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Trade penetration, sustainable finance and carbon peak: evidence from China

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ABSTRACT

Following the “dual carbon” goals in 2021, which emphasize achieving the carbon peak by 2030 and carbon neutral by 2060, China introduced a “dual circulation” strategy to connect domestic and international trade. Leveraging the quantile regression model, this study examines the impact of green total factor productivity, trade penetration, foreign direct investment, and sustainable finance on carbon emissions (CO2). Furthermore, a mediating model is established from another perspective to discover the mechanism, respectively, testing how trade, foreign direct investment, and sustainable finance affect carbon emissions via green total factor productivity. The findings indicate that green total factor productivity exerts an inverted “U-shaped” effect on carbon emissions within a certain threshold of the total CO2 volume. While the relationship between the green total factor productivity and CO2 becomes a significant “U-shaped” when the total CO2 goes beyond a certain level. Meanwhile, foreign direct investment penetration and sustainable finance contribute positively to carbon emissions reduction, whereas trade penetration notably increases carbon emissions. Transition mechanisms with international cooperation, trade penetration, foreign direct investment penetration, and sustainable finance also affect CO2 through the green total factor productivity channel. As suggested, China should tailor its low-carbon transition strategies, drawing on global insights and considering its unique national development. Broadly, efficiency in the production process and low-carbon transition are preferred (i.e. improved green total factor productivity), which will balance economic development and environmental protection. The adoption and promotion of a consistent framework for sustainable finance are crucial, as they help enterprises in developing countries access more global sustainable finance. This study also notes that participating more in international trade that embodies low-carbon concepts and introducing green foreign direct investment helps developing countries improve resource efficiency and productivity.

1. Introduction

According to the report released by the World Resources Institute, >50 countries around the world have reached their carbon peak, accounting for approximately 40 % of the global total carbon emissions. And the vast majority are developed economies, while developing countries will become the main contributors to global carbon emissions in the future with more international trade, financial assistance, and investment in low-carbon cooperation [1]. China has set the “double carbon” goal of reaching the carbon peak by 2030 and becoming carbon neutral by 2060. To advance this objective, China insists on actively promoting the transformation of its energy structure, striving to achieve a non fossil energy to energy consumption ratio of around 25 % and 35 % by 2030 and 2035, respectively [2]. Alongside this, China also notes the “dual circulation” strategy integrated into the government work report, putting forward a new development pattern with the domestic circulation (i.e. inter-provincial trade) as the mainstay and mutual promotion of international trade. In terms of international carbon emission reduction cooperation, the State Council[1] has proposed to strengthen green standards and expand cooperation in clean and

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[1] Guidelines on Accelerating the Establishment and Improvement of a Green, Low-carbon and Circular Development Economic System

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green-related fields, including trade, foreign investment, and sustainable finance.

In recent years, the research focus more on the impact of international trade and foreign direct investment (FDI) penetration on the environment, with rising concern about environmental responsibility allocation and equity issues. Studies flag that trade may increase carbon emissions [3,4]. However, due to differences in environmental regulatory policies, the impact of trade on developed and developing countries may vary. Specifically, developed countries tend to relocate pollution-intensive industries to developing countries, which is regarded as a significant contributor to the increase in carbon emissions in developing countries [5]. As a guide for capital flow to industrial low-carbon transition under this trend, where global investors focusing more on environmental, social, and governance (ESG) development and clean trade, sustainable finance policies are advancing at an unprecedented pace [6,7]. A 102 % increase in the number of companies with science-based targets in 2023 can be seen compared to 2022. While India saw the most growth in the number of complied companies (520 %), China has 104 % annual growth of the companies that set the science-based targets. Studies also indicate that sustainable finance can not only effectively reduce carbon emissions but also significantly improve the general quality of the environment [8–10]. To effectively address global environmental and economic challenges and promote sustainable development, it is crucial to develop sustainable finance continuously [11,12]. In 2024, green bonds reached over USD670 billion (CBI, 2024), indicating the continuously important role that sustainable finance plays.

To measure the outcome of environmental governance, based on the theoretical framework of total factor productivity [13,14], green total factor productivity (GTFP) has become an important indicator [15]. As the world's largest developing country and energy consumer, international trade, direct investment, and sustainable finance development in China can significantly impact the global low-carbon transition. Therefore, taking China as an example, this paper focuses on three questions: (1) How can GTFP, trade, and FDI penetration, and sustainable finance affect the carbon reduction process in China? (2) As a comprehensive index for green productivity, can GTFP be the pathway of how trade FDI penetration and sustainable finance affect carbon reduction? (3) Will the relationship between GTFP and carbon emission differ across different regions? In this paper, the quantile regression model is adopted first, taking GTFP, trade, FDI, and domestic sustainable finance progress in an open economy as the main factors for carbon peak. Also, as GTFP is a combination of both input and output, trade, FDI, and sustainable finance may influence its development. Hence, their path to carbon emission and the mediating effect of GTFP are discussed separately. While previous studies mainly focus on the relationship between urbanization [16], industrial structure [17], energy consumption [18], research and development (R&D) expenditure [19], and carbon emission, respectively, this study takes all of them as control variables to reduce the omitted variable bias. Their impacts on carbon emissions are discussed theoretically and empirically, following the model.

Potential marginal contributions of this paper are as follows: (1) The existing research on the reaching of carbon peak and carbon emission reduction mostly adopts a single domestic development or international trade perspective and method, which cannot distinct the new pathway of carbon peak under the "dual circulation" policy or domestic and international cooperation background. This paper integrates the pattern of domestic and international commerce (i.e. "dual circulation") to refine the specific types of trade and finance. (2) There is a lack of studies on the mechanism of carbon emission at different stages in developing countries, leading to confusion about potential future CO2 reduction paths in developing countries. This study comprehensively explores the mechanism of carbon peak in China: first, providing a rough view of how GTFP affects CO2; Then, including GTFP for mediating tests for trade and FDI, and green finance, deducing the possible emission reduction effects and mechanisms of various factors in China as an example to provide general suggestions. (3) While previous studies apply direct measurement that cannot detail the low-carbon development, sustainable finance, trade, and FDI characteristics, which oversimplify their effects on CO2, this study enriches the impact indicators of carbon peak and carbon emission reduction. In terms of domestic influencing factors, GTFP, sustainable finance, and industrial rationalization indicators are introduced. In terms of international influencing factors, trade penetration and FDI penetration indicators are used.

The remaining sections of this paper are organized as follows. Section 2 is the literature review. Section 3 proposes a theoretical hypothesis. Section 4 presents the methodology, including the measurement, models, and data. Section 5 presents the results of trade penetration, FDI, and sustainable finance on the carbon peak path in China, and further explores robustness tests, mediating tests, and heterogeneity tests. Section 6 concludes the study and provides policy recommendations, research deficiencies and future directions.

2. Literature review

2.1. Traditional perspectives examining the carbon peak path

Existing domestic research on carbon peak and carbon emission reduction mostly focuses on the simulation of carbon peak paths across China and some parts of the country. Only a single influencing factor is included to predict the carbon peak situation and explore the way to reduce carbon emission [20–23]. However, international researchers often choose regional economic alliances or developing economies for path studies on carbon peak and emission reduction from a domestic perspective, and these studies are mostly based on the environmental Kuznets curve (EKC) [24].

Some scholars classify different economic or low-carbon development types as the basis for conducting group studies on various regions at home and abroad [25,26]. Economic development is employed as a classification criterion, which is proven to have an inverted "U-shaped" or double threshold impact on developed countries from the perspective of industrialization and urbanization [27–29]. Other studies are mostly based on verifying the mechanism of the EKC from traditional perspectives, such as energy consumption, economic development, environmental regulation, and population from the perspective of national development [29,30]. Meanwhile, owing to the importance of energy and population/urbanization in reaching the carbon peak, these factors are also applied as control variables for each other when conducting the mechanism analysis from a certain perspective [16–19]. Regarding regions, these studies pay more attention to China, India, the European Union, and OECD countries [31–33].

2.2. Finance and trade role in carbon reduction

In terms of financial development, during the United Nations Climate Change Conference (COP26) in 2021, the International Platform for Sustainable Finance (IPSF) released the "Common Classification Catalogue for Sustainable Finance on Climate Change Mitigation" (abbreviated as "Common Classification Catalogue"), which is a list of economic activities recognized by China and the EU that guide investors to invest in green projects and is a pioneering practice in international cooperation in green finance [34]. Green finance, which always represents sustainable finance, is used for quantitative research. Research by Saidi and Mbarek [35] shows that financial development has a long-term negative impact on carbon emissions, while Wu et al. [9] find that green finance can promote low-carbon transition. Its impact can be demonstrated from the carbon quantity and intensity perspective. Wang and Yi [36] demonstrated that the scale effect of development in the financial industry is positively correlated with the quantity of emissions and negatively correlated with the emission intensity. Additionally, specific green financial products such as green credit and green bonds have been found to significantly reduce CO2 emissions [37,38]. It has also been noted that the impact of green finance development on emission reduction varies across different national development levels, as demonstrated by methods like quantile regression [39].

Studies on the carbon peak mechanism from an international perspective mainly focus on the impact of trade and international financial flow and development on carbon emissions. Most of the research connects it with domestic factors [40]. Among them, the main perspective of financial openness is FDI [41,38]. The trade-related studies often apply a comprehensive index or trade commodity quantity [29,41,42]. It is proven that trade and financial openness mostly reduce carbon emissions by helping a country absorb advanced technologies and enhance its competitive effect [29,43,44]. However, it may also lead to the depletion of natural resources and an increase in carbon emissions [45,46]. Trade openness generally has a more significant emission reduction effect, while the impact of financial openness and development is relatively small [40,47]. Specifically, trade openness may increase carbon emissions through imports and exports, FDI flowing into high-carbon industries, etc. [48]. However, the spillover of environmental technology and the flow of human resources are channels of trade openness to reduce carbon emissions [49,50].

2.3. Model application in carbon peak path

At present, research on carbon peak or carbon emission reduction mechanisms and low-carbon economic development mostly adopts the following methods. First, based on the EKC curve or its derived IPAT and STIRPAT models, explore the impact of various domestic and international economic development indicators on carbon emissions [25,41,51,52]. Second, the panel error correction and the ARDL model are used to discuss the different effects of various elements on carbon emissions in the short and long term [53]. Third, a dynamic panel model is constructed to explore the mechanism of FDI, global trade, energy consumption, or urbanization on carbon emission reduction [54–56]. Fourth, through the quantile regression model, the quantile points of carbon emissions and the role paths of green finance, energy consumption, and technological innovation were judged [57,58]. Fifth, the mediating effect model is used to explore the mechanism of mediating variables such as green technology development and industrial structure upgrading on the realization of carbon peak [59,60].

Most of the existing research on the carbon peak and carbon emission reduction focuses on the following aspects. First, in terms of research perspective, research adopts a single perspective and rarely explores the specific types of trade and finance after integrating the "dual circulation" approach at home and abroad. Second, in terms of research depth, there is a lack of research on the impact mechanism of carbon emissions at different stages, and the quantitative research on the action channels is relatively single and traditional. Third, in terms of research methods, the existing studies mostly adopt a single panel model measurement scheme, without combining various research methods to support it.

Therefore, this study integrates the perspective of domestic and international "dual circulation" to study the mechanism of sustainable finance, trade, and FDI penetration on the carbon peak process of China, which includes both basic quantile regression and a mediating channel. Specifically, the panel quantile regression scheme is used to explore the feasible carbon emission reduction with GTFP improvement, trade, and FDI penetration, and sustainable development in China, without considering the interaction between these factors. As the GTFP is a comprehensive indicator for green productivity development, which may be affected by other factors, the mediating effect model is used to study the GTFP pathways for trade, FDI, and sustainable finance. This aims to help China and other developing countries achieve the "double carbon" target as soon as possible.

3. Mechanisms and hypotheses

3.1. Mechanisms of sustainable finance, trade and FDI development on carbon peak

After the development of sustainable finance is refined into the field of green finance, it will work with FDI penetration to reduce carbon emissions by reducing the cost of clean industry, forming a capital orientation, and promoting technology development and innovation to help the transformation of industrial structure (see Fig. 1). For example, financial institutions increase the amount of finance or lower the asset standards that should be met to provide loans for firms in clean industries, and directly or indirectly increase the expenditure on high-polluting projects. For FDI penetration, it can promote carbon emission reduction through structural and technical effects. On the one hand, the global net-zero transitions push developed countries to invest more in developing countries, helping them adapt and mitigate climate change. Therefore, FDI flows more to the clean industry now, reducing the clean industry's costs and expanding clean production, thus reducing pollution [61,62]. On the other hand, the inflow of FDI into the clean industry may attract and bring more green technologies, increase the possibility of future green self-innovation in existing technologies, which may bring potential clean technology cooperation, thereby reducing carbon emissions [63,40].

The mechanism of import and export of carbon emissions can be divided into three aspects: structural effect, technical effect [49,40], and resource effect [45] (Fig. 1). The structural effects of trade is mainly reflected in industry. If most of them are clean industries or industries with low carbon emission intensity [64], environmental pollution is expected to be alleviated. However, if most of the industries are heavily polluting or have high carbon emission intensity, carbon emissions may increase [65–67]. This is mainly due to the huge revenue from trade within these industries, which use the comparative advantage in product price. Consequently, the production will be boosted due to the revenue incentives, scale effect will come into being. If trading more in the polluting industry, the emissions will increase. But if trading more in the clean industry, emission can be reduced more. As for the technical effect, technological advances may push developed countries with strongly environmental regulations to develop clean, low-carbon, high--value-added industries and transfer their pollution-intensive industries to developing countries, thereby imposing more environmental costs on developing countries like China [68]. In terms of resource effect, in resource-based industries, trade can make full use of scarce and renewable resources, which improves resource efficiency without using them too much [69,70]. This helps reduce carbon emissions. But if the resource is common, such as fossil fuels, it may also exhaust natural resources to increase CO2 as firms need to expand their production [71]. As a result, trade in China could reduce pollution in developed countries but increase its carbon emissions.

Hypothesis 1. Sustainable finance development and FDI penetration will reduce carbon emissions. Trade penetration will increase carbon emissions in China, but carbon emissions may be reduced in countries that have realized carbon peaks.

3.2. Mechanisms of carbon emission reduction and low-carbon development under the GTFP channel

As a key factor in measuring the development of a green economy, GTFP improvement is mostly through the optimization of industrial structure, the level of technological efficiency or innovation, and the improvement of environmental awareness [72], and also indirectly through FDI flow and environmental regulation [73,74]. As input, desirable output, and undesirable output make up the GTFP indicator, it is better to decompose the potential influence factors of GTFP to the above ones (see Fig. 2).

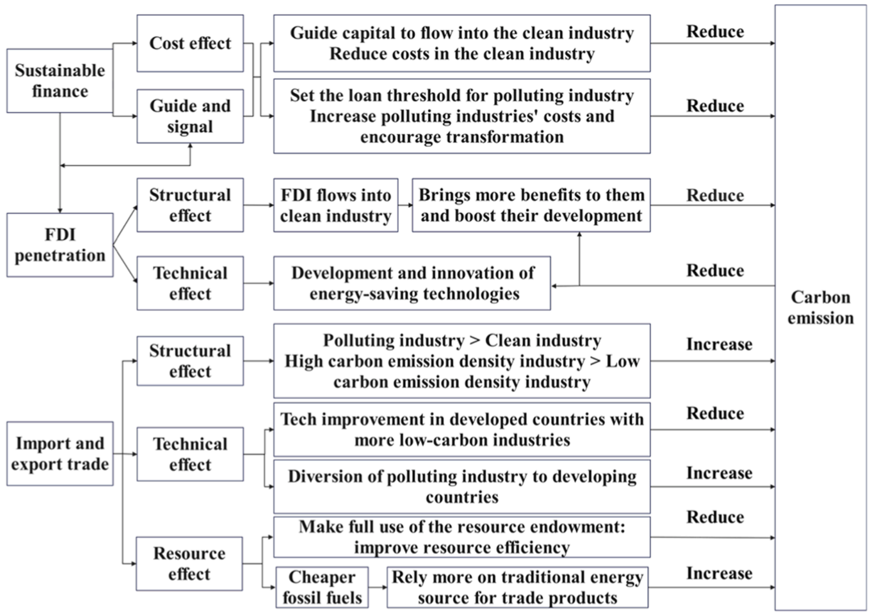

Fig. 1. The pathway of external and internal factors on carbon emission.

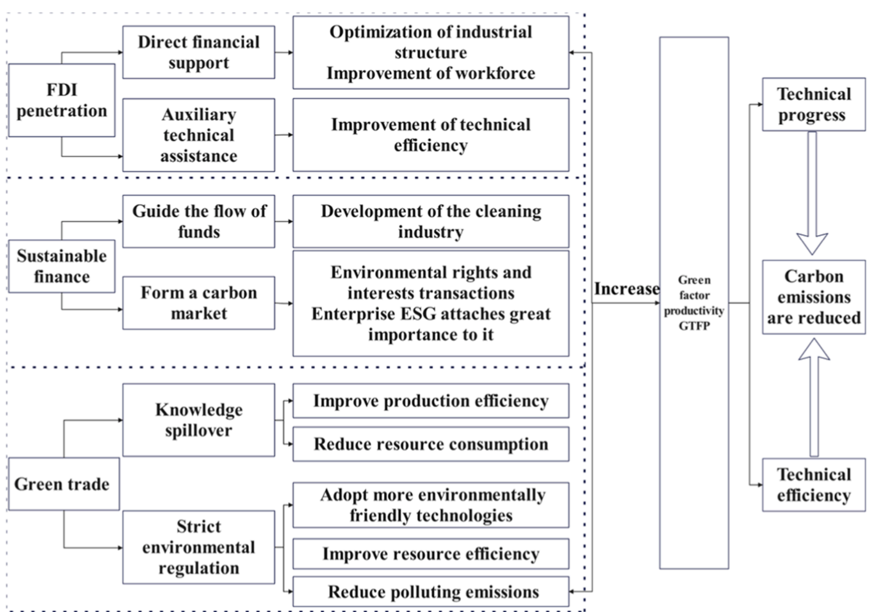

Fig. 2. The pathway of GTFP acting as a mediating channel on carbon emission.

The development of the green sector trade and sustainable finance has an indirect impact on GTFP, mainly by the guidance for capital flow or advanced technology to environmentally friendly industries and improving technological efficiency [48,75]. This can both increase the efficiency of the inputs, reducing the use of the natural resource and reducing the undesirable outputs (carbon emission) as sustainable/-green finance only favors those with certain emission levels. Therefore, firms will try to limit emissions to gain more financial assistance or meet international trade standards (e.g. the European Union’s Carbon Border Adjustment Mechanism). Moreover, there is a positive relationship between the development of green finance and GTFP. On the one hand, green trade promotes international technology transfer and knowledge spillover, which helps countries improve production efficiency, reduce resource consumption, and improve GTFP [76]. On the other hand, green trade is often accompanied by strict environmental regulations. These regulations encourage companies to adopt more environmentally friendly technologies in their production processes, improve resource efficiency, and reduce polluting emissions [77]. In the long run, this will help enterprises form a green production model and improve GTFP.

Hypothesis 2. As a mediating channel for trade penetration and sustainable financial development, GTFP may directly affect the level of carbon emissions, and have positive and negative effects according to different stages of economic development.

3.3. *Mechanisms of the traditional development mode on the carbon peak*

For control variables, energy consumption is derived from and impacts the environment through two types of channels: the structural effect and driving effect (e.g., Fig. 3). If a country uses more clean energy, the possibility of reducing carbon emissions will increase

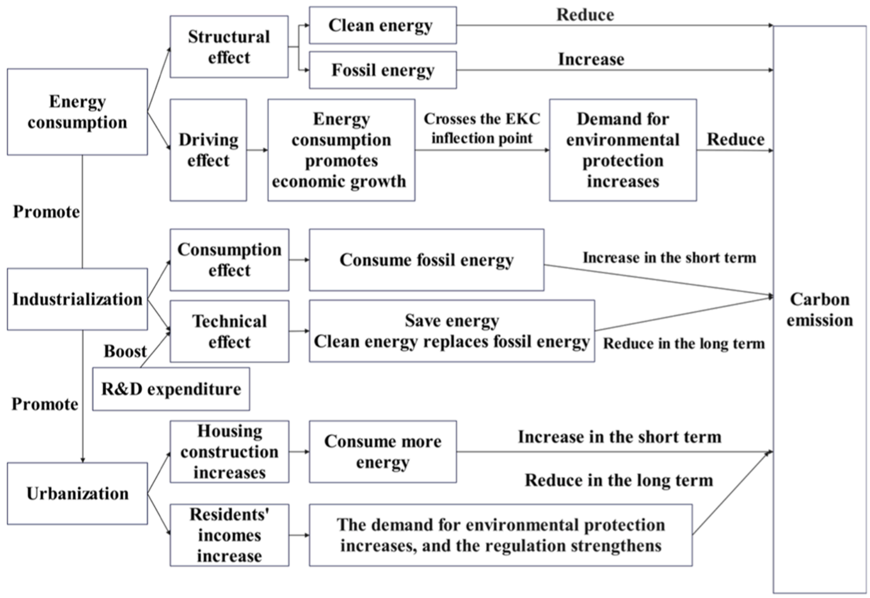

Fig. 3. The pathway of traditional internal factors on carbon emission.

significantly [78]. On the contrary, if the consumption of fossil fuels and other traditional energy sources is higher, it will directly increase carbon emissions [79–81]. In addition, energy consumption may have a driving effect. Energy is an important input in industrial production, and the increase in energy consumption can often directly increase the enterprise's production capacity, consequently promoting economic growth. With economic development, countries will shift their major development path: from focusing on economic development to environmental protection [82,83]. It will increase the demand for sustainable development and reduce carbon emissions.

Industrialization is often driven by large-scale energy consumption [84]. Therefore, the capital stock in most industrial countries is highly polluting, which has a direct negative impact on carbon emission reduction. Industrialization has a consumption effect and a technical effect (see Fig. 3). To achieve rapid economic development, factories will increase industrial output, which will consume more fossil energy, increasing carbon emissions. However, with the rapid advancement of industrialization and the continuous investment in R&D expenditure, technology has embraced significant progress. These advanced technologies not only greatly optimize the efficiency of resource utilization, but also strongly promote the replacement of traditional energy sources with clean energy, consequently contributing to carbon emission reduction [29].

In addition, industrial development comes with an acceleration of urbanization, due to the agglomeration of industries and the scale economy effect [85,86]. Specifically, urbanization has a two-sided impact on carbon emissions (Fig. 3). On the one hand, the migration of people to cities places a higher demand on the construction of houses and public facilities, which often leads to a greater demand for building materials, leading to energy consumption and the emission of greenhouse gases. At the same time, the production of urban factories reduces green spaces, and heavy traffic can also increase carbon emissions [87,88]. However, it is worth noting that urbanization can increase income levels and stimulate demand for environmental protection to help reduce emissions, and this effect is more pronounced when urbanization has made some progress [27,40,89].

Hypothesis 3. Energy consumption, industrialization, and urbanization will increase carbon emissions in China. However, in countries that have already reached the peak, they are all likely to promote carbon emission reduction.

4. Methodology and data

4.1. Measurement

4.1.1. The DEA-SBM methodology for provincial GTFP

As an important indicator of the synergy between economic growth and environmental benefits, GTFP is widely used in the field of low-carbon research. As GTFP involves undesired output, the SBM model is often used. Therefore, this study draws on the basic analysis framework of total factor productivity (TFP) proposed by Thoreau and synthesizes the existing research on GTFP and TFP. To avoid colinearity with CO2, SO2 was chosen as the non-expected output, and GDP as the expected output. Finally, the DEA method is selected. The input-output indicator system, as shown in Table 1, is constructed.

4.1.2. International trade penetration at the provincial level in China

This study focuses on the measurement of trade penetration of international trade in goods, which represents the trade penetration. Using the method of Deng et al. [90] for reference, trade penetration is measured by gauging how intensively a region's final demand is satisfied by imports. Using GDP as the proxy for regional economic size, we first strip out the net-export component to isolate domestic final demand. And trade penetration is then calculated as the ratio of regional imports to this domestic final demand. Where t represents the year t and i

Table 1
Calculation framework of GTFP.

Primary Index	Secondary Index	Third Level Index	Data Source
Input	Labor	People employed per year	China Labor Statistics Yearbook
	Capital	Capital Stock	China Statistical Yearbook
	Energy	Total Energy Consumption	China Statistical Yearbook
Output	Expected output-GDP	2010 Constant USD/ Constant GDP	China Statistical Yearbook
	Unexpected output-SO2	SO2 Emission per year	China Statistical Yearbook

Source: Data are compiled according to China Statistical Yearbook and World Bank database.

represents the region, as shown below:

$$TRADE_{ti} = \frac{Import_{ti}}{GDP_{ti} - (Export_{ti} - Import_{ti})} \quad (1)$$

In addition, to measure the impact of foreign capital on regional carbon emissions in different ways, the FDI penetration index is introduced. The higher the FDI penetration rate, the greater the proportion of foreign capital in the region. Therefore, based on the research of Blomström [91] and the availability of data, this paper uses the proportion of FDI in GDP to calculate and measure the penetration rate of foreign capital.

4.1.3. The level of sustainable finance development at China provincial level

The current international research on sustainable and green finance primarily focuses on qualitative policy analysis, with a noticeable absence of in-depth quantitative studies. This oversight results in substantial gaps and deficiencies within the quantitative assessment frameworks for sustainable finance. Green finance, a crucial component of sustainable finance [92], has increasingly emerged as a key academic metric for evaluating its progress. According to the Common Classification Catalogue, the IPSF uses green finance as a measure for the development of sustainable finance [34]. Therefore, this study applies the widely used green finance index in China to partly represent the development and importance of sustainable finance.

For the development of domestic green finance, academics mostly regard green credit as a single representative. This study integrated the existing academic methods for measuring the development of green finance in provinces, combined the availability of data, and referred to the green finance indicator model constructed by Nepal et al. [93] to estimate the development of provinces. Table 2 presents the indicator system.

This paper uses subjective and objective methods to determine the index weight of the development level of green finance. The subjective weight is based on the weight of Li and Xia [94] in the China Green Finance Report [95], while the objective weight is based on previous research experience. Finally, the weighted average of subjective and objective weights is taken.

4.1.4. CO2 emission at provincial level in China

At present, there is no unified measurement method for the measurement of carbon emissions. In this study, the default CO2 coefficients and fuel consumption of 8 types of fuels provided by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and the China Energy Statistical Yearbook were used to calculate CO2 emissions. The specific calculation formula is shown below, and then the carbon emissions of all provinces in China are calculated based on the relevant data of China from 2000 to 2017.

$$CO2 = k \cdot \sum_{i=1}^{n} E_i \cdot \delta_i \quad (2)$$

Among them, CO2 is carbon dioxide emissions; k is the fixed coefficient (k = 44/12), that is, the ratio of carbon dioxide to carbon molecular weight; E_i is the consumption of Class i fossil fuels; δ_i is the emission factor for Class i fossil fuels, as shown in Table 3.

4.1.5. Rationalization of industrial structure at the provincial level in China

The rationalization of industrial structure not only reflects the coordination between industries but also shows whether the industry uses resources properly. In this study, the comprehensive Thiel index proposed by Gan et al. [96] is introduced to measure the rationalization of industrial structure. The overall calculation method is as follows:

$$TL = \sum_{i=1}^{n} \left(\frac{Y_i}{Y}\right) \ln \left(\frac{\frac{Y_i}{Y}}{\frac{Y}{L}}\right) \quad (3)$$

Among them, TL stands for Gan Chunhui - Thiel Index, Y stands for total output value, L stands for employment data, and Y_i stands for the output value of various industries (i.e. primary, secondary, and tertiary industries respectively).

4.2. Model

4.2.1. Panel quantile regression model

The advantage of quantile regression is its capability to effectively estimate nonlinear equations. On one hand, quantile regression permits researchers to investigate the impact of explanatory variables on different quantiles of the dependent variable, uncovering potential nonlinear relationships among variables. On the other hand, quantile regression exhibits greater robustness to outliers, as it minimizes the absolute values of residuals rather than their squares. Regarding the real-life analysis, as far as China is concerned, there are obvious differences in energy structure and economic development level among provinces. For provinces with different economic and development bases, the mechanism of the same factors on CO2 is different. In this study, leveraging the quantile regression method, we construct an analysis which takes carbon emissions as the dependent variable. We establish three quantiles (0.25, 0.5, 0.75) to delve into the effects of trade penetration, GTFP, and green finance on carbon emissions,

Table 3
Fossil fuel emission coefficient.

Fuel Type	Default Carbon Content (kgc/GJ)	Default Carbon Oxidation Rate	Average Low Calorific Value (KJ/kg, m^3)	Carbon Coefficient (kgc/kg, $m^{3)}$
Coal	25.8	1	20,908	0.53943
Coke	29.2	1	28,435	0.83030
Crude Oil	20	1	41,816	0.83632
Gasoline	18.9	1	43,070	0.81402
Kerosene	19.6	1	43,070	0.84417
Diesel Oil	20.2	1	42,652	0.86157
Fuel Oil	21.2	1	41,816	0.88232
Natural Gas	15.3	1	38,931	0.59564

Source: Data were compiled according to the 2006 IPCC Guidelines for National Greenhouse Inventories and the China Energy Statistical Yearbook.

Table 2
Measurement framework of the overall development of green finance.

Primary Index	Secondary Index	Third Level Index	Indicator Definition
Green Finance Development	Green Bond	The proportion of high energy consumption industry interest expenses	Six high energy-consuming industrial interest expenditure/total industrial interest expenditure
	Green Investment	The proportion of investment in environmental pollution control in GDP	Environmental pollution control investment /GDP
	Green Insurance	Agricultural insurance depth	Agricultural insurance income/gross agricultural output value
	Governmental Support	The proportion of expenditure on fiscal environmental protection	Fiscal environmental protection expenditure/general budget expenditure

Source: Data are compiled according to China Statistical Yearbook and regional Statistical Yearbook.

alongside traditional economic factors [97–99]. Furthermore, based on previous research highlighting the nonlinear causality between TFP and carbon emissions [100], we incorporate the squared term of GTFP to explore its relationship with carbon emissions, and the model is established as follows:

$$Q_T LNCO2_i = \alpha_1(T)GTFP_{i1} + \alpha_2(T)GTFP^2{}_{i2} + \alpha_3(T)GFIN_{i3} + \alpha_4(T)TRADE_{i4} + \alpha_5(T)FDI_{i5} + \alpha_6(T)INDUS_{i6} + \alpha_7(T)URBAN_{i7} + \alpha_8(T)ENERGY_{i8} + \alpha_9(T)RD_{i9} + \beta Z_t \quad (4)$$

Through the Hausman test, the study used a fixed panel quantile model. In addition, to avoid endogenous effects of regions and periods, the study fixed regions and time at the same time. The model has no constant term, and *T* represents the quantile point, *i* represents the provinces, municipalities, and autonomous regions.

4.2.2. Mechanism model: GTFP as mediating factor

At the same time, due to the complex connection between GTFP and CO2 and the relatively robust mechanism of action confirmed above, referring to Liu and Zhu [98] and Cheng et al. [101], this study establishes a model with GTFP as a mediating variable to clarify the causal relationship between variables. This project intends to first explain the relationship between the variables of the first model and GTFP, and then continue to explore the mechanism of action between the core variables and GTFP and CO2 emissions. Among them, X_t represents trade penetration *TRADE*, foreign investment penetration *FDI* and green finance development *GFIN*.

$$CO2_t = \alpha_0 + \alpha_1 X_t + \beta Z_t + \delta_t + \nu_t + \varepsilon_t \quad (5)$$

$$GTFP_t = \alpha_0 + \alpha_1 X_t + \beta Z_t + \delta_t + \nu_t + \varepsilon_t \quad (6)$$

$$CO2_t = \alpha_0 + \alpha_1 GTFP_t + \alpha_2 X_t + \beta Z_t + \delta_t + \nu_t + \varepsilon_t \quad (7)$$

4.3. Variable selection and data

4.3.1. Variable selection

Core variables are shown in Table 4. Explained variable CO2: Carbon dioxide emissions in various regions of China. Due to the large difference in absolute values, to reduce the error caused by the model, the logarithm is taken.

Core explanatory variables: (1) Green total factor productivity (GTFP): Reflecting the development of green economy in various regions; (2) trade penetration (TRADE): Expressed by the proportion of the trade volume of imported goods in GDP, and the trade data are obtained according to the statistical yearbooks of each region [23]; (3) FDI penetration rate (FDI): Expressed as the proportion of foreign direct investment in GDP, the data source is the same as above; (4) Green finance development (GFIN/GFINloan): Representing the green finance field in sustainable finance, where the former is the overall development index of green finance, and the latter is the green credit data as a robustness test index.

Control variables: (1) Industrial structure rationalization (INDUS): Referring to Gan et al. [96], we use the Theil index to measure it. The higher the value is, the lower the degree of rationalization of the industrial structure is; and the reason why choosing industrial rationalization is because it can better describe the development of Chinese industries and provide future suggestions for the transition of industries; (2) R&D expenditure (RD): Measured by internal expenditure of research and experimental development funds, the greater the value is, the more R&D expenditure is made; (3) Urbanization level (URBAN): Measured by the proportion of urban population in the total population, the higher the value is, the higher the level of urbanization is in the country; (4) Energy consumption (ENERGY): Referring to Chen et al. [25], expressed in terms of per capital oil use. The larger the value is, the more energy consumption is.

Table 4
Table of main variables.

Category	Variables	Definition	Data sources
Explained variable CO2	CO2	Total annual carbon emissions in each region	China Statistical Yearbook / China Energy Statistics Yearbook
Core explanatory variable "dual-circulation"	TRADE	Trade penetration level	China Statistical Yearbook
	FDI	Foreign investment penetration	China Statistical Yearbook
	GFIN	Green finance development	China Statistical Yearbook / China Insurance Yearbook / Provincial Statistical Yearbook
	GFINloan	Green credit development	China Industry Statistical Yearbook / Economic Census Bulletin
	GTFP	Green total factor productivity, reflecting the development of green economy in various regions	China Statistical Yearbook / Input-Output Table
Control variable	INDUS	Rationality of industrial structure	China Industry Statistical Yearbook / China Statistical Yearbook
	RD	Research and development funds	China Statistical Yearbook
	URBAN	The proportion of the urban population in the total population	China Statistical Yearbook
	ENERGY	Per capita oil use	China Statistical Yearbook / China Energy Statistics Yearbook

Source: The data is based on the China Statistical Yearbook and local statistical yearbooks.

4.3.2. Data

Table 5 is the descriptive statistics in domestic regions. Among them, the number of observations of the core explanatory variables is relatively complete, except for the lack of green credit data, which is only 330. However, considering that GFINloan is a proxy for the robustness test of GFIN and a large sample in China, this difference can be temporarily ignored. At the same time, the standard deviation of each value is within a reasonable range (no more than 5), except for CO2 emissions, whose average value is 10.261, the difference between the indicators is not large, which ensures the credibility of the regression parameters and is of a high reference value.

Table 5
Description of the variables.

Variable	Number of observations	Mean	Standard deviation	Min	Max
LNCO2	420	10.261	0.770	7.377	11.914
GTFP	420	1.462	0.833	0.307	4.572
$GTFP^2$	420	2.829	4.019	0.094	20.906
TRADE	420	0.146	0.173	0.004	0.894
FDI	420	0.023	0.018	0	0.082
GFIN	420	0.150	0.093	0.044	0.759
GFINloan	330	0.536	0.147	0.199	0.906
ENERGY	420	0.637	0.158	0.045	0.903
URBAN	420	0.535	0.139	0.269	0.896
INDUS	420	0.248	0.155	0.017	0.853
RD	420	0.167	0.210	0.014	1.432

Source: The data is based on the China Statistical Yearbook and local statistical yearbooks.

5. Results

5.1. Panel quantile regression: basic influences of domestic and international factors

The models have passed the Hausman test, that is, the fixed effect model is adopted. Because there are often different regional and temporal developments in China, to reduce the endogenous effects of spatial and temporal changes, time and samples were fixed. Among them, the logarithm of carbon emission CO2 as the explained variable is taken to reduce the influence of heteroscedasticity.

From Table 6, in the process of achieving a carbon peak in China, GTFP has an inverted "U-shaped" effect on carbon emissions before the quantile of 0.5. That is, carbon emissions first increase with the growth of GTFP, and then gradually decrease. However, when carbon emissions reach the 0.75 quantile, GTFP may have a "U-shaped" effect on CO2 emissions–which means the growth of GTFP drives the lower carbon emission level. All the impacts have been proven statistically significant. As GTFP is about productivity and efficiency, the different impacts may be due to the combined effects of the clean production scale resulted from the increased GTFP. Therefore, the two growth boosts the development of clean production and reduce the CO2. Meanwhile, the increased GTFP can be driven by different inputs. Before the threshold, the key input triggering the GTFP growth may be resources, which can also increase the CO2; while after the threshold, the leading factor change to capital and reduce the CO2.

Import penetration in China always has a positive impact on carbon emissions, and after crossing the 0.5 emission quantile, the effect is weakened. China is a developing country, so China re-imports finished products after exporting more intermediate products, which is inconsistent with the trade mode of the developed countries. Most of these intermediates contain a large amount of embodied carbon. In addition, most of the largest trading partners of China export minerals to China, which is not conducive to emission reduction. As far as the impact of FDI on the realization of the carbon peak is concerned, its ability to reduce carbon emissions decreases with the increase in total carbon. This may be because the overall FDI in its target industries is mostly capital-intensive rather than resource-dependent, including the spillover effect of environmentally friendly technologies [102].

However, the development of green finance in sustainable finance reduces the level of carbon emissions. This effect is more obvious with the increase of carbon quantile, which is significantly increased at the 0.75 quantile point and reaches −1.852. The possible reason is that sustainable finance can reduce pollution emissions by re-planning energy consumption structure [103], guiding industrial restructuring, and promoting capital inflows into clean industries and high-productivity industries. Green finance also encourages investment in climate-friendly technology, financing the environmentally friendly projects and clean energy production, which reduces the emission level [104].

5.2. Robustness test

The green finance index depends on the framework set by different people. Though this study combines the subjective and objective weighting of sub-indicators in the index, there are still concerns about the validity and robustness of the green finance development index and its impact on emission reduction. Therefore, to prove the robustness of our results, two different robustness tests are conducted.

The first one is about changing the weights of sub-indicators of the green finance index and shortening the time window (from 2010 to 2018). The changed index weights are based on the one proposed by Li and Xia [94] and Zhou and Tian [105]. They argue that green bonds are one of the most important components of green finance, and their scale and influence are relatively large, while green insurance and green investment are relatively small in terms of model and influence. Therefore, they assign weights to the above first-level indicators according to the ratio of 50 %: 25 %: 15 %: 10 %, which has also been applied by [106]. Secondly, the third-level indicators under the same second-level indicators are relatively independent, so they are given the same weight. The range normalization method is used to process the dimensionless data.

It can be seen in Table 7 that the inverted "U-shaped" relationship between GTFP and carbon emissions in quantiles 0.25 and 0.5 is the same as the one in the baseline regressions. Meanwhile, the U-shaped relationship at 0.75 quantiles is also the same as the former regression, which further proves the robustness of our analysis.

Second, this study replaces the overall indicators of green financial development with green credit development indicators. The above regression results show that the positive and negative effects and significance of the core variables green total factor productivity GTFP, trade penetration TRADE, foreign direct investment penetration FDI and

Table 6
Benchmark regression results of quantile model: overall development of green finance.

	Q = 0.25	Q = 0.50	Q = 0.75
GTFP	0.850***	0.605***	0.278***
	(69.110)	(20.050)	(83.020)
$GTFP^2$	−0.102***	−0.058***	0.004***
	(−49.820)	(−10.000)	(7.830)
TRADE	0.485***	0.575***	0.528***
	(14.120)	(29.050)	(100.240)
FDI	−16.126***	−15.128***	−11.758***
	(−42.220)	(−36.530)	(−244.060)
GFIN	−0.282***	−0.408***	−1.852***
	(−3.560)	(−7.460)	(−182.160)
INDUS	−0.461***	−0.805***	−1.507***
	(−13.660)	(−25.390)	(−256.250)
RD	−2.330***	−1.683***	−1.358***
	(−120.940)	(−28.190)	(−288.380)
URBAN	0.407***	1.265***	1.774***
	(8.410)	(47.480)	(107.500)
ENERGY	2.303***	2.966***	2.912***
	(73.740)	(83.600)	(559.550)
Year	Control	Control	Control
Region	Control	Control	Control

Note: Values in parentheses are the t-values. *, ** and *** indicates the significant levels of 10 %, 5 % and 1 %, respectively.

Table 7
Regression results of quantile model: robustness test of green finance with different weights in green finance index.

	Q = 0.25	Q = 0.50	Q = 0.75
GTFP	0.796***	0.457***	0.050***
	(24.300)	(38.080)	(8.360)
$GTFP^2$	−0.111***	−0.025***	0.046***
	(−20.250)	(−12.710)	(36.250)
TRADE	1.507***	1.001***	1.045***
	(90.140)	(33.130)	(105.460)
FDI	−4.540***	−7.183***	−8.738***
	(−28.400)	(−36.190)	(−100.700)
GFIN	−1.284***	−0.822***	0.175***
	(−77.430)	(−26.600)	(19.120)
INDUS	−0.038	0.206***	−1.263***
	(−1.450)	(10.070)	(−46.930)
RD	−1.168***	−1.214***	−1.332***
	(−77.370)	(−67.910)	(−188.630)
URBAN	−1.168***	0.166***	0.143***
	(−36.740)	(3.430)	(7.660)
ENERGY	2.713***	2.737***	3.383***
	(134.260)	(71.000)	(195.880)
Year	Control	Control	Control
Region	Control	Control	Control

Note: Values in parentheses are the t-values. *, ** and *** indicates the significant levels of 10 %, 5 % and 1 %, respectively.

green finance indicator (GFINloan) have not changed, and the robustness of the regression results of the core variables has been verified. Table 8 shows the results of the robustness test of green finance.

5.3. Mediating model: another perspective of carbon peak under international cooperation

It is suggested empirically based on the above regressions, that GTFP has a nonlinear impact on carbon emission. However, as a comprehensive green development indicator, it contains many economic indicators as inputs and outputs, which can be measured, changed, and applied directly. Though the relationship between GTFP and carbon emission has been figured out, how we can change GTFP and whether the method we use to change GTFP will affect CO2 remains unknown. Therefore, to provide more real-life benefits, this study tries to figure out what we can do directly to reduce CO2 in an international communication environment. GTFP is applied as a mediator, and import and FDI penetration are employed as the explanatory variables to see how they can change GTFP to influence CO2. Moreover, playing the role of incentives and transition risk management, green finance can also influence the GTFP and its impact on CO2 has been widely discussed [9,36], while whether it can affect CO2 through GTFP has not gained enough attention. Therefore, this study also uses green finance as the explanatory variable in the mediating test.

The reason why GTFP is selected as the mediator channel is that it is not affected by the changes of other variables, which indicates that its impact on carbon emissions may be more direct. In addition, existing studies have proved that agricultural GTFP has a significant impact on carbon reduction [107], and GTFP is also used as an explanatory variable to study the path of various factors on low-carbon development [62, 73]. In summary, GTFP is more suitable as a mediator channel to explore the possible emission reduction mechanism of each core variable in this study. The model results are shown in Table 9. GFIN, TRADE, and FDI all significantly affect CO2 emissions through GTFP, that is, the mediating effect of GTFP is significant. This proves that GTFP does have a more direct effect on carbon emissions than other core explanatory variables.

Specifically, the green financial development GFIN only has a mediating effect on the path of carbon emissions through GTFP. This may be because the development of the green field in sustainable finance often directly helps to allocate capital to the industries with the highest green marginal efficiency; A t the same time, the green finance development promotes the progress of green clean technology, thus first improving the GTFP of the region and then affecting carbon emissions.

Table 8
Regression results of quantile model: robustness test of green finance with green loan index.

	$Q = 0.25$	$Q = 0.50$	$Q = 0.75$
GTFP	0.806***	0.621***	0.220***
	(628.930)	(31.480)	(555.300)
$GTFP^2$	−0.138***	−0.072***	0.009***
	(−521.750)	(−14.640)	(138.170)
TRADE	1.099***	0.526***	0.690***
	(255.450)	(11.530)	(639.320)
FDI	−6.998***	−10.773***	−9.310***
	(−154.780)	(−7.100)	(−3149.750)
GFINloan	−1.341***	−1.298***	−0.656***
	(−502.530)	(−31.200)	(−1445.080)
INDUS	0.145***	0.183***	−0.780***
	(−31.490)	(2.890)	(−1091.420)
RD	−1.293***	−1.117***	−1.178***
	(−1016.070)	(−24.220)	(−5366.330)
URBAN	−0.691***	0.513***	0.620***
	(−153.750)	(2.720)	(1069.400)
ENERGY	2.117***	2.097***	3.216***
	(1040.280)	(19.370)	(4309.040)
Year	Control	Control	Control
Region	Control	Control	Control

Note: Values in parentheses are the t-values. *, ** and *** indicates the significant levels of 10 %, 5 % and 1 %, respectively.

Similarly, for trade penetration TRADE, its separate impact on carbon emissions is not significant, but there is a significant negative impact on GTFP. This may be due to trade embodied carbon. As imported products are of cleaner technology, import trade is more convenient and cost-saving than domestic industrial transformation and technology upgrading, making it possible to occupy the green industry market in China. If the cost-dependence effect of the industry is greater than the advanced technology spillover effect, the regional enterprises are more dependent on imports, and their own GTFP will be difficult to increase through the increase of trade penetration. The direct and indirect effects of FDI on carbon emissions exist, and there is no masking effect [108,109], as the inflow of foreign capital is more direct than the funds guidance of green finance in promoting green technology innovation in the industry.

5.4. Heterogeneity test

Because the northeast area only includes three provinces, it is not included in the scope of the test. This study explores both the panel quantile regression and the mediating effect of the selected three types of regions, and the results of the panel quantile regression are shown in Tables 10, 11 and 12. The results of the mediating effect are shown in Tables 13, 14 and 15.

5.4.1. Quantile regression in western, eastern, and central regions

Among them, the three types of regions show similar patterns in the path of GTFP, FDI penetration, and energy consumption to CO2: The relationship between GTFP and carbon emissions is inverted “U-shaped” (see Tables 10, 11 and 12). In addition, at the carbon emission 0.5 quantile, GTFP has the most significant impact on it. As far as FDI penetration is concerned, it helps to reduce carbon emissions. At the same time, for China, energy consumption always increases carbon emissions, while R&D expenditure is conducive to carbon emission reduction in most cases. The explanation may be that the essence of GTFP is related to pollution emissions and production efficiency, and the inflows and sources of FDI in various regions of China are roughly similar, that is, mainly from developed countries and flowing into basic industries or technology industries.

In terms of differences, there is a big difference between the trade penetration of eastern and western regions in China for the local low-carbon development. It may be because the largest trading partners of the two are mostly traditional resource exporters, so the embodied carbon in the import industry is more and not conducive to carbon reduction. However, for the central region, the reduction in the influence of trade penetration after the 0.25 carbon quantile has always been conducive to low-carbon development. The reason may be that the trade development in the central region is relatively lagging, and the highly dependent partners are mostly underdeveloped economies, so the embodied carbon in trade is less.

In addition, the development of green finance has a significant negative impact on carbon emissions in the eastern region and has the greatest effect at the 0.75 quantiles. While in the central and western regions of China, it is possible to increase carbon emissions. First of all, from the perspective of the industrial structure, the output value of the heavy industry in the western region accounts for nearly 80 %, and it is difficult to achieve a rational allocation of funds through green financial development. Secondly, from the perspective of the basic conditions of green finance, green finance in the central and western regions started later than that in the eastern regions [110]. Therefore, the lack of financial markets, institutions, and tools makes the development of green finance unable to accurately reduce carbon emissions. In the eastern region, the more reasonable the structure is, the less significant the emission reduction effect is. In the central region, the reason why the impact is always not significant is that environmental regulation in the

Table 9
Regression results of mediational GTFP.

	Model 1			Model 2			Model 3		
	LNCO2	GTFP	LNCO2	LNCO2	GTFP	LNCO2	LNCO2	GTFP	LNCO2
GFIN	0.869**	4.788***	−0.464						
	(1.770)	(8.200)	(−0.930)						
GTFP			0.278***			0.267***			0.213***
			(7.140)			(7.290)			(0.037)
TRADE				−0.162	0.898***	0.078			
				(−0.680)	(−2.990)	(0.350)			
FDI							−12.368***	−14.586***	−9.254***
							(−6.600)	(−6.040)	(−4.920)
CONS	8.415***	0.964***	8.146***	8.478***	1.312***	8.128***	8.863***	1.742***	8.491***
	(31.390)	(3.020)	(31.820)	(31.740)	(3.880)	(31.720)	(33.970)	(5.180)	(32.770)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: Values in parentheses are the t-values. *, ** and *** indicates the significant levels of 10 %, 5 % and 1 %, respectively.

Table 10
Regression results of quantile model in western China.

	$Q = 0.25$	$Q = 0.50$	$Q = 0.75$
GTFP	0.457***	0.722***	0.499***
	(4.800)	(12.870)	(5.710)
$GTFP^2$	−0.214***	−0.248***	−0.186***
	(−8.850)	(−13.490)	(−10.810)
TRADE	−2.269***	−2.005***	3.647***
	(−6.520)	(−8.870)	(11.030)
FDI	−33.964***	−34.477***	−11.610***
	(−20.190)	(−50.850)	(−13.620)
GFIN	−0.137	0.448	3.184***
	(−0.180)	(1.450)	(10.020)
INDUS	1.766***	0.169	−0.324**
	(10.970)	(1.420)	(−2.370)
RD	−2.482***	−2.389***	−1.288***
	(−46.590)	(−58.500)	(−19.280)
URBAN	7.044***	5.030***	3.636***
	(41.790)	(42.280)	(48.310)
ENERGY	0.692***	2.066***	2.266***
	(7.760)	(11.970)	(40.420)
Year	Control	Control	Control
Region	Control	Control	Control

Note: Values in parentheses are the t-values. *, ** and *** indicates the significant levels of 10 %, 5 % and 1 %, respectively.

Table 11
Regression results of quantile model in eastern China.

	$Q = 0.25$	$Q = 0.50$	$Q = 0.75$
GTFP	1.402***	1.137***	1.244***
	(387.250)	(30.440)	(117.560)
$GTFP^2$	−0.170***	−0.158***	−0.162***
	(−247.130)	(−15.880)	(−75.140)
TRADE	2.236***	1.224***	0.642***
	(269.820)	(5.590)	(86.020)
FDI	−16.396***	−12.800***	−10.533***
	(−218.710)	(−17.280)	(−115.500)
GFIN	−0.188***	0.595	−0.748***
	(−15.930)	(3.770)	(−34.720)
INDUS	−6.725***	−1.889**	−1.032**
	(−215.080)	(−1.990)	(−21.040)
RD	0.056***	−0.152	−0.603***
	(17.190)	(−1.430)	(−27.450)
URBAN	−3.514***	−1.815***	−0.768***
	(−197.520)	(−3.510)	(−42.100)
ENERGY	3.928***	3.700***	3.083***
	(513.150)	(22.970)	(104.980)
Year	Control	Control	Control
Region	Control	Control	Control

Note: Values in parentheses are the t-values. *, ** and *** indicates the significant levels of 10 %, 5 % and 1 %, respectively.

Table 12
Regression results of quantile model in middle China.

	$Q = 0.25$	$Q = 0.50$	$Q = 0.75$
GTFP	−0.003	2.164**	2.274
	(0.000)	(2.350)	(1.470)
$GTFP^2$	−0.313	−1.016***	−1.054
	(−1.110)	(−3.170)	(−1.170)
TRADE	−10.201***	−1.884	−5.218*
	(−6.480)	(−1.130)	(−1.740)
FDI	−11.183***	−16.425***	−32.041
	(−4.630)	(−3.910)	(−1.450)
GFIN	10.958***	13.236	7.577*
	(6.380)	(11.210)	(1.830)
INDUS	−0.096	−0.016	−1.444
	(−0.210)	(−0.030)	(−0.380)
RD	−2.198**	−0.400	0.345
	(−2.210)	(0.500)	(0.290)
URBAN	1.903***	−0.991**	3.525
	(3.250)	(−2.310)	(0.950)
ENERGY	4.182***	4.048***	3.155***
	(12.200)	(24.470)	(3.320)
Year	Control	Control	Control
Region	Control	Control	Control

Note: Values in parentheses are the t-values. *, ** and *** indicates the significant levels of 10 %, 5 % and 1 %, respectively.

eastern region inhibits economic growth through industrial rationalization and slows down the emission reduction process [111].

5.4.2. The mediating model of the western, eastern and central regions

Tables 13, 14 and 15 present the mediation analysis results. In general, the channel effect of green finance development and trade penetration on carbon emissions through GTFP in the eastern region of China is the most significant. The masking effect of green finance and trade penetration in the western region is very significant, while the indirect effect of green finance and FDI penetration in the central region is not significant.[2]

Firstly, there are differences in the way green finance affects carbon emissions through GTFP between the East and the West. The development of green finance in the western region has a masking effect, that is, after controlling GTFP, the impact of green finance development on carbon emissions in the western region will be further expanded. However, for the eastern region, GTFP has only a mediating effect on green finance. The indirect effect of the channel in the central region does not exist. These differences may be due to the unbalanced and time-lag development of green finance in the central, eastern, and western regions of China, which started late and had few norms in the western and central regions.

[2] The indirect effect is judged by Sobel test. If the p-value is less than 0.05, the mediating effect is considered to be significant.

Table 13
Regression results of the mediation model of green finance.

	Western region sobel 0.03			Eastern region sobel 0.00			Central region sobel 0.2		
	LNCO2	GTFP	LNCO2	LNCO2	GTFP	LNCO2	LNCO2	GTFP	LNCO2
GFIN	0.456	2.704**	1.738	3.273***	8.403***	0.170	8.915***	7.474***	11.186***
	(0.340)	(2.260)	(1.380)	(4.790)	(8.780)	(0.230)	(5.650)	(11.160)	(4.410)
GTFP			−0.474***			0.369***			−0.304
			(−5.580)			(6.970)			(−1.140)
CONS	7.594***	0.424	7.795***	6.690***	−5.090***	8.570***	5.555***	1.553***	6.027***
	(22.300)	(1.410)	(24.950)	(6.360)	(−3.450)	(9.090)	(11.180)	(7.360)	(9.330)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: Values in parentheses are the t-values. *, ** and *** indicates the significant levels of 10 %, 5 % and 1 %, respectively.

Table 14
Regression results of mediation model of trade penetration.

	Western region sobel 0.02			Eastern region sobel 0.00			Central region sobel 0.06		
	LNCO2	GTFP	LNCO2	LNCO2	GTFP	LNCO2	LNCO2	GTFP	LNCO2
TRADE	−0.726	−3.344**	−2.338*	−0.600*	−3.562***	1.050***	−6.758***	−3.502***	−5.328***
	(−0.480)	(−2.540)	(−1.680)	(−1.740)	(−7.460)	(3.310)	(−3.990)	(−3.520)	(−2.990)
GTFP			−0.482***			0.463***			0.408**
			(−5.670)			(9.600)			(2.170)
CONS	7.727***	1.071***	8.243***	8.993***	−1.108	9.506***	4.594***	0.531*	4.377***
	(19.590)	(3.090)	(22.280)	(9.160)	(−0.820)	(12.520)	(9.800)	(1.930)	(9.340)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: Values in parentheses are the t-values. *, ** and *** indicates the significant levels of 10 %, 5 % and 1 %, respectively.

Table 15
Regression results of a mediation model of FDI penetration.

	Western region sobel 0.01			Eastern region sobel 0.00			Central region sobel 0.8		
	LNCO2	GTFP	LNCO2	LNCO2	GTFP	LNCO2	LNCO2	GTFP	LNCO2
FDI	−27.524***	13.927***	−22.564***	−22.841***	−27.901***	−16.499***	−12.155***	0.603	−12.534***
	(−5.840)	(3.060)	(−4.930)	(−10.410)	(−6.730)	(−7.170)	(−2.710)	(0.220)	(−3.000)
GTFP			−0.356***			0.227***			0.630***
			(−4.440)			(5.480)			(3.600)
CONS	7.632***	0.584**	7.840***	7.950***	0.321	7.877***	5.000***	0.126	4.921***
	(25.620)	(2.030)	(27.550)	(11.160)	(0.240)	(12.190)	(8.220)	(0.340)	(8.680)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: Values in parentheses are the t-values. *, ** and *** indicates the significant levels of 10 %, 5 % and 1 %, respectively.

The trade penetration in the western region has a significant masking effect, and the single effect coefficient of −0.726 is not significant. The separate effect coefficient of trade penetration in the eastern region is −0.6, but not significant enough, and −3.562 * 0.463 and 1.050 are different signs, indicating the masking effect. The level of economic development and internal integration in the western region is lower than those in the central and eastern regions, so trade penetration cannot directly increase GTFP.

The trade penetration in the central region shows a partial mediating effect under the premise of 5.328 significance. There may be other mediating channels, such as scale expansion and production structure adjustment. The two types of potential channels are reflected in the fact that after the central region undertook the industries transferred from the east around 2010, it imported more intermediate goods, which helped to adjust its mode of production and form economies of scale [112].

FDI penetration in the eastern and western regions has a partial mediating effect. In general, FDI penetration may achieve carbon emission reduction by accelerating technological progress and innovation, or reduce CO2 levels by regulating environmental regulation effect. Therefore, in the eastern region where FDI flows more into capital-intensive industries, it will be more obvious to reduce emissions through technological innovation. In the West, CO2 is reduced due to the expansion of production scale caused by FDI.

6. Conclusion, implications, and research deficiencies

6.1. Conclusion

By establishing a possible carbon peak mechanism model in China, this study further explores the possible development path of GTFP, trade, FDI, and green/sustainable finance, and how they can have a positive impact on carbon emission reduction. It draws the following conclusions:

Firstly, according to the panel quantile model of fixed effect, although GTFP in China is an inverted "U-shaped" within a certain level of CO2 total emission, the GTFP in the late peak period has a more significant effect on achieving carbon neutrality. When the total CO2 goes beyond a certain level, the relationship becomes a significant "U-shaped" version. In addition, trade penetration and FDI penetration have opposite effects on carbon emissions in China. FDI has a significant negative impact while trade penetration is positive.

Secondly, based on the quantile regression, the overall development of sustainable finance is expected to greatly reduce carbon emissions in China, and it will be more significant after reaching a carbon peak (i.e. a certain threshold of CO2). It is specifically reflected in the green finance field. In addition, the development of green finance in various regions is one of its characteristics, which also leads to the fact that the green credit index can not accurately measure the overall development of green finance. The overall development of the green field of sustainable finance will help clean technology generation and innovation and limit the further output of high-energy-consuming industries through funds guidance, thereby reducing carbon emissions.

Thirdly, in another detailed way, the study verifies that GTFP has a significant impact on carbon emissions as a mediating variable, as trade penetration and the development of green fields in sustainable finance have a significant effect on carbon emissions through GTFP. What may explain why the indirect effect is often greater than the direct one is that GTFP is more affected by FDI, trade, and green finance, which directly contributes to low-carbon development. Therefore, as a key measurement index in the process of carbon peak, GTFP can not only directly affect the process, but also help to achieve carbon peak by being affected by other factors.

Fourthly, in the eastern region, the advancement of the green field development process in sustainable finance has a significant impact on reducing CO2, and carbon emission reductions are significantly achieved by increasing GTFP. In addition, its trade penetration is not conducive to reducing the level of pollution emissions, and GTFP has a masking effect currently. The upgrading of industrial structure is consistent with the overall situation in China and has little effect on carbon emission reduction. However, for the central and western regions, the development of the green field in sustainable finance has no significant impact on CO2. At the same time, because the export types of the central and western regions are mostly resource products, the strengthening of trade penetration has effectively promoted the process of carbon emission reduction. However, the mediating mechanism of green finance and trade penetration on GTFP is not significant enough.

6.2. Policy implications

Drawing on the path experience of countries that have achieved carbon peak and combined with the actual emission reduction process in China and relevant regional differences, this study puts forward the potential suggestions for China and other developing countries to the low-carbon transition.

Firstly, at the macro level, central banks and ministries need to further improve the regulatory framework and measures in sustainable and green finance to cope with the frontier development, such as the Sustainable Finance Action Plan in the EU, gradually refining it to the industry, and financial product guidance. At the same time, at the industry level, it is necessary to strengthen the construction of industry self-discipline organizations and promote the improvement of mutual supervision mechanisms. At the market level, the government needs to not only ensure the steady improvement of the quantity and quality of green financial instruments and markets but also encourage the diversification of green financial products and improve environmental disclosure. In addition, China can incorporate more industries into the carbon market mechanism and ensure the gradual increase of carbon emissions trading volume.

Secondly, to be part of the general international sustainable finance cooperation, FDI can reduce CO2 in most cases and boost GTFP. Hence, China and other developing countries need to direct foreign investment towards clean and high-tech industries, leveraging the innovative effects of clean technology and its spillover. Simultaneously, domestic capital of all kinds needs to be motivated and incorporated with FDI, focusing on emerging technologies and "double carbon" related industries. Mobilizing the "domestic circulation" of trade is crucial to establishing a sustainable link between the financial market and the real economy. Additionally, a key focus should be placed on enhancing production efficiency while advocating for the comprehensive and recycled use of resources in developing countries. Moreover, it is essential to address the regional differences, driving carbon emission reduction in traditional industries as well as the development of clean industries in developing regions, such as the western part of China.

Thirdly, trade penetration in China can hinder carbon reduction when CO2 reaches 0.75 quantiles, probably because China is responsible for more carbon-intensive production and processing than developed countries. So, developing countries' companies can shift their business focus to R&D expenditure and imports, which help reduce carbon emissions from production through technological advancements, and limit the negative environmental externalities of participating in the international division of labor. With great differences in geographical conditions and economic development in different regions of China, attention to the diversification of trade types is suggested. For example, for the eastern region, imports need to be expanded to prevent the rebounding environmental effects of export-driven polluting products, which may raise the CO2 level. Further, encouraging the imports and exports of high-tech industrial products can enhance CO2 reduction by establishing a free, clean, and sustainable trade pilot area to form a local "dual-circulation" to reach the carbon peak.

Based on all the above, energy efficiency should be the cornerstone of the low-carbon transition. To achieve this, we need a market-driven approach that balances supply and demand, internalizes pollution costs, and invests in digital and intelligent systems. Building new energy infrastructure and encouraging innovation in clean energy technologies are also essential for most developing countries. In terms of international cooperation, China and other developing countries can actively carry out dialogue with EU countries on sustainable finance and carbon market construction, while paying attention to the establishment and improvement of the carbon border adjustment tax. They can also strengthen their interaction with international climate, environment, and other organizations, acquire cutting-edge experience and knowledge, and have the courage to assume the responsibility of a great power.

6.3. Research deficiencies and future directions

Regarding the fast development of climate change-related research and policy roll out, this study has several deficiencies that can be improved in future studies. First, this study only focuses on provinces in China, while the CO2 reduction should be a global effort; the national difference is larger than the provincial difference within one country. Future studies can integrate more country-level data to analyze the carbon peak route. Second, given the data limitations, our analysis has a limited time span. Considering that China introduced the Emission Trading Scheme (ETS) in recent years, which may have a significant impact on the GTFP as well as CO2. Therefore, future studies could include the ETS to further identify the updated carbon peak path. Finally, the measurement of GTFP in this study is only from the SO2 perspective, while it can also be measured by other outputs. Hence, future studies could expand the output variable in GTFP measurement.

CRediT authorship contribution statement

Lu Wan: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Yanxi Zhou:** Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Ying Wang:** Writing – original draft, Visualization, Investigation, Formal analysis. **Tiantian Zhao:** Writing – original draft, Visualization, Investigation, Formal analysis.

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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Data availability

Data will be made available on request.

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