Study on the Heterogeneity and Regulatory Effects of Financial Development and Technological Innovation on Carbon Emission Reduction

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Abstract. Based on provincial panel data from 2008 to 2017 as the research sample in China, this study examines the impact of financial development on carbon emissions. Regression models are employed to estimate the influence of financial development on carbon emissions in different regions. The research reveals that the level of carbon emissions is influenced by differentiation and heterogeneity, with different regions showing varying sensitivities to factors such as financial development, technological innovation, and industrial structure. Financial efficiency has a negative impact on carbon emissions, being positive in regions with low carbon emissions. In areas with higher carbon emissions, the impact of financial efficiency on carbon emissions is greater. Industrial structure has a negative impact on carbon emissions, and in regions with lower carbon emissions, the upgrading of industrial structure has a greater impact on carbon reduction. Technological innovation has a negative impact on carbon emissions in regions with medium to high levels of emissions, while its impact in low-emission areas is positive but not significant. Per capita GDP, energy structure, and urbanization level overall have a positive impact, while foreign investment has a negative impact. The introduction of technological innovation as a moderating variable significantly enhances the significance level of financial efficiency.

Keywords: Financial Development, Technological Innovation, Carbon Emissions, Quantile Regression.

1. Introduction

In the current world, rapid industrial development and continuous technological progress have led to a continuous increase in carbon emissions. The climate change caused by the emissions of greenhouse gases, mainly carbon dioxide, profoundly affects normal human life and the sustainable development of the socio-economic system. To address climate change, carbon emissions have become an urgent issue for countries worldwide.

According to statistics from the British Petroleum, as the largest developing country and the second-largest economy globally, China accounts for a significant proportion of the world's total carbon emissions, reaching 30.9%. The pressure to reduce carbon emissions is particularly severe. In 2020, Chinese President Xi Jinping announced China's dual-carbon goals at the 75th United Nations General Assembly, aiming to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. The 20th National Congress of the Communist Party of China emphasized the need to improve financial, tax, investment, pricing policies, and standards systems that support green development and the development of green, low-carbon industries.

Meanwhile, China's financial development and technological innovation have been rapidly advancing this year, not only promoting the optimization of industrial structure, thereby facilitating the low-carbon development of enterprises but also significantly reducing pollution emissions by introducing investments in technological innovation. The impact of financial development and technological innovation on carbon emissions reduction should not be underestimated. The government needs to accelerate the green transformation of development patterns and the development and application of advanced energy-saving and emission-reducing technologies.

In light of these developments, this paper will investigate the efficiency of financial development on carbon emissions, incorporating factors such as technological innovation, industrial structure, and

considering the differences and regulatory effects of carbon emissions across different provinces. The research will utilize quantile regression models and moderation effect models to further analyze the relationships between financial efficiency, financial scale, technological innovation, and carbon emissions. Therefore, questions such as the current status of carbon emission efficiency in various provinces in China, whether financial efficiency and scale have inhibitory effects on carbon emissions, and how technological innovation promotes carbon emission efficiency improvement and its underlying mechanisms need to be further studied in the current process of sustainable economic and social development in China.

2. Literature Review

In recent years, many domestic scholars have conducted in-depth research on financial development, technological innovation, and carbon emissions, achieving rich results. Zhang Ruifeng and Liu Shuai (2023) conducted a study based on panel data from 30 provinces and autonomous regions from 2005 to 2019, establishing a spatial panel model. They believe that financial development has a restraining effect on carbon emissions, and spatial spillover effects decline with distance. There is spatial heterogeneity in the impact of carbon emissions. Yu Xiaoyu (2023), combining nearly 20 years of data on per capita GDP and technological progress in China, analyzed the impact of various factors on carbon emissions from multiple perspectives. They argued that financial relevance and technological progress can suppress carbon dioxide emissions, and the inhibitory effect of financial system efficiency on carbon emissions is relatively small. Du Jianyong and Cao Wenchan (2022) measured the development of green finance from four dimensions: green credit, green insurance, green investment, and government spending. They found that it can effectively reduce carbon emission intensity and alleviate financing constraints, promote industrial upgrading and technological innovation, facilitating carbon reduction.

Tian Li and Wu Xuxiao (2023) selected panel data from 30 provinces in China for the years 2011-2020 to examine independent and synergistic effects. They found that urbanization has a significant promoting effect on carbon emission efficiency in both the national and central-western regions. Additionally, technological innovation has a significantly promoting effect on carbon emission performance in the national and eastern regions. Fang Xingcun and Xue Fan (2023), using panel data from 26 prefecture-level cities in the Yangtze River Delta region for the years 2003-2021, constructed a spatial econometric model to study the impact of economic growth and technological innovation on carbon emissions. They observed significant positive spatial correlations among economic growth, technological innovation, and carbon emissions.

Pan Haiying et al. (2023), based on China's provincial panel data from 2008 to 2020, constructed a panel threshold model to test the nonlinear effects of green finance development on carbon emissions. The study found a dual-threshold effect of green finance development on carbon emissions. As the financial ecosystem successively crossed two threshold values, the carbon reduction effect of green finance development gradually strengthened. Zhang Hongrui and Wu Ping (2023), using provincial panel data from 2008 to 2020 and employing a spatial Durbin model for empirical analysis, argued that green credit has a significant inhibitory effect on carbon emissions and spatial spillover effects. Environmental regulation plays a significant moderating role in the inhibitory effect of green credit on carbon emissions. Zhao Yuxiang and Liu Jun (2023), based on provincial panel data from 2005 to 2019, elaborated on the impact mechanism of green technological innovation on carbon emission efficiency from the perspectives of industrial structure upgrading and reducing carbon emission intensity. They indicated that substantive green technological innovation can significantly improve carbon emission efficiency, while strategic green technological innovation has no effect. Lan Zhongju and Mai Qiangsheng (2023), based on China's provincial panel data from 2011 to 2019, found that digital finance inhibits the improvement of carbon emission efficiency and has an opposite trend to its carbon emission efficiency. However, the mediating role of industrial structure upgrading

and technological innovation manifests as the promotion of carbon emission efficiency by digital finance.

In summary, domestic scholars have predominantly focused on studying the inhibitory effect of financial development on carbon emissions, with a relatively narrow research scope. There is insufficient research on the interactions between financial development, technological innovation, and carbon emissions. Moreover, there is a lack of in-depth exploration into the impacts of financial scale and financial efficiency on carbon emissions, as well as whether technological innovation has a moderating effect on carbon emissions. Based on this, using China's provincial panel data from 2008 to 2017 as the research sample, this paper examines the effectiveness of financial development on carbon emissions. The emphasis is on exploring the roles of financial scale and financial efficiency and investigating how the inhibitory effect of financial development on carbon emissions varies with the development of technological innovation. The goal is to provide a theoretical basis for optimizing the external environment in China's carbon reduction practices.

3. Mechanisms

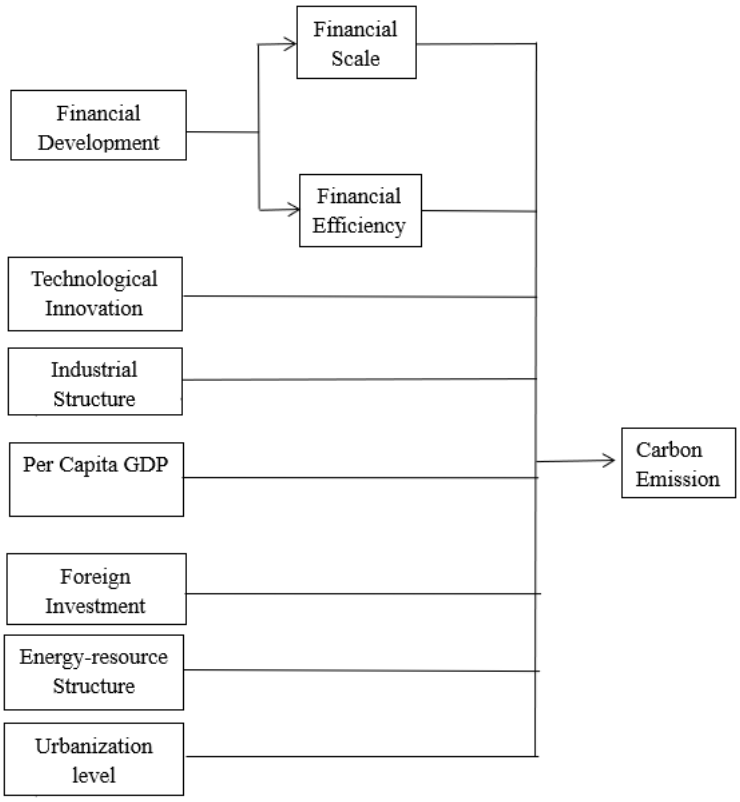

Figure 1. Mechanisms of financial development, technological innovation and industrial structure on carbon emissions

In Figure 1, the mechanism of the impact of eight variables including financial development, technological innovation, and industrial structure on carbon emissions is illustrated. This primarily reflects how financial scale, financial efficiency, technological innovation, and industrial structure influence carbon emissions. Financial development not only provides abundant funds for the research and innovation of green industries by expanding financing through financial scale, promoting the development of low-carbon and environmentally friendly industries, and increasing public awareness of carbon reduction; but also, through financial efficiency, it optimizes industrial structure and resource allocation to maximize economic benefits while ensuring carbon reduction. This encourages industries to accelerate energy transformation, improve energy efficiency, attract more foreign investment, drive technological innovation, and ultimately reduce carbon emissions.

4. Model and Data

4.1. Quantile regression model

The basic equation for quantile regression is:

$$Lny=aLnx_1+bLnx_2+cLnx_3+dLnx_4+eLnx_5+fLnx_6+gLnx_7+hLnx_8+z \quad (1)$$

Where y is the explanatory variable, x1-x8 are the explanatory variables, a-h are the regression coefficients, and z is the constant term.

In this paper, eight factors such as financial scale and financial efficiency are analyzed for their impact on carbon emissions, and the following quantile regression model is set:

$$LnCE=aLnFS+bLnFE+cLnTI+dLnIS+eLnPCG+fLnFI+gLnERS+hLnUI+z \quad (2)$$

Among them, *LnCE* represents carbon emissions, and *LnFS, LnFE, LnTI, LnIS, LnPCG, LnERS, LnFI* and *LnUI* represent financial scale, financial efficiency, technological innovation, industrial structure, GDP per capita, energy structure, foreign investment, and urbanization level, respectively.

4.2. Moderated effects model

Considering that technological innovation has a moderating effect on financial development, the inclusion of the technological innovation variable makes the financial efficiency variable more significant. Assuming the moderating effect holds, the improvement in financial efficiency, along with the increase in technological innovation, is hypothesized to have a stronger promoting effect on reducing carbon emissions.

4.3. Data sources and description of variables

The carbon emissions data for each province are obtained from the CEADs database. Financial development data is divided into financial scale and financial efficiency. The financial scale for each province is calculated by dividing the loan balance by GDP, and the financial efficiency for each province is calculated by dividing loans by deposits. The data sources for financial development are from the "China Financial Statistics Yearbook." Technological innovation for each province is represented by internal expenditure on R&D, and the data source is the "China Science and Technology Statistics Yearbook." Industrial structure data for each province is determined by the ratio of the value-added of the secondary and tertiary industries, and the data source is the "China Statistical Yearbook." Energy structure for each province is represented by the percentage of coal consumption, and the data sources are the "China Energy Statistics Yearbook" and the "Energy Balance Sheet of Provinces." Per capita GDP, foreign direct investment for each province are sourced from the "China Statistical Yearbook." Urbanization level is determined by urban built-up area, and the data source is the "China Urban Statistics Yearbook."

(1) Dependent Variable:

The dependent variable in this study is carbon emissions, using provincial carbon emissions data from the China Carbon Accounting Database as the measurement indicator.

(2) Independent Variables:

The core independent variables in this study are financial efficiency, technological innovation, and industrial structure. For financial efficiency, the ratio of loans to deposits in each province reflects both the market economy situation and the profitability of banks, serving as a measure of financial efficiency. For technological innovation, the internal expenditure on research and development (R&D) in each province reflects the scale and level of technological investment, as well as the actual technological innovation performance of enterprises, making it a measure of technological innovation. For industrial structure, the ratio of value-added of the secondary and tertiary industries in each province can assess the development level and optimization direction of industrial structure, serving as an indicator of industrial structure.

(3) Control Variables:

This study includes control variables such as per capita GDP, foreign direct investment, energy structure, and urbanization level, which may affect carbon emissions.

Table 1. Descriptive statistics for each variable

variables	mean	standard deviation	minimum	maximum
CE	301.99	194.76	24.80	842.20
FS	1.33	0.46	0.58	2.54
FE	0.74	0.14	0.23	1.09
TI	3736680.00	4425753.00	33479.20	2.34e+07
IS	1.04	0.60	0.50	4.24
PCG	44994.92	24010.86	8824.00	128927.00
ERS	0.43	0.15	0.04	0.72
FI	0.37	0.46	0.06	4.60
UI	1567.53	1128.52	110.65	5808.12

The maximum and minimum values are shown above.

5. Empirical Analysis

Table 2 presents the regression results for eight variables, including financial efficiency, financial scale, technological innovation, etc., and their significant heterogeneity in influencing carbon reduction. The impact of each variable on carbon reduction varies at different levels of carbon emissions.

The regression results indicate that at the 10th percentile level, financial scale, financial efficiency, technological innovation, and industrial structure are all significant. For each 1% increase in financial scale, carbon emissions decrease by 0.128%, a 1% increase in financial efficiency corresponds to an increase of 0.358% in carbon emissions, a 1% increase in technological innovation results in an increase of 0.0585% in carbon emissions, and a 1% increase in industrial structure corresponds to a decrease of 0.298% in carbon emissions. At the 25th percentile level, industrial structure is significant, with a 1% increase resulting in a corresponding decrease of 0.366% in carbon emissions.

At the 50th percentile level, financial efficiency, technological innovation, and industrial structure are significant. A 1% increase in financial efficiency leads to a 0.276% decrease in carbon emissions, a 1% increase in technological innovation results in a corresponding decrease of 0.171% in carbon emissions, and a 1% increase in industrial structure corresponds to a decrease of 0.304% in carbon emissions. At the 75th percentile level, financial efficiency and technological innovation are significant. A 1% increase in financial efficiency leads to a corresponding decrease of 0.680% in carbon emissions, and a 1% increase in technological innovation results in a corresponding decrease of 0.247% in carbon emissions.

At the 90th percentile level, financial scale, financial efficiency, and technological innovation are all significant. A 1% increase in financial scale leads to a 0.231% increase in carbon emissions, a 1% increase in financial efficiency corresponds to a 0.689% decrease in carbon emissions, and a 1% increase in technological innovation leads to a 0.225% decrease in carbon emissions.

In summary, financial efficiency has a negative impact on carbon emissions. In areas with low carbon emissions, the impact is positive, while in areas with higher carbon emissions, the impact of financial efficiency on carbon emissions is greater. Industrial structure has a negative impact on carbon emissions. In areas with lower carbon emissions, the impact of industrial structure upgrading on carbon reduction is greater. Technological innovation has a negative impact on carbon emissions in areas with medium to high levels of carbon emissions, while the impact is not significant in areas with low levels of carbon emissions. Per capita GDP, energy structure, and urbanization level have an overall positive impact, while foreign direct investment has a negative impact. Overall, financial efficiency, technological innovation, and industrial structure upgrading have the most prominent impact on carbon reduction.

Table 2. Quantile regression results

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	10%	25%	50%	75%	90%
LnFS	-0.0279	-0.128*	-0.0175	-0.104	0.105	0.231***
	(0.0767)	(0.0699)	(0.113)	(0.0895)	(0.145)	(0.0802)
LnFE	-0.244***	0.358***	-0.0163	-0.276***	-0.680***	-0.689***
	(0.0882)	(0.0804)	(0.131)	(0.103)	(0.167)	(0.0923)
LnTI	-0.108***	0.0585*	0.0106	-0.171***	-0.247***	-0.225***
	(0.0365)	(0.0333)	(0.0541)	(0.0427)	(0.0692)	(0.0382)
LnIS	-0.189***	-0.298***	-0.366***	-0.304***	-0.149	-0.0521
	(0.0675)	(0.0615)	(0.0999)	(0.0788)	(0.128)	(0.0706)
LnPCG	0.457***	0.0556	0.195**	0.534***	0.736***	0.623***
	(0.0616)	(0.0562)	(0.0912)	(0.0720)	(0.117)	(0.0645)
LnERS	0.584***	0.106*	0.292***	0.433***	0.718***	0.700***
	(0.0598)	(0.0545)	(0.0884)	(0.0698)	(0.113)	(0.0625)
LnFI	-0.0596**	-0.140***	-0.0711*	-0.0566*	-0.0611	-0.131***
	(0.0281)	(0.0256)	(0.0415)	(0.0328)	(0.0532)	(0.0294)
LnUL	0.824***	0.703***	0.745***	0.926***	0.956***	0.938***
	(0.0530)	(0.0483)	(0.0785)	(0.0619)	(0.100)	(0.0555)
_cons	-3.276***	-1.236***	-2.068***	-4.077***	-5.006***	-3.998***
	(0.497)	(0.453)	(0.735)	(0.580)	(0.941)	(0.519)

Table 3 presents the results of the moderation effect regression. The results indicate that after adding the moderating variable technological innovation, the significance level of the model's core explanatory variable, financial efficiency, significantly increases. This suggests the presence of a moderation effect.

Table 3. Moderated effects regression results

	Model 1	Model 2	Model 3	Model 4	Model 5
	LnCE	*LnIS*	*LnPCG*	*LnCE*	*LnCE*
LnFS				-0.037	-0.023
				(0.080)	(0.079)
LnFE	-0.169**	-0.721***	-0.451***	-0.157*	-0.243***
	(0.084)	(0.135)	(0.068)	(0.088)	(0.092)
LnTI					-0.112***
					(0.037)
LnIS	-0.202***	0.133		-0.188**	-0.179**
	(0.069)	(0.110)		(0.075)	(0.074)
LnPCG	0.354***	1.120***	0.044	0.362***	0.485***
	(0.0588)	(0.0942)	(0.051)	(0.061)	(0.073)
LnERS	0.576***	0.062	-0.526***	0.577***	0.584***
	(0.063)	(0.101)	(0.045)	(0.063)	(0.062)
LnFI	-0.080**	0.047	-0.005	-0.079**	-0.074**
	(0.035)	(0.055)	(0.030)	(0.035)	(0.034)
LnUL	0.696***	1.230***	-0.040*	0.690***	0.830***
	(0.252)	(0.040)	(0.022)	(0.028)	(0.054)

6. Research findings and policy recommendations

Researching from the current national situation in China and considering the introduction of the dual-carbon policy, this study, based on panel data from 29 cities between 2008 and 2017, investigates the impact of financial development on carbon emissions. By establishing a moderation effect model

and regressing eight variables, including financial efficiency, technological innovation, and industrial structure, the study suggests:

(1) Overall, financial development plays a suppressive role in carbon emissions in surrounding areas. Financial efficiency has a negative impact on carbon emissions, and this impact is greater in areas with higher carbon emissions.

(2) Industrial structure has a negative impact on carbon emissions, and in areas with lower carbon emissions, upgrading the industrial structure has a greater impact on carbon reduction.

(3) Technological innovation has a negative impact on carbon emissions in areas with medium to high levels, and the impact is not significant in low-level areas. The introduction of the moderating variable of technological innovation enhances the significance level of financial efficiency.

(4) Per capita GDP, energy structure, and urbanization level have an overall positive impact, while foreign investment has a negative impact.

Based on the empirical analysis in this study and considering the current background of green financial development, carbon neutrality, and peak carbon policies, the following recommendations are proposed:

(1) To address the issue of low financial efficiency in traditional financial institutions due to information asymmetry, promoting the development of regional chains and accelerating the circulation speed of digital currencies can reduce transaction costs and improve financial efficiency. Additionally, cross-industry collaboration should be encouraged to provide more personalized solutions for different clients, further enhancing financial efficiency.

(2) Carbon emission levels are influenced by differentiation and heterogeneity. Sensitivity to factors such as financial development, technological innovation, and industrial structure varies among regions. Therefore, tailored strategies should be adopted for different regions. In areas with higher carbon emission levels, emphasis should be placed on enhancing financial efficiency. In areas with lower carbon emission levels, in-depth research on upgrading industrial structures and exploring the impact of technological innovation on regions with medium to high carbon emissions should be prioritized.

(3) Pay attention to the regulatory role of technological innovation in carbon emissions. With the increasing level of technological innovation, the significance level of financial efficiency is significantly enhanced. Industries should be encouraged to invest in green innovation projects, providing ample financial support for the development of innovative green products. Rewards for technological innovation should be strengthened to elevate the development level of high-tech industries.

(4) Improve energy structure and promote green and renewable energy. Actively promote the optimization of energy structure, guide industries towards green transformation, encourage enterprises to use clean energy, and refine policies and regulations. Further detail the development goals of various green industries and introduce corresponding rewards and penalties based on goal achievements.

(5) Strengthen the attraction of foreign investment, diversify channels for attracting foreign capital, and provide preferential policies to encourage foreign enterprises to introduce emerging technologies. Foster innovation enthusiasm in relevant enterprises and enhance the legal framework for foreign investment. Increase personnel allocation for foreign-funded enterprises and establish special coordination mechanisms for significant foreign-funded projects to promptly address encountered issues.

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