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Can green finance improve carbon emission efficiency? Evidence from China

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The improvement of carbon emission efficiency and the realization of the goal of "carbon peaking and carbon neutrality" are the key issues that China needs to solve urgently at this stage. The green and low-carbon transformation of the economy requires sufficient financial support. Whether green finance is an opportunity to improve China's carbon emission efficiency is worth studying. For the aim, based on the macro-panel data of 30 provinces in China from 2010 to 2019, this paper uses fixed effect model and spatial Durbin model to study the impact of green finance on regional carbon emission efficiency. The results show that: First, the development of green finance can improve the carbon emission efficiency; Second, in addition to the "local effect", the influence of green finance on carbon emission efficiency has a "neighborhood effect", that is, it has a spatial spillover effect on carbon emission efficiency in neighboring areas, and this effect only exists in a short time; Third, the impact of green finance on carbon emission efficiency is heterogeneous in different regions with different environmental regulations. This paper has reference significance for green finance development and the implementation of the goal of "carbon peaking and carbon neutrality" in China.

KEYWORDS

green finance, carbon emission efficiency, China, environmental regulation, sustainable development

1 Introduction

Climate warming caused by greenhouse gases, especially carbon dioxide emissions, has become one of the global environmental problems and has attracted much attention (Rezanezhad et al., 2020; Işık et al., 2021a, Işık et al., 2021b; Pan et al., 2022). Climate change has led to the frequent occurrence of extreme weather events around the world, further causing ecological imbalances, environmental damage (Işık et al., 2019), and affecting the normal production and living order (Wolff and Haase, 2019; Tuladhar et al., 2021). As the backbone of the global ecological civilization construction and green responsibility, China attaches great importance to climate governance (Meng et al., 2021). In September 2020, Chinese President Xi Jinping made it clear at the 75th United Nations General Assembly that China's carbon dioxide emissions should peak by 2030 and achieve carbon neutrality by 2060 (Huang et al., 2022). Achieving the goal of "carbon peaking and carbon neutrality" is a broad and profound systemic change related to energy,

environment, economy and society, and a historic turning point for China's carbon emission reduction (Rehman et al., 2021; Dong et al., 2022; Pata et al., 2022; Ullah et al., 2022). As the world's second largest economy and the largest developing country, China must focus on both economic development and environmental governance, and promote carbon emission reduction in the process of economic activities. Therefore, in addition to the rigid constraints of carbon emission quotas, China should pay more attention to carbon emission efficiency. Improving carbon emission efficiency is the key path to advance the "carbon peaking and carbon neutrality" goal, and it is an inherent requirement for the high-quality development of China's economy (Sun and Huang, 2020). Furthermore, according to China's Green Finance Development Report 2021, China needs to invest about 150–500 trillion yuan to realize the "carbon peaking and carbon neutrality" strategy, which cannot effectively meet such a huge capital demand only by fiscal strength. Therefore, financial support is an important part of improving carbon emission efficiency (Ali et al., 2022; Fareed et al., 2022; Rehman et al., 2022), and it is also an indispensable force for marketization to promote the realization of the "carbon peaking and carbon neutrality" goal (Zhang, 2011). In order to identify the flow of financial resources and ensure the accurate flow of supporting tools to the green development field, China actively explores green financial products and services and continuously improves the long-term development mechanism of green finance.

Green finance is a new financial development model that guides the transfer of financial resources to green and low-carbon industries and promotes the green transformation of industrial enterprises. Developing green finance to improve carbon emission efficiency is a requirement for China to achieve the carbon dioxide emission goal. In August 2016, seven ministries including the People's Bank of China jointly issued the "Guiding Opinions on Building a Green Financial System", which clearly proposed to establish a sound green financial system based on the overall situation of sustainable economic development. Since then, the top-level design of China's green financial system has been gradually clarified, and the market environment and institutional arrangements to support the development of green finance have been gradually improved. For example, in 2021, the central bank issued a carbon emission reduction support tool. As of the end of 2021, the balance of China's green loans is about 15 trillion yuan; as of the first half of 2021, the cumulative scale of green bond issuance in China and abroad has exceeded 1.73 trillion yuan. The scale of China's green finance market is developing rapidly. Has it played a role in promoting the efficiency of carbon emissions? Will this effect be heterogeneous with different environmental regulations? Will green finance have an impact on carbon efficiency in other regions through externalities (spillover effects)? This paper selects the macro panel data of 30 provinces in China from 2010 to 2019 as the research object, and explores the "local effect" and "neighborhood effect" of green finance in affecting carbon emission efficiency.

The possible marginal contributions of this paper are as follows: First, few studies currently focus on the impact of green finance development on carbon emission efficiency. This paper incorporates green finance and carbon emission efficiency into the same analytical framework, which broadens the research scope of green finance and carbon emission efficiency respectively, and provides evidence support for the government to continue to support the development of green finance in the future. Second, green finance has strong spatial spillover effects (Li and Gan, 2021). However, few literatures incorporate spatial factors into the research on the impact of green finance development on carbon emission efficiency. Therefore, this paper attempts to use the spatial Durbin model to analyze whether the carbon emission efficiency improvement effect of green finance has spatial spillover. Third, from the perspective of environmental regulation, this paper provides policy inspiration for promoting the realization of the goal of "carbon peaking and carbon neutrality" and establishing a sound green financial system. The conclusion shows that, with different environmental regulations, the impact of green finance on carbon emission efficiency is heterogeneous.

2 Literature review

At present, many scholars have conducted research on carbon emission, including the measurement and evaluation (Fang et al., 2022), dynamic change (Cheng et al., 2018b), influencing factors and effects analysis (Xu et al., 2021; Zhang H et al., 2021) of carbon emission efficiency. Scholars think that policy and supervision (Calvo et al., 2021; Yu and Zhang, 2021), technological innovation (Gouveia et al., 2021; He et al., 2021; Wu H et al., 2021; Wyse et al., 2021; Xie et al., 2021), human capital (Song et al., 2020), industrial structure (Cheng et al., 2018a; Wu L et al., 2021) and urbanization (Sun and Huang, 2020; Wang F et al., 2021) will affect carbon emission efficiency. Fang et al. (2022) and Meng et al. (2016) used DEA model to measure the carbon emission efficiency of 42 thermal power plants and 30 provinces in China from the micro and macro levels respectively, and found that there was regional imbalance in China's carbon emission efficiency. Cheng et al. (2018b) used NDDF function to calculate the total factor carbon emission efficiency (TCEI) of industrial sectors in various provinces in China. The results showed that TCEI showed an increasing trend from 2005 to 2015, but the growth rate decreased. Yu and Zhang (2021) evaluated the effect of the low-carbon city pilot policy, and found that the carbon emission efficiency of the pilot group (pilot city) increased by 1.7%, and the carbon emission was reduced by more than 8 million tons. He et al. (2021) constructed the

TABLE 1 Descriptive statistical analysis.

	N	Mean	S. D	Min	Max
CEE	300	0.560	0.170	0.110	1
CEE_SBM	300	0.600	0.270	0.120	1
GF	300	0.180	0.110	0.0600	0.790
Eco	300	1.500	0.470	0.250	2.800
Ind	300	0.440	0.0900	0.160	0.590
Hum	300	9.270	0.860	7.510	12.71
Urb	300	0.570	0.120	0.340	0.900
ER	210	0.100	0.200	0	1.710

Renewable Energy Technology Innovation Index (RETI) and Total Factor Carbon Emission Performance Index (TCPI). The research found that RETI can promote the growth of TCPI, but the relationship between them is affected by the market environment. The research of Xie et al. (2021) once again proves the importance of technological progress to carbon emission reduction.

Green finance has attracted more and more attention as a bright spot to support low-carbon transition and high-quality development (Tsoukala and Tsiotas, 2021; Yang et al., 2021). Green finance increases the social responsibility of financial institutions (Kurt and Peng, 2021), encourages banks to provide funds for enterprises' development (Liu et al., 2021), and then promotes technological innovation (Wang M et al., 2021). The impact of green finance can be divided into three levels: enterprise, industry and region. For the enterprise level, Zheng et al. (2021) uses data from Bangladesh to confirm that the development of green finance business has a positive impact on the medium and long-term development of financial enterprises themselves. But there are also different research conclusions. Umar et al. (2021) believe that some financial enterprises have increased external costs and decreased profits because they have assumed social and environmental responsibilities. Zhang et al. (2021) used the data of 945 A-share companies to find that green financial incentives and punishment effects coexist, affecting the investment and financing behavior of enterprises, which in turn affects the quality of the environment. For the industry level, Wang and Wang (2021) used the grey correlation method and the GMM model as tools to test and found that green finance has a greater role in promoting the tertiary industry. For the regional level, Lee and Lee (2022) constructed a multi-dimensional index of green finance and incorporated the index into the framework of the theoretical model of green productivity. The study found that green finance is one of the basic paths for improving green productivity. In addition, Wang et al. (2021), Wang et al. (2022) and Yin and Xu. (2022) examine the impact of green finance on China's high-quality development, ecological efficiency, and economic growth, respectively.

TABLE 2 Baseline result.

	(1)	(2)	(3)	(4)
	OLS		FE	
GF	1.061***	1.244***	0.492***	0.363***
	(14.526)	(9.842)	(4.800)	(2.841)
Eco		−0.109***		0.062
		(−3.036)		(1.205)
Ind		0.668***		0.242*
		(6.929)		(1.837)
Hum		0.018		0.039***
		(1.068)		(2.632)
Urb		0.424***		0.033
		(2.613)		(0.144)
Cons	0.372***	−0.203	0.759***	0.138
	(24.400)	(−1.585)	(12.970)	(0.473)
Fixed effect	No	No	Yes	Yes
N	300	300	300	300
R^2	0.415	0.525	0.581	0.608

t statistics in parentheses. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

To sum up, some scholars have studied the relationship between finance and ecology (Işik et al., 2017; Su et al., 2021), environment and energy (Haas et al., 2021), there are still areas that need to be improved. Although the impact of green finance and the influencing factors of carbon emission efficiency have been discussed, few studies have put green finance and carbon emission efficiency into the same research framework. Second, for related research at the macro level, the existing literature mostly focuses on the impact of green finance on the development of the region, while ignoring the spatial spillover effects or externalities. Based on this, this paper integrates green finance and carbon emission efficiency into the same analytical framework, and explores the local effect and spatial spillover effect of the former on the latter, in order to provide guidance for financial model innovation, the realization of the "dual carbon" goal and sustainable development.

3 Empirical models and variables

3.1 Empirical model

3.1.1 Baseline model

To test the impact of green finance on regional carbon emission efficiency, this paper constructs a two-way fixed effect model of time and individual as follows:

$$CEE_{it} = \beta_0 + \beta_1 * GF_{it} + \beta_i * Controls_{it} + \alpha_i + \gamma_t + \varepsilon_{it} \quad (1)$$

TABLE 3 Global Moran'I of carbon emission efficiency of 30 provinces in China from 2010 to 2019.

Year	Moran'I	E(I)	sd(I)	z	*p*-value
2010	0.216	−0.034	0.095	2.645	0.004
2011	0.233	−0.034	0.093	2.863	0.002
2012	0.241	−0.034	0.095	2.907	0.002
2013	0.221	−0.034	0.094	2.719	0.003
2014	0.233	−0.034	0.095	2.828	0.002
2015	0.223	−0.034	0.095	2.715	0.003
2016	0.200	−0.034	0.095	2.476	0.007
2017	0.191	−0.034	0.095	2.378	0.009
2018	0.196	−0.034	0.095	2.429	0.008
2019	0.101	−0.034	0.095	1.431	0.076

Among them, CEE stands for carbon emission efficiency; i refers to the province; t represents the year; β_0 is the intercept term; GF is the key independent variable of this paper, that is, the development level of green finance; And β_1 and β_i are coefficients respectively; Other control variables that affect CEE; α_i is individual effect; γ_t is the fixed effect of the year; ε_{it} is the random error term.

3.1.2 Spatial durbin model

The impact of green financial development on carbon emission efficiency may not only be limited to this region, but also have a certain impact on neighboring regions. Ignoring spatial correlation may lead to the bias of estimation results. Therefore, this paper uses spatial Durbin model to test the spatial impact of green finance on carbon emission efficiency. The spatial Durbin model can simultaneously examine the influence of green financial development and carbon emission efficiency in neighboring regions on the carbon emission efficiency in this region. In this paper, the spatial Durbin model is established as follows:

$$CEE_{it} = \beta_0 + \beta_1 * GF_{it} + \rho\sum_{j=1}^{N} W_{ij} * CEE_{jt} + \sigma\sum_{j=1}^{N} W_{ij} * GF_{jt} + \beta_i * Controls_{it} + \alpha_i + \gamma_t + \varepsilon_{it} \quad (2)$$

Where ρ is the spatial autocorrelation coefficient of the dependent variable; As the spatial weight matrix, according to the particularity of the research variables, this paper considers using economic weight matrix to set the spatial weight. In this paper, the economic weight matrix is constructed according to the average GDP of each region in the sample period.

3.2 Variable measurement

3.2.1 Carbon emission efficiency

CEE is the dependent variable of this paper. SBM model and NDDF model are constructed to calculate GEE of each province. The CEE calculated by the SBM model and the NDDF model are represented by *CEE_SBM* and *CEE*, respectively. The inputs indicators include the capital stock of each province (city, autonomous region), the total number of employees in urban units, and energy consumption. The expected output indicators are GDP and carbon emissions, and the unexpected output involves coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, and natural gas. Based on this, CEE of 30 provinces (municipalities and autonomous regions) in China is calculated. Among them, the perpetual inventory method is adopted to calculate the capital stock of each province.

3.2.2 Green finance

GF is the independent variable of this paper. GF is the independent variable of this paper. GF consists of four indicators: green credit, green investment, green insurance and government support. The specific indicators are as follows:

3.2.3 Other variables

1) Control variables. *Eco* is the logarithm of real GDP per capita, which is used to indicate the economic growth level of provinces (autonomous regions or municipalities). Economic growth has driven the change of energy consumption structure and changed people's awareness of environmental protection. Thus, economic growth directly or indirectly affects carbon emission efficiency (Salahuddin et al., 2016; Wu et al., 2021). *Ind* is the ratio of the added value of the secondary industry to GDP, which is used to indicate the industrial structure of each region. The continuous increase of the proportion of tertiary industry and the continuous decrease of the proportion of secondary industry are the main reasons for the decrease of carbon emission intensity (Zhang et al., 2020). *Hum* means regional human capital. Human capital is an important support for the continuous optimization of energy structure and the continuous decline of carbon emission intensity (Cheng and Yao, 2021). *Urb* is the level of urbanization, represented by the ratio of urban population to total population in each region, and the unit is 1. Urbanization mainly affects carbon emission efficiency through population structure, economic structure and energy consumption structure (Wang et al., 2021). 2) Heterogeneous analysis variables. *ER* is a case of environmental punishment in various regions (unit: 10,000 pieces), indicating the level of environmental regulation. When there are many cases of environmental punishment in a region, we think that the level of environmental regulation in that region is higher. The impact of *ER* on energy conservation and emission reduction efficiency has been confirmed by scholars (Wu et al., 2020). Table 1 is descriptive statistical analysis.

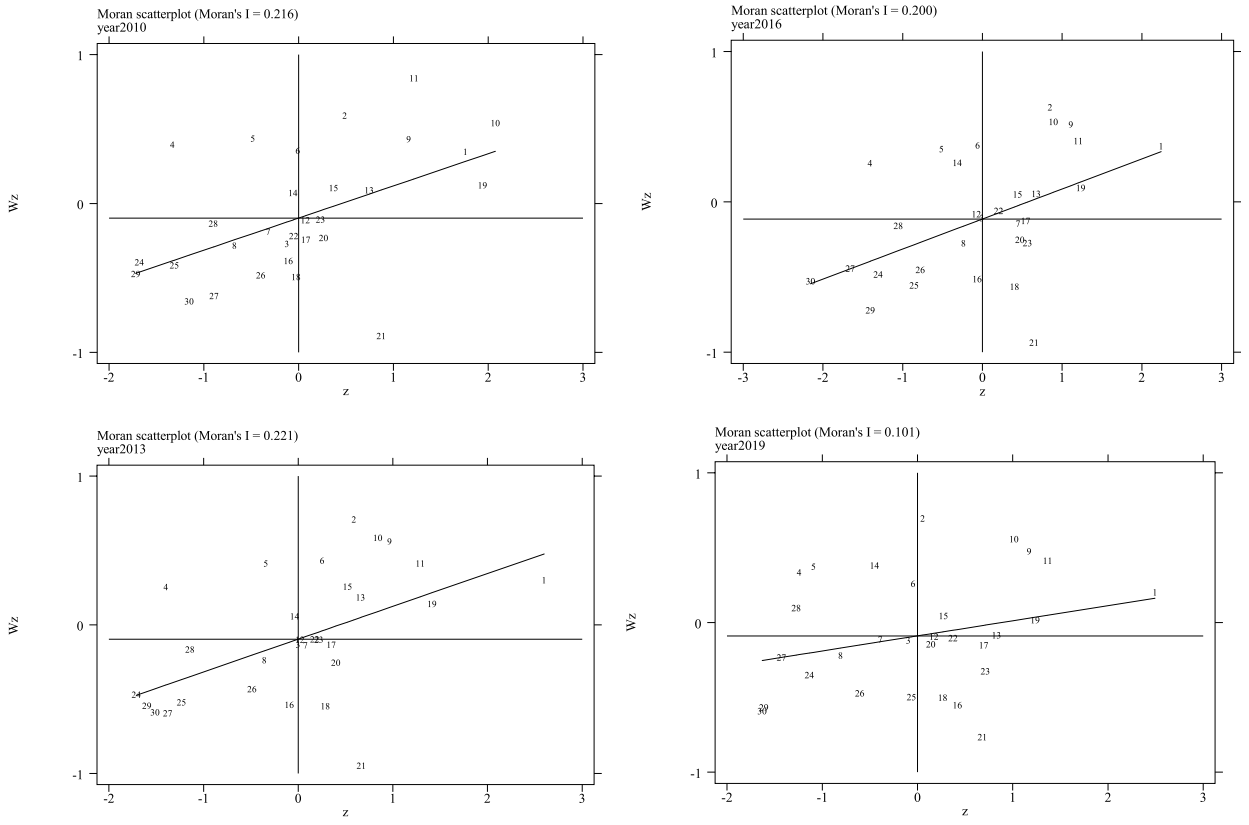

FIGURE 1
Local Moran'I scatter diagram of carbon emission efficiency of China's provinces in 2010, 2013, 2016, and 2019.

3.3 Data

Green finance data comes from *China Statistical Yearbook*, *Provincial Statistical Yearbook* and *China Insurance Yearbook*; carbon emission efficiency data comes from EPS (Express Professional Superior) database and the National Bureau of Statistics. The environmental regulation data comes from Chinalawinfo Pkulaw Database. Data for other control variables were obtained from the EPS database.

4 Empirical results and discussion

4.1 Baseline result

In Table 2, columns (1–2) and columns (3–4) are the analysis results using the OLS model and the FE (fixed effects) model, respectively. Among them, columns 1) and 3) do not add control variables, and columns 2) and 4) consider the influence of control variables. The fitting results show that no matter what model is used, and whether control variables are added or not, the coefficient of GF is always significantly positive at the level of 1%, which indicates that the development of green finance can promote the regional carbon emission efficiency and contribute to the realization of the "double carbon" goal. The overall regression results are in line with expectations. The reasons are as follows: First, green finance injects strong power into green technology innovation (Yu et al., 2021). Specifically, under the background of the development of green finance, the funds of financial institutions are inclined to green and high-tech industries, forcing the "two high and one surplus" industries to carry out green technological innovation under the constraint of funds (Wang et al., 2022). At the same time, the green finance policy can not only incite the resources of financial institutions, but also incite social capital to gather in green technology innovation of enterprises, and mobilize the vitality of green technology innovation and research and development of enterprises (Fang and Shao, 2022). Second, green finance contributes to the ecological transformation of industrial structure (Hu et al., 2020). Green finance can exert financing pressure on high-pollution industries, increase their capital cost, and force polluting industries to carry out ecological transformation (Cheng et al., 2022). To sum up, we believe that green finance can

TABLE 4 Spatial estimation result.

	Main spatial effect	Wx	Short run spatial effect			Long run spatial effect		
			Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L.CEE	1.130***							
	(0.023)							
GF	0.091**	1.428***	1.230***	0.035	1.195***	12.739	0.810	11.929
	(0.042)	(0.128)	(0.109)	(0.043)	(0.103)	(110.550)	(99.406)	(146.453)
Eco	−0.035***	−0.272***	−0.249***	−0.024*	−0.225***	−2.486	0.006	-2.491
	(0.012)	(0.036)	(0.035)	(0.013)	(0.037)	(26.221)	(21.188)	(33.139)
Ind	0.306***	0.744***	0.846***	0.280***	0.566***	8.781	−0.830	9.611
	(0.039)	(0.102)	(0.104)	(0.036)	(0.095)	(82.005)	(78.750)	(112.134)
Hum	0.011**	0.009	0.017	0.011**	0.006	0.191	−0.028	0.220
	(0.005)	(0.012)	(0.010)	(0.004)	(0.011)	(1.883)	(1.751)	(2.530)
Spatial rho	0.237***							
	(0.059)							
Year Fe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	270	270	270	270	270	270	270	270

Standard deviation in parentheses.

TABLE 5 IV estimation result.

	(1)	(2)	(3)	(4)
	First-stage regressions		Second-stage regressions	
GF			1.266***	0.918***
			[19.835]	[7.968]
IV	1.069***	1.056***		
	(206.49)	(105.92)		
Eco		0.005		0.146***
		(1.42)		[3.565]
Ind		-0.006		0.057
		(-0.70)		[0.551]
Hum		0.001		-0.024
		(0.90)		[-1.525]
Urb		-0.012		0.106
		(-0.97)		[0.694]
Cons	-0.004***	-0.011	0.231***	0.179
	(-1.87)	(-1.07)	[9.357]	[1.481]
N			270	270
R^2	0.994	0.994	0.613	0.667

() is t value; [] is the z value.

TABLE 6 Replace variable result.

	(1)	(2)	(3)	(4)	(5)
GF	1.705***	0.747***	0.956***	0.921***	0.982***
	(14.813)	(4.566)	(5.028)	(4.697)	(4.931)
Eco		0.319***	0.290***	0.274***	0.193***
		(7.650)	(6.647)	(5.612)	(2.754)
Ind			0.353**	0.399**	0.428**
			(2.123)	(2.254)	(2.411)
Hum				0.016	-0.011
				(0.763)	(-0.400)
Urb					0.415
					(1.605)
Cons	0.407***	0.199***	0.028	-0.125	-0.024
	(10.214)	(4.371)	(0.302)	(-0.567)	(-0.102)
Fixed effect	Yes	Yes	Yes	Yes	Yes
N	300	300	300	300	300
Adj R^2	0.431	0.526	0.531	0.531	0.533

() is t value.

TABLE 7 Heterogeneity effect based on environmental regulation.

	(1)	(2)	(3)	(4)
	OLS	OLS	FE	FE
	Weak ER	Strong ER	Weak ER	Strong ER
GF	1.129***	1.080***	0.921***	0.534***
	(4.343)	(7.155)	(2.997)	(2.999)
lnpgdp	0.123*	-0.014	0.181**	0.097
	(1.668)	(-0.217)	(2.156)	(1.116)
strind	-0.073	0.209	0.181	0.661***
	(-0.429)	(1.020)	(0.955)	(3.828)
hum	0.029	-0.106***	0.010	-0.011
	(1.072)	(-3.981)	(0.489)	(-0.422)
urban	-0.129	0.949***	-0.095	0.611**
	(-0.498)	(3.382)	(-0.325)	(2.020)
Fixed effect	√	√	√	√
N	105	105	105	105
R^2	0.658	0.721	0.618	0.629

t statistics in parentheses.

improve carbon emission efficiency through green technology innovation and green transformation of industrial structure.

4.2 Spatial estimation result

In the market economy, regional economic activities do not occur independently, but are integrated and influence each other (Griffith, 2021; Feng et al., 2022). Regional linkage development has become the trend of geo-economy (Hao et al., 2021). Studies have also shown that there are obvious spatial correlations between GF (Huang and Chen, 2022) and CEE (Liu and Song, 2020) in different regions. Therefore, this paper uses spatial Durbin model to empirically test the "neighborhood effect" of GF on CEE. Firstly, Moran's I index is used to test the spatial autocorrelation of carbon emission efficiency. From the test results of Moran's I index in Table 3, the Moran index of CEE from 2010 to 2019 is significantly positive. In addition, the local scatter plots of 2010, 2013, 2016 and 2019 in Figure 1 once again prove the positive correlation between them. It shows that China's CEE presents a positive spatial agglomeration.

In order to accurately measure the dynamic change of spatial spillover effect in the model, increase the explanatory power of the model and reduce the errors of the model, this paper uses the dynamic spatial model to further test. The direct and indirect effects of the dynamic Durbin two-way fixed effect model include short-term and long-term effects. It can be seen from the estimated results in Table 4: First, the lag term of the dependent variable is obviously not zero, indicating that the CEE of the previous period will promote the development of the current CEE, and it has inertia. Secondly, the estimated coefficients of GF and W*GF in columns (1–2) are all positive, indicating that GF has a positive direct impact on CEE and spatial spillover effect. Third, compared with the short-term spatial effect, the long-term spatial effect is not significant. This shows that in the long run, the influence of green finance on CC in "neighboring" areas is not clear. To a certain extent, this shows that the road of China's green financial construction still needs to be explored. While pursuing short-term ecological benefits, we should also pay attention to the improvement of long-term green financial mechanism.

4.3 Robustness test

4.3.1 IV estimation result

There are missing variables, measurement errors and two-way causality in the empirical test, which will lead to endogenous problems, so that the regression results can't converge to the real overall parameters. In order to make the research conclusion credible, this paper uses instrumental variable method to deal with endogeneity. In this paper, the lag period of independent variable is IV, and IV-2SLS regression is carried out. Generally, the selection of instrumental variables needs to meet two conditions: first, correlation: namely, instrumental variables are related to endogenous independent variables; Second, it is exogenous: that is, tool variables are not related to disturbance terms. The IV selected in this paper satisfies these two conditions. And the F value of weak tool variables test is far more than 10. According to the regression results in Table 5, there is a strong correlation between instrumental variables and independent variables, which is significant at 1%. The regression results of the second stage show that the main conclusions of this paper are still valid after dealing with endogenous problems.

4.3.2 Replace the measurement method of dependent variable

In order to ensure the reliability of the research conclusion, this part replaces dependent variables for robustness test. Specifically, the benchmark regression part is measured by NDDF model and replaced by SBM model here. Table 6 shows the results of stepwise regression estimation. With the gradual addition of control variables, the positive effect of GF on CEE still exists, and it is statistically significant. The positive effect of GF on CEE is steady.

5 Heterogeneity analysis of environmental regulation

Regional heterogeneity exists in regions with different economic development and carbon emission efficiency (Ahmad et al., 2021). Green finance expands more

financing channels for green enterprises, on the contrary, it restricts the financing of polluting enterprises (Zhang and Wang, 2021). Therefore, it essentially belongs to the market incentive environmental regulation policy. Compared with the "soft constraint" of green finance, the mandatory environmental regulation belongs to the "hard constraint". Has China's green financial sector and environmental regulatory authorities achieved synergy, that is, in areas with strong environmental regulation, does GF play a greater role in promoting CEE? In the other case, there is substitution effect between "soft constraint" and "hard constraint". Therefore, this paper takes the case of regional environmental punishment as the proxy variable of mandatory environmental regulation, and investigates what heterogeneous influence GF has on CEE. See Table 7 for the results: columns (1–2) and (3–4) are OLS and FE estimation results, and columns 1), 3) and 2) and 4) are the results of weak and strong environmental regulation. We found that, no matter the estimation results of OLS or FE, when the environmental regulation is strong, the promotion effect of GF on CEE in this area is weak. It shows that the linkage and coordination mechanism between China's financial and environmental supervision departments is not perfect, and the two departments should establish a joint law enforcement mechanism to jointly contribute to the "double carbon" goal.

6 Conclusions and policy implications

Promoting the improvement of carbon emission efficiency is the basic requirement to achieve the "double carbon" goal, and it is also the proper path of China's realization of high-quality and sustainable economic development. Based on the data of 30 provinces in China, this paper makes an empirical analysis, and finds that green finance can significantly promote the carbon emission efficiency in this region; This promotion utility has spatial spillover effect, but this effect is significant in the short term and not significant in the long term; The influence of green finance on carbon emission efficiency is obviously heterogeneous based on environmental regulation.

First, the government is required to establish and improve the green financial development system, and innovate and enrich green financial products. The conclusion of this article shows that green finance can improve the efficiency of carbon emission, so the Chinese government should speed up the innovation of green financial instruments and promote the diversified and sustainable development of green financial market. Specific measures include encouraging banking institutions to develop financing products and services based on the pledge of ecological resources rights and interests, and piloting other innovative green bond products such as green collective bonds, water-saving loans and climate bonds for small and medium-sized enterprises. In addition, China should continue to expand the scope of the green financial reform and innovation pilot zone and promote the business model of the pilot zone.

Second, the government is required to encourage green finance, environmental protection supervision departments, enterprises and other forces to link up, coordinate and extensively carry out cooperation in the field of green finance. Doing a good job in green finance is not something that one department or one region can accomplish alone, and it needs to gather all forces. Specific measures include: increasing financial incentives to guide carbon reduction, increasing the support of financial departments and institutions, and improving the carbon supervision and statistical system. In addition, market-driven environmental regulation policies (such as green finance) and mandatory environmental regulation tools (such as environmental protection law) should coordinate with each other, establish various environmental regulation systems, and work together to promote the realization of China's "3,060″ dual-carbon goal officially promised to the international community.

Third, the government is required to build a cross-regional cooperation platform for green finance and carry out regional cooperation projects to realize communication and cooperation with surrounding areas. In view of the conclusion that green finance has a positive impact on the carbon emission efficiency of surrounding areas, we think that government departments should encourage green financial institutions to innovate financial products, disclose environmental information and exchange and cooperate with professional and technical personnel, so as to avoid resource waste caused by information asymmetry, redundant construction and disorderly competition, and promote the efficiency of financial resource allocation and use.

This article empirically analyzes the impact of green finance on carbon emission efficiency from the perspectives of "local effect" and "neighboring effect". Although this article has expanded the research scope of green finance and carbon emission efficiency, there are still some shortcomings, which can also be considered as the future research prospect: First, due to the limitation of data volume, this article only selects provincial data as the research sample, but the data of prefecture-level cities or microcosmic data may be more representative and research-oriented. Second, this article does not deeply study the dynamic impact of green finance on carbon emission efficiency. With the sustainable development of China's green finance, we will pay attention to it dynamically and strive to make the research conclusion more accurate and perfect.

Data availability statement

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

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

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

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