The impacts of green finance on regional carbon emission: Evidence from China

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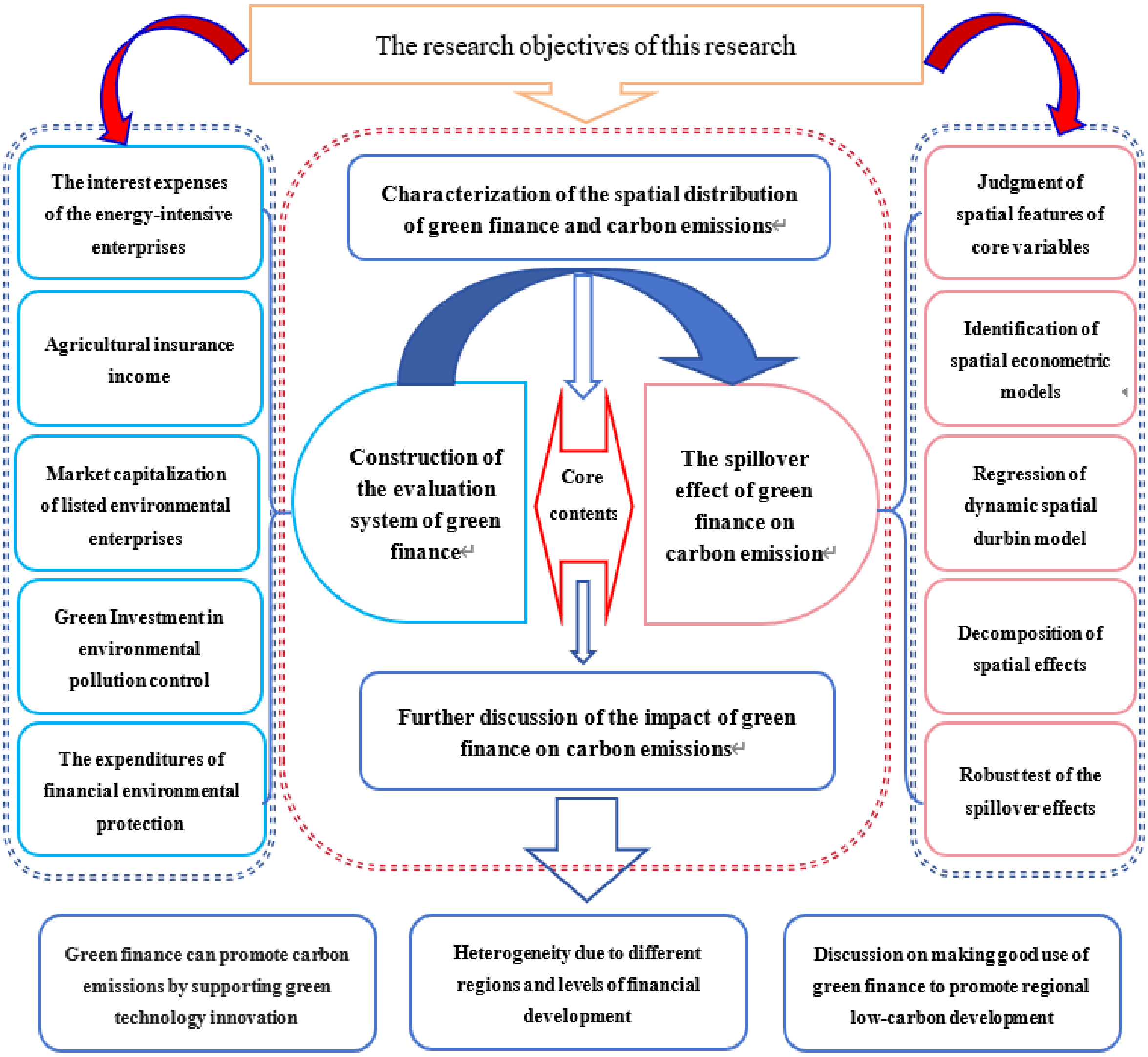
Graphical abstract:



Abstract: Green finance has become an important tool for the low-carbon development in China. This research constructs a comprehensive indicator system, and describes the spatial characteristics of green finance and carbon emissions in China from 2012 to 2021. Then, the dynamic SDM and the mediating effect model are used to explore the spatial spillover effect and the mechanism. The research finds that carbon emission levels are generally higher in the north of China, and the level of green finance shows a spatial distribution of higher in the east and lower in the west. Moreover, green finance can significantly reduce carbon emissions in the presence of spatial spillovers with heterogeneity. For 1% increase in green finance within the region, per capita carbon emissions are reduced by 0.68% in the short term and 0.60% in the long term, and by 0.75% in the short term and 0.33% in the long term in the surrounding areas. In addition, green technology innovation has become an important way for green finance to boost low-carbon development. This research provides a reference for the differentiated formulation of green finance policies.

Keywords: Carbon emission; Green finance; Spatial spillover effect; Green technology innovation

1. Introduction

Climate change is a challenge for all of humanity, and the future of the planet depends on tackling it successfully. After the industrial revolution, which led to rapid economic growth, global carbon emissions have increased significantly, and environmental problems such as melting glaciers and the greenhouse effects ave become increasingly serious. More than 130 countries and regions have announced carbon neutrality targets in an effort to address this problem that plagues all of humanity. Moreover, since the 1970s, governments and organizations, led by developed countries, have carried out a variety of attempts and explorations on green finance, and a relatively mature green financial system has been formed today. A communique issued by the WMO states that global CO_2 concentrations in 2022 will be 50% higher than the pre-industrial. Global energy-related CO_2 emissions increased by 0.9% year-on-year, significantly lower than the global economic growth (3.2%), with total emissions of about 36.8 billion tons. It hit a record high, but was still below expectations. What's more, the widespread application of green innovations reduces the actual growth in carbon emissions by about 60% in 2022 compared with the potential growth. Is the declining growth rate of global carbon emissions attributable to the advancement of green finance? In order to achieve the goal of "carbon neutrality" at the earliest possible date, it is crucial to determine whether and how green finance can influence regional carbon emissions.

As one of the largest emitters in the world, China has a great responsibility. Due to the backwardness of science and technology, the consequence of rapid economic development is the over-consumption of energy, resulting in low energy efficiency and high pressure on the natural environment. As one of the strongest powerhouses of the world's economic development over the past three decades, China's carbon emissions have shown rapid growth in tandem with economic growth in terms of total emissions. In response to this natural environmental challenge, China proposed the strategy to peak carbon emissions and achieve carbon neutrality in 2020, which implies a broad and deep systemic revolution. Since then, China has entered a new stage of development focusing on energy conservation and emission reduction. Before 2000, China had carried out a large number of green financial activities to promote the coordinated development of the economy, resources and the environment. Over the years, China has formed a diversified market and policy system of green financial products. Through market-oriented financial means, green finance will effectively move the governance port forward, effectively inhibit polluting investments, promote the green technological advances. It has become a powerful tool to support low-carbon development and realize the carbon peak and neutrality targets in China (Dingbang et al., 2021; Wang and Wang, 2021).

The literature related to this topic focuses on three main areas: first, most of the studies have explored the relationship between carbon emissions and green finance from the aspects of financing supports and resource allocation (Irfan, 2022; Song et al. 2022), and few scholars have studied the spatial spillover effects. Second, the environmental improvement effect of green innovation has been explored by many scholars (Li and Zhang, 2023), as well as the relationship between green finance and green innovation (Hu et al., 2021; Wang et al., 2022), but the conclusions of the latter have not yet been unified. Third, the heterogeneity of the spillover effect. Different regions can result in different development, triggering spatial heterogeneity in emission reduction (He et al., 2023). However, there are few studies on temporal heterogeneity.

Based on the inadequacy of existing research, the marginal contributions of this research are: firstly, green finance and carbon emissions are included in a unified research framework, and the spillover effect of green finance on carbon emission reduction is analyzed, which expands the research perspectives and scope of green finance. Secondly, from the perspective of green technology innovation, we establish a mediation effect model to explore how green finance promotes regional carbon emission reduction through its “reward and punishment” characteristics; thirdly, from the perspective of geographic location and temporal heterogeneity, we empirically examine the strong and weak effects of green finance development on carbon emission in regions with different levels of per capita carbon emission, which provides a good basis for the development of differentiated green finance from the perspective of green finance and carbon emissions. It provides a decision-making basis for formulating differentiated policy measures from the perspective of green finance to boost green and low-carbon development.

This research attempts to answer these questions: First, is there a spatial spillover effect of green finance on emission reduction? Second, can green technology innovation act as a mediating variable to transmit the impact of green finance on carbon emissions? Third, is there temporal and spatial heterogeneity in the spatial spillover effect?

2. Literature and hypothesis development

2.1 Green finance and carbon emission

With the increasing emphasis on global attention to environmental issues, green finance has emerged, which is not fundamentally different from traditional finance (Lee and Lee, 2022). However, the pursuit of the environment goals seems to be the most significant distinction between them (Zerbib, 2019). Green finance is able to alleviate environmental problems through various financial instruments. Initial studies have utilized single product or policy to measure green finance to explore its environmental benefits (Zhang et al., 2021; Pang et al., 2022).

Considering the dominant position of green credits and green bonds in the market, current research mostly focuses on them. The emission reduction effect of green credit is significantly superior to that of green bonds and has stronger environmental value. It can force heavily polluting firms to transform into green through financing constraint channels (Chai et al, 2022; Lu et al., 2022), and suppress the output of energy-intensive industries in the short term (Wang et al, 2023). Green bonds are designed to alleviate issuers' financing constraints in order to encourage them to allocate more resources to green innovation and other carbon reduction efforts (Wang et al, 2022). The reason for this disadvantage is due to the existence of greenwashing risk, where firms divert funds originally allocated for green projects towards more profitable ventures, thereby undermining the unique environmental benefits of green bonds (Xu et al., 2022; Ghaemi et al., 2023).

Over the years, green finance products have diversified in high quality, giving rise to various products. The measurement of green finance development is no longer limited to a single indicator, but a diversified evaluation system has been developed to explore the carbon emissions reduction effect of green finance. (Fan et al, 2021; Zhang et al., 2022; Yin and Xu, 2022). Green finance can guide funds towards green industries, support the development of environmentally friendly enterprises. It can also improve the structure of the energy industry, and optimize fund allocation to achieve the goal of sustainable development (Ran and Zhang, 2023). Additionally, positive externality, as an important characteristic of green finance, cannot be ignored in terms of its spillover effects on surrounding provinces, which usually manifests itself as a positive spatial spillover effect (Wan et al., 2023).

Therefore, H1 is proposed: green finance has spatial spillover effects and can reduce carbon emissions in neighboring regions.

2.2 Green finance, green innovation and carbon emission

Green technological innovation, as an important driving force for improving environmental quality, has made significant contributions to carbon reduction through environmentally friendly products and technologies (Umar and Safi, 2023; Chang et al., 2023). Green innovation can help enterprises to improve resource production and consumption methods, thereby reducing emissions and saving costs (Cheng et al., 2021).

However, green innovation inevitably faces a significant funding gap, and the market itself is not effective in bridging this gap and promoting green innovation (Rennings and Rammer, 2011). As a result, green finance plays a crucial role when the willingness of businesses to engage in green innovation is not strong. It supports the innovation of environmentally friendly enterprises through financing constraints while penalizing the high-emission polluting companies (Lu et al., 2022; Bai and Lin., 2024).Simultaneously, green finance can facilitate inter-sectoral cooperation, reduce the cost of resource matching, and enhance the willingness and competitiveness of enterprises to engage in green innovation (Huang et al., 2022). On the other hand, the financing constraints of green finance also hinder the financing of heavy polluters and reduce their R&D expenses, thus inhibiting green innovation (Yu et al., 2021). Therefore, it remains uncertain whether green technology innovation can act as a mediating variable to transmit the impact of green finance on carbon emissions

Accordingly, H2 is proposed: By promoting green innovation, green finance can realize carbon emission reduction.

2.3 Heterogeneity of the spatial spillover effect

Al Mamun et al. (2022) explored the carbon emissions reduction effect of green finance from a long and short-term perspective in 46 countries around the world. They concluded that the long-term impact of green finance on carbon emissions is greater than the short-term, and is more pronounced in countries with developed credit markets and higher climate risk. However, when green bonds are used as the independent variable instead of green finance, the conclusion is opposite.

Green finance development in China exhibits heterogeneity among regions, showing a trend of polarization between north and south (Lv et al., 2021). Similarly, carbon emissions also exhibit this characteristic, with larger carbon emissions in provinces such as Inner Mongolia, Jiangsu, and Hebei, which develop their economies mainly through manufacturing (Zhou et al., 2023). There are significant differences in policies, technologies, industrial structures, and natural resources among different geographical regions, which may lead to heterogeneity in the spatial spillover effects (Ran and Zhang, 2023).

In summary, H3 is proposed: there is heterogeneity in the spatial spillover effects in both the temporal and spatial dimensions.

Green finance has been proven by scholars from various angles and using various methods to be able to regulate resource allocation, promote industrial structure upgrading, and assist in carbon emission reduction. Nevertheless, few scholars have considered the positive externality and spillover effects of green finance in exploring its role in carbon emission reduction in neighboring regions. Moreover, the carbon emission reduction effect of green innovation has been tested in global emission reduction practices. However, there is still disagreement among scholars regarding whether green finance can achieve the mechanism of carbon emission reduction by promoting green technological innovation. In addition, due to the heterogeneity in the distribution of green finance and carbon emission, the spatial spillover effect in different regions is also still unclear, requiring further research and exploration.

3. Methodology and data sources

3.1 Methodology

(1) The spatial weight matrix is crucial for constructing spatial models. Following the principle of simplicity and extensiveness of matrix setting (Lesage and Pace, 2009), this research mainly constructs the spatial adjacency matrix, geographic distance matrix, and nested matrix as spatial weight matrices. Spatial adjacency matrix W_1, $W_1=\left[W_{ij}\right]$, when $i \neq j, W_{ij}=1$, $i=j, W_{ij}=0$; Geographic distance matrix W_2, $W_2=\left[W_{ij}\right]$, when $i \neq j$, $W_{ij}=d_{ij}^{-1}$, $i=j, W_{ij}=0$; Nested matrix W_3, $W_3=\left[W_{ij}\right]$, when $i \neq j, W_{ij}=\left(GDP_i \times GDP_j\right) d_{ij}^{-1}$, $i=j, W_{ij}=0$. where d_{ij} is the distance between the centers of provinces i and j, and GDP_i and GDP_j are the annual averages of GDP in provinces *i* and *j* during the sample period. In order to avoid the situation that Hainan has no neighboring provinces, Guangdong and Hainan are set as neighbors.

(2) Spatial correlation analysis. Before conducting the spatial empirical analysis, the spatial relevance of the variables should be examined to ensure that they are applicable to the spatial econometric analysis. The global Moran's *I* is applied to examine the global spatial agglomeration of per capita carbon emissions as well as green finance in China. The local Moran's I_i is introduced to further identify the local spatial agglomeration. The formulas of

global and local Moran's I are given in the following equation:

$$I=\frac{\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}(x_i-\bar{x})(x_j-\bar{x})}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}} \quad (1)$$

$$I_i=\frac{(x_i-\bar{x})}{S^2}\sum_{j=1}^{n}w_{ij}(x_j-\bar{x}) \quad (2)$$

$$S^2=\frac{\sum_{i-1}^{\mathrm{n}}(x_i-\bar{x})}{n} \quad (3)$$

where w_{ij} is the spatial weight matrix, x_i is the per capita carbon emission or green finance index of province i, n represents the number of provinces, and S^2 is the sample variance.

(3) Econometric model. In order to explore the impact of green finance on carbon emissions, this research constructs the following baseline regression model as Eq. (4):

$$\ln CE_{it}=\alpha+\alpha_1\ln GF_{it}+\alpha_2\ln Control_{it}+\varepsilon_{it} \quad (4)$$

Where i represents the province, t represents the year, $\ln CE_{it}$ and $\ln GF_{it}$ are the natural logarithm of per capita carbon emissions and green finance development, and the control variables include population, economy, education, industry and trade.

It has been shown that there is a spatial correlation in carbon emissions between different regions in China, and ignoring the spatial factors will lead to biased research results (Yan et al., 2022). Therefore, the research mainly constructs a spatial model to investigate the effect of green finance on carbon emissions. We establish the following dynamic SDM for subsequent empirical analysis, which can analyze spillover effects from both a long-term and short-term perspective and mitigate endogeneity problems:

$$\ln CE_{it}=\alpha+\rho\sum_{j=1}^{n}W_{ij}\ln CE_{jt}+\beta\ln X_{it}+\lambda\sum_{j=1}^{n}W_{ij}\ln X_{jt}+\mu_i+v_t+\varepsilon_{it} \quad (5)$$

$$\ln CE_{it}=\alpha+\theta\sum_{j=1}^{n}W_{ij}\ln CE_{j(t-1)}+\sigma\ln CE_{i(t-1)}+\rho\sum_{j=1}^{n}W_{ij}\ln CE_{jt}+\beta\ln X_{it}$$

$$+\lambda\sum_{j=1}^{n} W_{ij} \ln X_{jt} + \mu_i + v_t + \varepsilon_{it} \tag{6}$$

Eq. (5) is the SDM, X_{it} contains the independent variable and control variables, ρ is the spatial lag coefficient of the dependent variable. W_{ij} is the element in the spatial weight matrix, u_i and v_t are the individual and time fixed terms, and ε_{it} is the random error term. Eq. (6) which is the dynamic SDM adds spatial and temporal lag terms to the Eq. (5), and θ and σ are their coefficients.

In addition, a mediation effect model with green innovation as a mediating variable will be constructed to verify the mechanism of "green finance-green innovation-carbon emission", where $Mediating_{it}$ represents the green innovation:

$$\ln CE_{it} = a_0 + a_1 \ln GF_{it} + a_2 \ln Control_{it} + \mu_i + v_t + \varepsilon_{it} \tag{7}$$

$$\ln Mediating_{it} = b_0 + b_1 \ln GF_{it} + b_2 \ln Control_{it} + \mu_i + v_t + \varepsilon_{it} \tag{8}$$

$$\ln CE_{it} = c_0 + c_1 \ln GF_{it} + c_2 \ln Control_{it} + c_3 \ln Mediating_{it} + \mu_i + v_t + \varepsilon_{it} \tag{9}$$

3.2 Variable declaration

3.2.1 Independent variable: *GF*

Referring to the current literature (Lee and Lee, 2022), this research constructs a comprehensive system based on the five dimensions to measure green finance (Table 1). Then, we apply the entropy method to measure provincial green finance index from 2012 to 2021 in China. Fig. 1 shows the spatial distribution of green finance levels. Overall, the development level of green finance has improved in the past decade, with the focus on the development in the eastern coastal regions. The spatial distribution shows a gradual decline from east to west. However, the enhancement of the level of green finance in the northern region is not obvious, indicating the necessity of realizing the development of green finance in the current stage.

Table 1 green financial index system

Variables	Definitions	Directions
Green credit	The interest expenses of the six energy-intensive enterprises to the whole industries	-
Green investment	Investment in environmental pollution control/GDP	+
Green insurance	Agricultural insurance income/gross agricultural output	+
Green securities	Market capitalization of LEE to the total market capitalization of listed enterprises	+
Governmental support	Financial environmental protection expenditures/financial general budget expenditures	-

LEE: listed environmental enterprises

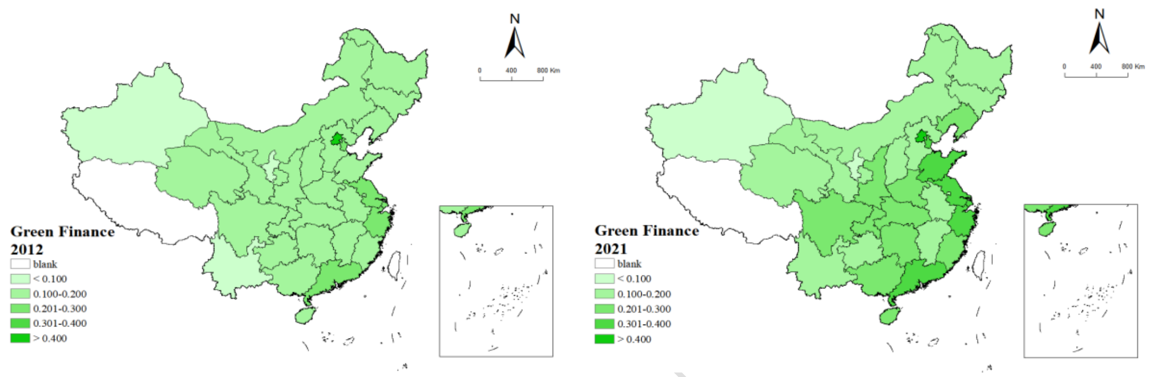


Fig.1. Spatial distribution of the green finance development in 2012 and 2021

3.2.2 Dependent variable: *CE*

This research uses per capita carbon emissions as a dependent variable to measure the carbon emission, which is measured by the ratio of total provincial CO_2 emissions to regional resident population.

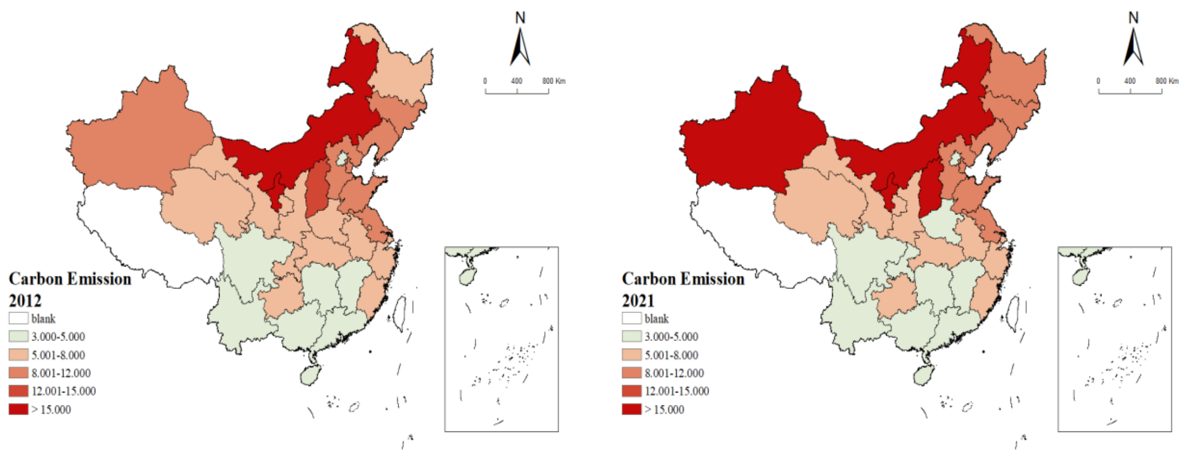


Fig. 2. Spatial distribution of the level of carbon emission per capita in 2012 and 2021

As far as the spatial distribution of carbon emissions in Fig. 2 is concerned, high carbon emission regions are mainly concentrated in the north of China, and their carbon emissions have also increased significantly over the past decade. Carbon emissions in the three pilot zones for green financial reform and innovation, including Guangdong, Guizhou and Zhejiang, have declined, indicating the effectiveness of green financial policies. Horizontally, per capita carbon emissions have gradually declined from north to south, probably due to the fact that the direction of development in the northern region is dominated by heavy industry, leading to greater heterogeneity compared with the southern regions.

3.2.3 Control variables

This research refers to the existing literature (Ran and Zhang, 2023; Zhu et al., 2023) and controls for the following variables:

Population (*POP*) expansion increases business demand, which naturally leads to an increase in carbon emissions, represented by the year-end resident population.

Economic development is measured by GDP per capita (*Pgdp*), and considering the inverted U-shaped relationship between the economic development and carbon emissions (Liao and Cao, 2013), this research introduces the quadratic term of it.

The export of energy-intensive products may cause more pollution, but the strict environmental regulation brought about by increased openness in turn leads to positive externality (Du et al., 2012). Therefore, the net effect of trade openness on carbon emissions depends on the relative strength of each role, and it is represented by the total amount of imports and exports/GDP (*Open*) in each province.

The level of education (*Edu*) determines the strength of its environmental awareness, which represents by the average years of education in each province.

The changes in the industrial structure (*IS*) have led to a significant increase in the efficiency of the production sector, which is a key strategy for realizing environmental protection and economic growth (Hu et al., 2023; Lin and Liao, 2023). Therefore, we use the ratio of the value added of the secondary industry to the GDP to measure it.

3.2.4 Mediating variable

Green low-carbon development should be led by innovation. Therefore, we choose green innovation (*GI*) as the mediating variable. Referring to Irfan et al. (2022), this research calculates the total number of green patents by summing up the number of utility model patents and green invention, and uses it per 10,000 people to measure green innovation in each province.

3.2.5 Sample data and descriptive statistics

Carbon emissions data are from the MEIC of the Ceads. The green finance index is calculated based on data from the China Statistical Yearbook, China Industrial Statistical Yearbook, China Environmental Statistical Yearbook and CSMAR database. Other data sources are from the Wind. All missing data are filled in using the interpolation method. In addition, to exclude the influence of price factors, GDP per capita is deflated to the baseline level of 2012, and all variables are logarithm zed.

Since 2012, the CBRC has issued and gradually refined the Green Credit Guideline, making them a guiding and programmatic document for the green credit system. More financial institutions have launched green credit, and green financial products have become increasingly abundant. Under the promotion of regulatory policies, the number of banks entering the green finance market has begun to increase. At the same time, China clearly proposed to vigorously promote the construction of ecological civilization. Therefore, the sample interval set in this research is from 2012 to 2021, and limited to the availability of indicator data and the consistency of statistical caliber, the research sample only includes 30 mainland provinces and cities except Tibet. Table 2 gives the descriptive statistics of variables.

Table 2 Descriptive statistics

Variables	N	S.D.	Max	Min
CE	300	5.62	34.66	3.26
GF	300	0.117	0.86	0.07
POP	300	28.59	126.84	5.71
Pgdp	300	2.91	18.75	1.89
Open	300	27.22	135.41	0.76
Edu	300	1.05	13.34	7.05
IS	300	7.88	58.65	15.87

4. Results and discussion

4.1 Spatial correlation test

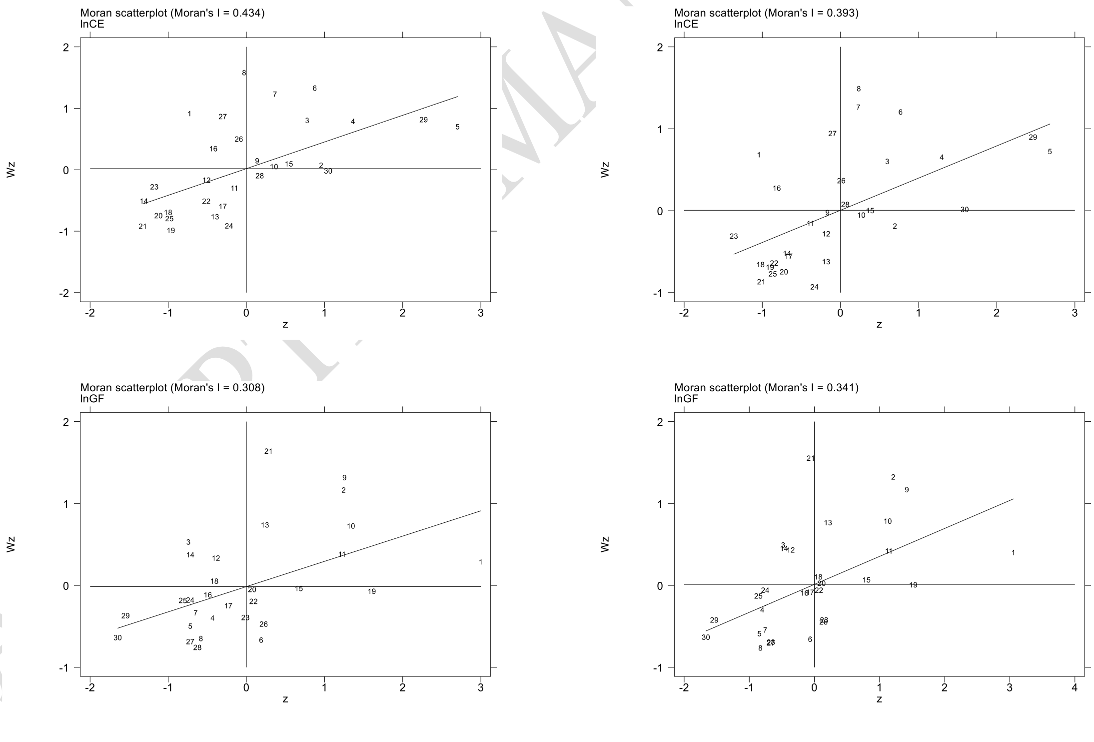
(1) Global correlation test. Based on the spatial adjacency matrix, the global Moran's I is used to measure the spatial correlation of carbon emissions and green finance in China, and the results are shown in Table 3. From 2012 to 2021, the Moran's I of carbon emissions and green finance are both significant at the 1% level and are greater than 0. It indicates that the variables have positive spatial correlation, the high-level regions are clustered together. Therefore, the variables meet the characteristics of spatial measurement and can be analyzed in the subsequent spatial analysis.

Table 3 Global correlation test results

Year	ln *CE*			ln *GF*		
	Moran's I	z-value	p-value	Moran's I	z-value	p-value
2012	0.434	3.877	0.000	0.308	2.866	0.004
2013	0.436	3.869	0.000	0.294	2.749	0.006
2014	0.437	3.873	0.000	0.293	2.759	0.006

2015	0.421	3.748	0.000	0.303	2.835	0.005
2016	0.428	3.790	0.000	0.274	2.661	0.008
2017	0.372	3.362	0.001	0.275	2.632	0.008
2018	0.377	3.407	0.001	0.326	3.036	0.002
2019	0.376	3.414	0.001	0.336	3.112	0.002
2020	0.387	3.509	0.000	0.339	3.13	0.002
2021	0.393	3.560	0.000	0.341	3.155	0.002

(2) Local correlation test. In order to visualize the spatial clustering of the variables, this research plots the Moran scatter plots of each region in 2012 and 2021, as shown in Fig. 3. Specifically, the points are distributed in the first and third quadrants, showing the characteristics of "both high" and "both low" clustering pattern. It indicates that there is a spatial aggregation of the variables. In conclusion, it is necessary to conduct empirical analysis from a spatial perspective to study the impact of green finance on carbon emissions.



2012 2021

Fig. 3. Moran scatter plot of carbon emissions and green finance in 2012 and 2021

4.2 Identification of spatial econometric models

The spatial correlation test can only be used as a preliminary basis for conducting spatial econometric analysis. The LM test and the robust LM test is needed to make further judgments on whether there are spatial effects of the model. Subsequently, LR and Wald tests were conducted to select the specific form of the spatial model, and the results are shown in Table 4.

Table 4 Optimal model identification

	Statistical value	p-value
LM-Log	36.31	0.000
Robust LM-Log	55.73	0.007
LM-Error	88.54	0.012
Robust LM-Error	146.52	0.000
LR-Log	55.06	0.000
LR-Error	63.71	0.000
Wald-Log	11.18	0.071
Wald-Error	19.52	0.005
Husman	21.78	0.014

The results show that all tests are significant at the 10% significance level, rejecting hypothesis that the model does not contain spatial lag and spatial error terms. It indicates that the SDM cannot be degraded into the SLM and SEM, and it is necessary to introduce spatial effects. Therefore, the fixed effects SDM is more suitable for the empirical analysis.

4.3 Analysis of the model regression results

Tables 5(1)-(3) control for provinces, years and the both. Referring to the joint significance test of the models, the both fixed SDM explains the variables better and has the highest goodness of fit (R^2=0.627). Therefore, the subsequent analysis was mainly conducted based on Table 5(2). It is found that the ρ is 0.412, which is significant at the 1% significance level, indicating that there is a strong spatial correlation of carbon emissions in China. The per capita carbon emissions of a certain region will be influenced by its neighboring regions.

In addition, the coefficients of the lag term of carbon emissions are also positive, indicating that the carbon emissions in the previous period will negatively affect the carbon emissions in the current period. The coefficient of W×ln*CE*(-1) is significantly negative, which indicates that the growth of per capita carbon emissions in the lagged period in the neighboring regions will have a significant negative impact in the region. This shows that the carbon emission reduction has a long way to go and requires long-term planning.

Table 5 regression results

Variables	(1)	(2)	(3)
W×ln*CE*(-1)	0.198^{*} (1.32)	0.273^{**} (2.44)	-0.016 (-0.91)
ln*CE*(-1)	0.264^{**} (2.49)	0.037 (0.66)	0.301^{****} (4.48)
ln*GF*	-0.575^{***} (-3.94)	-0.746^{***} (-6.72)	-0.526^{***} (-6.86)
W×ln*GF*	-0.441^{**} (-2.25)	-0.573^{**} (-2.44)	-0.194 (-0.82)
ln*POP*	1.538^{***} (3.48)	0.508^{**} (2.11)	0.977^{***} (3.47)
W×ln*POP*	0.755^{*} (1.07)	-0.388 (-0.76)	1.319^{***} (2.36)
ln*Pgdp*	1.332 (1.19)	0.239 (0.25)	-0.952 (-1.03)
W×ln*Pgdp*	-1.409^{***} (-2.62)	0.869 (0.58)	-2.026^{**} (-2.27)
ln$Pgdp^2$	-0.679^{**} (-2.14)	-0.912^{*} (-1.78)	0.042 (0.24)
W×ln$Pgdp^2$	0.446^{*} (1.78)	-0.079 (-0.89)	0.380^{**} (2.15)
ln*Open*	-0.644^{***} (-5.82)	-0.079 (-1.14)	-0.125 (-1.32)
W×ln*Open*	-0.697^{***} （-2.70）	-0.271^{**} (-2.34)	-0.460^{**} (-2.23)
ln*Edu*	0.041 (0.95)	-0.855^{**} (-2.22)	-1.063^{***} (-2.88)
W×ln*Edu*	0.497^{***} （5.67）	0.411 (0.59)	-0.734 (-1.07)
ln*IS*	0.303^{***} (7.73)	0.077^{*} (2.13)	0.096 (0.89)

W×ln*IS*	-0.385*** (-4.49)	0.113* (1.92)	0.142** (1.91)
ρ	0.412*** (6.48)	0.048* (1.80)	0.361** (2.03)
R^2	0.627	0.366	0.210
Individual	Yes	Yes	No
Time	Yes	No	Yes
N	270	270	270

Notes: This table reports the Pearson correlation coefficients of the variables. ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively.

The estimation results of SDM cannot effectively reflect the real effects of the direct and spillover effects of the coefficient. Therefore, it is necessary to decompose the effects of the independent variables on per capita carbon emissions using partial differentiation and discuss the empirical results in terms of long-term direct (L-D), long-term indirect (L-I), short-term direct (S-D) and short-term indirect (S-I) effects.

As the results shown in table 6, the green financial development in a certain region not only reduces the level of carbon emissions in the region, but also has an inhibitory effect on the carbon emissions of neighboring regions, thus H1 is valid.

Since both green finance and carbon emissions have strong externalities, our findings add a discussion of spatial spillover effects to Huang et al. (2023). Comparing the absolute values of the coefficients, it is found that the indirect effect (-0.746) is greater than the direct effect (-0.677) in terms of the short-term effect. Green finance reduces the negative impact on neighboring regions by reducing the carbon emissions in the region. What's more, the demonstration effect of green finance is beneficial to drive the development of green finance in neighboring regions and promote the synergistic carbon emission reduction. Inevitably, there is also competition among officials about government performance. In the long run, the role of green finance in carbon emission reduction decreases, while the reduction in spillover effects is more pronounced. Although the green financial system continues to improve and mature, the marginal utility of green financial policies is diminishing, probably due to the fact that the difficulty of carbon emission reduction is also increasing year by year.

Table 6 Decomposition results of the spatial effect

	ln*GF*	ln*POP*	ln*Pgdp*	ln$Pgdp^2$	ln*Open*	ln*Edu*	ln*IS*
S-D	-0.677*** (-8.35)	0.467*** (7.72)	0.051 (0.50)	-0.196 (-1.26)	0.081 (1.34)	-0.601** (-2.11)	-0.124*** (-4.27)
S-I	-0.746** (-2.29)	0.408* (1.82)	-0.097 (-0.81)	-0.026 (-0.19)	0.121*** (6.17)	-0.353*** (-5.53)	-0.104 (-1.05)
S-T	-1.424*** (-6.22)	0.875* (1.83)	-0.148** (-2.14)	-0.222 (-0.65)	0.202* (1.70)	-0.954** (-2.74)	-0.228 (-0.96)
L-D	-0.604*** (-6.81)	0.299 (0.24)	0.030 (0.91)	-0.204 (-0.62)	-0.160** (-2.33)	-0.755*** (-7.19)	-0.468** (-2.05)
L-I	-0.328*** (-5.76)	0.281*** (3.52)	-0.018 (-0.18)	0.411* (1.91)	0.084 (0.51)	-0.564** (-2.47)	-0.204 (-0.11)
S-T	-0.932*** (-7.89)	0.580* (1.83)	0.012 (0.01)	0.207 (0.44)	-0.076* (-1.68)	-1.318** (-2.44)	-0.672 (-0.14)

Notes: This table reports the Pearson correlation coefficients of the variables. ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively.

Combined with Table 6, the population has a stronger effect on promoting carbon emissions in the neighboring regions, probably because population growth strengthens inter-regional economic cooperation and linkages, resulting in capital expansion and carbon growth in the neighboring regions; the direct effect of GDP per capita is not significant, but its quadratic term is significantly negative, and thus the relationship between economic development and carbon emissions is roughly "inverted U-shape". With the popularization of green technology and the public environmental protection awareness, the level of economic development across a certain threshold, it will slow down carbon emissions (Yang et al., 2021). The direct effect of trade openness is not significant, but the indirect effect is significant at the 1% level, probably due to less regulation outside the province, which is more likely to be affected by trade openness; the direct effect of education level on carbon emissions is greater, indicating that the strength of environmental protection awareness can significantly affect carbon emissions; the upgrading of industrial structure has a significant inhibiting effect on carbon emissions. This is because the more rational the industrial structure is, the lower the energy consumption, the smaller the negative externalities on the environment (Wang et al., 2020).

4.4 Robust test

In order to enhance the credibility of the research findings, the research conducts a robustness test of the empirical results. Tables 7(1)-(2) conduct spatial econometric analysis using the geographic distance matrix W_2 and the economic geography nested matrix W_3 instead of the spatial adjacency matrix; Column (3) replaces the dependent variables with carbon emission intensity (*CEI*), which is measured by the ratio of carbon emission *CE* to GDP; and Column (4) adds the energy structure (*ES*) and the urbanization level (*UR*) to the model, which are represented by the share of coal consumption in total energy demand and the ratio of urban population to the total resident population at the end of the year; Column (5) shows the empirical results of the static SDM, implying that the model does not include the lagged terms of the dependent variables in time and space.

Table 7 The results of robust test

Variables	W_2	W_3	CEI	Control	SDM
	(1)	(2)	(3)	(4)	(5)
W×ln*CE*(-1)	-0.493^{**} (-2.21)	-0.192 (-1.32)	-	-0.135^{***} (-2.61)	-
ln*CE*(-1)	0.354^{*}	0.379^{*}	-	0.187	-

		(1.89)	(1.80)		(0.74)	
W×ln*CEI*(-1)		-	-	-0.036 (-0.65)	-	-
ln*CEI*(-1)		-	-	0.076 (0.34)	-	-
ln*GF*		-1.152*** (-5.87)	-0.624*** (-7.30)	-0.609*** (-5.31)	-0.548*** (-6.54)	-0.707*** (-6.96)
ln*GF*	S-D	-0.559*** (-7.59)	-0.682*** (-7.74)	-0.484*** (-7.28)	-0.631*** (-7.85)	-
	S-I	-0.631*** (-5.74)	-0.670* (-1.73)	-0.414** (-2.31)	-0.762** (-2.20)	-
	L-D	-0.611*** (-6.95)	-0.672** (-6.71)	-0.945*** (-7.34)	-0.598*** (-5.13)	-0.606*** (-8.39)
	L-I	-0.435 (-1.01)	-0.502*** (-5.59)	-0.738*** (-7.27)	-0.632*** (-3.48)	-0.846** (-7.83)
Control		Yes	Yes	Yes	Yes	Yes
ρ		0.157* (1.81)	0.372* (1.85)	0.149** (2.16)	0.113** (2.04)	0.359** (1.97)
R^2		0.467	0.404	0.396	0.386	0.433
Log-L		-178.015	-188.216	-142.248	-153.429	-175.202
N		270	270	270	270	300

Notes: This table reports the Pearson correlation coefficients of the variables. ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively.

As can be seen from Table 7, the coefficients of the independent variables based on the W_2 are larger, indicating that the spillover effect of green finance on carbon emissions has a stronger correlation with geographic distance. The closer the distance is, the more convenient and quicker the industrial linkage, technological learning and resource exchange, leading to significantly enhanced cooperation efficiency. Compared with Table 5, after replacing the dependent variable and adding control variables, the conclusion is robust. What’s more, the coefficients of green finance are slightly enhanced under the SDM, which may be due to the omission of the lagged effect of the dependent variable on the current period in the static model, resulting in an overestimation of the coefficients of the independent variables. Specifically, in Table 7(1)-(5), the estimation results with Table 5 have a high degree of consistency, which suggests that the estimation results are more robust, and the research conclusions are highly reliable.

4.5 Mechanisms identification

Green finance effectively promotes social green innovation and reduces carbon emissions by tightening financing channels for highly polluting enterprises and increasing green credit to encourage R&D and expansion of environmentally friendly enterprises. Therefore, this research takes green innovation as the mediating variable to explore whether there is a mechanism of “green finance - green innovation - carbon emissions”, and the specific results are shown in Table 8.

Table 8 The results of mediation effect

Variables	(1)	(2)	(3)
	ln*CE*	ln*GI*	ln*CE*
ln*GF*	-0.877*** （-8.21）	0.453*** （11.65）	-0.550*** （-3.94）
ln*GI*	-	-	-0.644*** （-5.82）
ln*POP*	0.778** （1.97）	0.110 （0.22）	1.538* （1.71）
ln*Pgdp*	0.091* （1.88）	-0.018 （-1.19）	0.340 （1.19）
ln$Pgdp^2$	-0.207** （-2.49）	0.171 （0.09）	-0.089 （-0.99）
ln*Open*	0.132 （0.92）	0.702** （2.38）	0.041 （0.95）
ln*Edu*	-0.225*** （-5.98）	0.364*** （9.71）	-0.303*** （-7.73）
ln*IS*	-0.770** （-2.28）	-0.051 （-0.83）	-0.114*** （-3.44）
Time	Yes	Yes	Yes
Individual	Yes	Yes	Yes
N	300	300	300
R^2	0.428	0.591	0.510

Notes: This table reports the Pearson correlation coefficients of the variables. ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively.

Table 8 shows the mediating effect of green innovation in the carbon emissions reduction effect of green finance based on the stepwise regression. Column (1) shows the empirical results of Eq. (7), the coefficients of green finance is negative at 1% significance level, which again illustrates the inhibitory effect of green finance on carbon emissions; Column (2) shows the results of Eq. (8), and the coefficient of green finance is 0.453 at 1% significance level, indicating that for 1% increase in the level of green finance, the number of green patents is able to increase by 0.453%. It probably because green finance can provide the capital needed for green innovation, and it is easier than internal financing; Column (3) shows the results of Eq. (9), and the coefficients of green finance and green innovation are -0.550 and -0.644 at 1% significance level. It verifies that green technology innovation can act as a mediating variable to transmit the impact of green finance on carbon emissions, thus verifying H2.

4.6 Heterogeneity effect

4.6.1 Heterogeneity effect of temporal dimension

Since September in 2015, green finance has been elevated to an important position, and China has proposed the goal of "establishing a green financial system". The policy framework for green finance has been continuously strengthened, and China has become one of the countries with a relatively comprehensive green financial policy system. Therefore, considering the policy timeliness, this study takes 2016 as the time point and conducts regression analysis on the sample data from 2012 to 2015 and from 2016 to 2021, to explore the temporal heterogeneity of the impact of green finance on carbon emissions.

Table 9 reports the empirical results of the impact in the two time periods. In terms of the short-term direct effect, the coefficients of the two time periods are -0.664 and -0.689 at the 1% significance level with little difference. In the early stage of green finance development, the degree of perfection of relevant policies and products is not high enough, so that the effect of emission reduction is also reduced. However, as heavy polluters have started emission reduction work, the difficulty of emission reduction has begun to rise. Although the level of green finance is increasing, its marginal utility is also decreasing, so the effect is offset. The short-term indirect effect is -0.412 from 2012 to 2015, which is only significant at the 10% level, and -0.770 from 2016 to 2021 at the 1% significance level, almost twice as much as the former. As the level of green finance increases, its spillover effect on neighboring regions is stronger. In terms of long-term effects, apart from the long-term indirect effects from 2012 to 2015, the remaining coefficients show a declining trend. This indicates that in order to achieve carbon emissions reduction at the current pace in the future, more attention must be paid to the construction of the green finance system to ensure the timely completion of the "dual carbon" goals.

Table 9 Results of Heterogeneity effect

matrix	effect	2012-2021	2012-2015	2016-2021
Spatial adjacency matrix	S-D	-0.677^{***} (-8.35)	-0.664^{***} (-3.40)	-0.689^{***} (-6.15)
	S-I	-0.746^{**} (-2.29)	-0.412^{*} (-1.70)	-0.770^{***} (-5.22)
	L-D	-0.604^{***} (-6.81)	-0.510^{***} (-2.89)	-0.649^{**} (-1.99)
	L-I	-0.328^{***} (-5.76)	-0.564^{***} (-4.74)	-0.724^{***} (-6.31)

Notes: This table reports the Pearson correlation coefficients of the variables. ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively.

4.6.2 Heterogeneity effect of spatial dimension

The core of this research mainly on the spatial spillover effect of green finance on carbon emissions, so the spatial heterogeneity of this effect is also our focus. The economic foundation provides a conditional basis and financial guarantee for the development of green finance, which is conducive to the ecological environmental effects of green finance and promotes the development of a low-carbon economy. Considering the close relationship between finance and economy and whether the differences in economic development in different regions affect the emission reduction effect of green finance, this research divides the sample into eastern, central, and western regions and conducts regression analysis on each group.

Meanwhile, in order to further explore the spatial heterogeneity of the impact of green finance on carbon emissions, this research refers to Li and Zhang (2023), and divides the sample into two groups based on the average per capita carbon emissions of each province. Those below the average considered as low-carbon regions and those above the average considered as high-carbon regions, and the results are shown in Table 10.

Table 10 Results of spatial heterogeneity

	Effect	Total	East	Central	West	High Carbon	Low Carbon
Spatial adjacency matrix	S-D	-0.677*** (-8.35)	-0.652*** (-6.03)	-0.759*** (-6.85)	-0.441*** (-7.50)	-0.694*** (-3.48)	-0.371*** (-3.92)
	S-I	-0.746** (-2.29)	-0.935*** (-7.98)	0.087 (0.76)	-0.116 (-0.65)	-0.227* (-1.77)	-0.673*** (-5.03)
	L-D	-0.604*** (-6.81)	-0.662*** （-5.52）	-0.656*** （-6.70）	-0.429*** （-4.11）	-0.600*** （-4.69）	-0.426*** （-4.39）
	L-I	-0.328*** (-5.76)	-0.351** (-2.16)	-0.035 (-1.15)	-0.133 (-0.38)	-0.283** (-2.30)	-0.371** (-2.37)

Notes: This table reports the Pearson correlation coefficients of the variables. ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively.

The results grouped by regions show that the direct effect coefficients are all significant at the 1% significance level, again verifying that green finance can benefit carbon emissions reduction. However, our conclusion differs from Wang et al. (2023), the indirect spillover effects, except for the east, are not significant. It probably because the green financial development, green technology and financing constraints on high-polluting enterprises are still to be improved, so the spillover effect on neighboring regions is also smaller.

The results grouped by per capita carbon emissions show that the direct and indirect effects are significantly negative at the 10% level. From the perspective of direct effect, the absolute value of coefficients in high-carbon regions are larger than those in low-carbon regions, indicating that green finance can more effectively reduce per capita carbon emissions in high-carbon regions. The high carbon regions are inevitably high energy consumption industry gathered in the region, so the demand for energy saving and emission reduction is urgent. The original intention of green finance is to make resources allocation to environmental protection industry and inhibit carbon emissions. Moreover, the absolute value of the indirect effect coefficient is greater in low-carbon regions. Since regional carbon emissions are already at a low level, regional green construction is relatively well-developed. Its green technology, green credit policy and energy industry structure will be learned by the neighboring regions, which leads to stronger spatial spillover effects, and H3 is verified.

5. Conclusion

Green finance is an important tool for combating climate change and helping to achieve the “dual carbon” goal. Taking the panel data of 30 provinces in China from 2012 to 2021 as a research sample, this research constructs a green finance index and analyzes the spatial characteristics of green finance development and carbon emissions. After that, the dynamic SDM is used to explore the spatial spillover effect, the mechanism identification, and the heterogeneity of the carbon emissions reduction effect of green finance, and the following conclusions are drawn:

(1) The carbon emission reduction effect of green finance is significant, and its spatial spillover effects can also effectively reduce carbon emissions in neighboring regions. The conclusion is still valid after replacing the dependent variables and spatial weight matrix. (2) The long-term effect of green finance emission reduction effect is slightly smaller than the short-term, in line with the law of diminishing marginal utility in economics. (3) The “reward and punishment” characteristics of green finance can effectively promote green technological innovation of enterprises and thus inhibit carbon emissions. (4) The emission reduction effects of green finance exhibit heterogeneity across different time periods and spatial regions. The increase in national attention to green finance significantly enhances the carbon emission reduction effect and spatial spillover effect of green finance. And green finance is more effective when applied directly to high-carbon regions and has stronger spillover effects in low-carbon regions.

On the basis of the above conclusions, suggestions are proposed to promote carbon emission reduction: first, the demonstration effect of low-carbon development pilot zones should be emphasized, and a regional factor docking mechanism should be established to facilitate low-carbon development. Secondly, the spatial spillover effect of green finance should be fully utilized to achieve balanced regional low-carbon development through building cross-regional technological cooperation and innovation. Thirdly, the role of green finance should be strengthened to provide enterprises with incentives for green innovation. Fourth, formulate targeted strategies based on regional and temporal characteristics. Utilizing the high spillover effect of low-carbon regions, in conjunction with the increased strength of green financial policies in high-carbon regions, will help to reduce carbon emissions.

At last, this research discusses the spatial spillover relationship between green finance and carbon emission, but there are still some questions and limitations that have not been addressed and solved. It offers more directions for future research. First, since the target of green finance is mainly enterprises, this research does not discuss the mechanism of carbon emission reduction in green finance from the micro level. In order to fill the gap in green finance research, it is interesting to discuss how green finance reduce carbon emissions by influencing corporate behavior. Second, although this research verifies that green finance can promote carbon emission reduction by improving the green innovation, it does not explore the mechanism from a spatial perspective. This dimension could be further considered to enrich the literature on green finance in the future research.

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