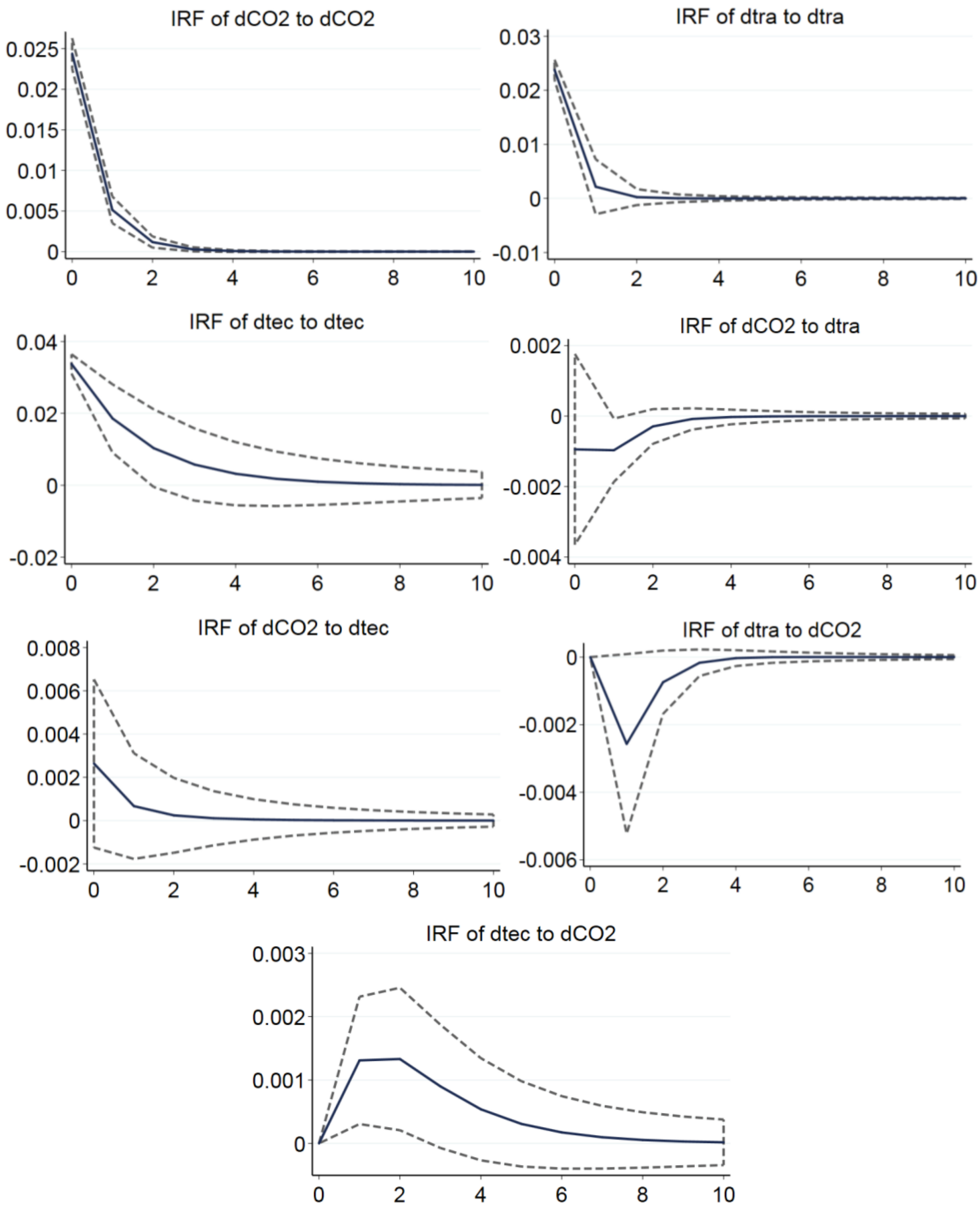

FIGURE 2
Impulse response.

When carbon emissions are used as a shock, foreign trade reacts quickly in an prominent, smooth negative way. After one period, the adverse reaction gradually approaches zero. It demonstrates that the intensity of carbon emissions has a detrimental impact on the expansion of international trade. It could be due to current trade restrictions such as "carbon labeling" and "carbon tariffs," which raise the commercial criterion for carbon-related firms. Technological innovation produces immediate and overwhelming favorable responses. It shows that an increase in carbon emission intensity can stimulate an advance in technological progress. The strengthening of environmental regulations has prompted companies to make significant technological breakthroughs and develop low-carbon technologies to improve energy efficiency.

When foreign trade is deemed a shock, carbon emission intensity does not respond immediately, but rather develops

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over time until it peaks in period one. Following that, the negative reaction gradually fades. It demonstrates that expanding international trade is an effective method for reducing carbon emissions. It may be due to the learning and imitation effects triggered by the spillover of the technology and environmental effects and the strengthening of environmental controls over a longer time dimension, where foreign trade drives economic growth. It enables a significant increase in productivity and energy usage within the enterprise, thus enhancing energy conservation and emission reduction.

When technological progress is deemed a shock, the intensity of carbon emissions first fails to adjust quickly. Then the favorable response gradually increases to phase I and remains relatively stable until phase II. Eventually, the response fades. It implies that the rise of carbon emissions is accelerated by technological development. On the one hand, it might be due to an expansion of economic scale brought by technological progress in each province, as well as a constrained capacity to advance technology, which leads to increased carbon emissions. On the other hand, it may be due to the long time span and long transmission path of the technology level in the provinces. As a result, there is a certain lag in its impact on carbon emissions.

TABLE 6 Variable variance decomposition results.

Variable	Lag phase	dCO_2	Dtra	Dtec
dCO_2	1	1	0	0
	2	0.987	0.010	0.003
	3	0.983	0.011	0.006
	4	0.982	0.011	0.007
	5	0.981	0.011	0.007
	6	0.981	0.011	0.007
	7	0.981	0.011	0.007
	8	0.981	0.011	0.007
	9	0.981	0.011	0.007
	10	0.981	0.011	0.007
dtra	1	0.002	0.998	0
	2	0.003	0.981	0.016
	3	0.003	0.974	0.023
	4	0.003	0.971	0.025
	5	0.003	0.971	0.026
	6	0.003	0.970	0.026
	7	0.003	0.970	0.026
	8	0.003	0.970	0.026
	9	0.003	0.970	0.026
	10	0.003	0.970	0.026
dtec	1	0.006	0.009	0.985
	2	0.005	0.007	0.988
	3	0.005	0.006	0.989
	4	0.005	0.006	0.989
	5	0.005	0.006	0.989
	6	0.005	0.006	0.989
	7	0.005	0.006	0.989
	8	0.005	0.006	0.989
	9	0.005	0.006	0.989
	10	0.005	0.006	0.989

The variance decomposition can demonstrate each shock variable's relative importance to the explanatory variables' evolution in the PVAR model. It can also look into the interaction between global trade, technological progress, and carbon emissions. The variance contribution of dCO_2 in **Table 6** shows that the most significant contribution of carbon emissions is to themselves. It stabilizes at 98.1% after period 5. Foreign trade and technological progress both contribute increasingly. In periods 3 and 4, technological progress stabilizes at 0.7 and 1.1%, respectively. Foreign trade contributes the most to itself in terms of the variance contribution of dtra, which has stabilized at 97% as of period 6. Carbon emissions contribute more in Period 2 and stabilize at 0.3%. In terms of the variance contribution of dtec, technological progress contributes the most to itself. It stabilizes at 98.9% after period 3. The contribution of carbon emissions decreases and it stabilizes at 0.5% in period 2.

Conclusion and discussion

Theoretical significance

In order to achieve the goal of "carbon peaking and carbon neutrality," we must clarify the mechanism and degree of interaction between foreign trade, technological progress, and China's carbon emissions. There is a large body of literature that merely investigates the relationship between foreign trade, technological progress, and carbon emissions. However, there is scant literature that investigates the synergistic relationship among the three indicators and considers the lagged effects of the three. PVAR models combine the advantages of VAR models and panel data, which can circumvent the complex endogeneity problem, and better demonstrate the long-term dynamic relationship between variables. Therefore, this paper will enrich the literature on foreign trade, technological progress, and carbon emissions by constructing a PVAR model, which can provide a relevant theoretical basis for industrial restructuring and development of a low carbon economy in China.

Practical significance

First of all, China must accelerate the process of export tax rebates and improve export tax refunds for low-carbon products. China should concurrently reduce import and export taxes for low-carbon products and implement "tax reduction" and "tax rebate" measures. It is critical to develop new trade patterns and promote the trade structure upgrading. Increasing trade in low-carbon goods and services is also urgent. To stimulate the expansion of high-quality international trade, China must focus on "maintaining growth," "maintaining stability," and "raising quality" at the same time. To effectively implement carbon emission standards, provinces should establish green low-carbon trade standards and certification systems. They should encourage traditional businesses to make the optimal transition to green and environmentally friendly. Provinces should encourage the foreign trade supply chain to move toward green development and develop reasonable environmental management mechanisms.

Besides, China should also increase funding and credit support for equipment upgrades and R&D innovations in traditional businesses to increase the share of low-carbon technologies. China should strengthen subsidies for low-carbon technologies in high-carbon industries and strengthen intellectual property protection for low-carbon technologies. China needs to motivate the technology developers. Furthermore, China should also encourage and facilitate the sharing of technological knowledge and expertise among organizations. It is necessary to eliminate distinctions between national and regional technological capabilities and stress technology's rapid evolution and flexibility. The government should simultaneously establish stricter carbon emission standards and a push-back mechanism supporting R&D to accelerate technological development toward low-carbon development. The government should take into account low carbon requirements while pursuing technological innovation.

At last, the low-carbon economy, international trade, and technology progress all require their own stable foundations because of their intrinsic "economic inertia." Green supply chain development must be accelerated and carbon emissions from the entire industry must be reduced and controlled. Low-carbon laws and regulations must be introduced and improved. Enterprises should act as policy advisors to create a good low-carbon environment. Enterprises should try their best to overcome the fundamental low-carbon core technologies and update the structure of international trade to create a positive social cycle by low carbon for low carbon, technology for technology and commerce for trade. The relationship between international trade and technological progress policies should also be improved, and the "$1 + 1 > 2$" synergistic effect of the two on lowering carbon emissions should be thoroughly utilized.

Limitations and future research directions

There are some limitations to this paper. Firstly, this study bases on panel data for 30 provinces in China from 2007 to 2019. The paper focuses on a relatively short time period of 12 years. Also, from a regional scope perspective, the study is limited to the provincial level in China, which can guide neither other countries nor the prefecture-level cities in China. Secondly, the study introduces an overall technological progress indicator, and the results may not be the same if there is a bias toward low carbon technological progress. Lastly, Currently, there is no Clear Definition and uniform international standard of carbon emissions. In this paper, only CO_2 emissions are chosen as the carbon intensity indicator, without considering other polluting gases.

Therefore, researchers can further lengthen the time span in the future and conduct studies from the perspective of Chinese prefecture-level cities or from the perspective of other countries. Researchers may also focus on biased low-carbon technology progress and consider the carbon emissions of other pollutants to build a better carbon emission system.

Conclusion

This research uses panel data from 30 provinces in mainland China, excluding Tibet, Hong Kong, Macao, and Taiwan, to explore the dynamic interplay between carbon emissions, international trade, and technological progress from 2007 to 2019. The following are the conclusions.

Firstly, the Granger causality test results show that carbon emissions and international trade have a two-way causal link. Furthermore, technological progress and carbon emissions have a bidirectional causal link. The results suggest a direct or indirect link between technological progress, international trade and carbon emissions. However, there is no causal relationship between foreign trade and technological progress.

Secondly, according to the impulse response analysis, international trade, technological progress, and carbon emissions have some "economic inertia" and a particular self-motivating effect. Higher carbon emissions, international trade, and technological progress will be followed by higher carbon emissions, foreign trade, and technological progress in the following period. They can promote themselves better, but the impacts of international trade on self-promotion are minor and fleeting. In the long run, China's foreign trade is taking a high-quality development path. Foreign trade and carbon emissions have a significant mutually inhibiting effect. Foreign trade stimulates economic growth, but technology spillovers and environmental effects greatly increase companies' productivity and energy consumption, promoting energy saving and emission reduction. Some countries are implementing trade barriers such as "carbon labeling" and "carbon tariffs" at the same time. Carbon emissions and technological progress have significant long-term mutually reinforcing consequences. The increased economic scale of technological innovation may contribute to increased carbon emissions. Furthermore, the increase in carbon emissions slows technological progress. The need to reduce carbon emissions is likely to drive further technological progress. The paper takes into account the overall technological progress. The conclusion might be changed if the biased low-carbon technology was chosen as the primary measurement indicator.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

GZ: conceptualization, methodology, software, and writing—original draft preparation. HW and LP: data curation and writing—review and editing. XH: validation, formal analysis, investigation, resources, funding acquisition, and supervision. YL: writing—original draft preparation and data collection. All authors have read and agreed to the published version of the manuscript.

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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.

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