Financial development, heterogeneous technological progress, and carbon emissions: Empirical analysis based on Provincial Panel Data in China

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Financial development, heterogeneous technological progress, and carbon emissions: Empirical analysis based on Provincial Panel Data in China

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Abstract

Global warming, caused by an increase in carbon emissions, is a phenomenon that has attracted considerable attention worldwide. Financial development affects technological progress and carbon emissions. Based on the provincial panel data of 30 provinces and cities in China from 2006 to 2018, combined with the heterogeneity of technological progress, this study constructs an intermediary effect model for empirical analysis. Combined with different regional characteristics in the east, middle, and west of China, this study explores the impact of financial development on carbon emissions and the transmission path of heterogeneous technological progress as an intermediary variable. The results show that at the national level, in the eastern and central regions, the relationship between financial development and carbon emissions conforms to the characteristics of Environmental Kuznets curve, and the relationship between financial development and carbon emission in the western region increases linearly. Among the intermediary effect transmission paths of heterogeneous technological progress, generalised technological progress, environmental technological progress, energy technological progress, capital embodied technological progress and FDI technology spillover are the transmission paths of financial development on carbon emissions at the national level. However, after the regional division of the east, middle, and west, heterogeneous technological progress shows different carbon emission reduction effects. Through quantitative analysis, this study provides reference suggestions for financial development to help reduce carbon emissions, to prevent the emergence of ‘one size fits all’ technology policy or regional overall planning concept.

Keywords：Financial development; Technological progress; Heterogeneity; Carbon emissions

Introduction

The fifth anniversary of the 22 April signing of the Paris Agreement was on the 22nd Apirl 2021, which marked the beginning of the climate summit attended by world leaders. At the summit, climate change, renewable energy, and green economic development received great attention from all countries. Chinese President Xi Jinping delivered a speech titled ‘Jointly Building a Community of Life between Man and Nature’ in which he elaborated on the importance of China, as a developing country, to uphold the harmonious coexistence between human beings and nature while liberating and developing productive forces. The implementation of China’s reform and opening-up strategy has led to remarkable achievements. In the early stages of rapid industrialisation, urbanisation, and economic development, high energy consumption and environmental pollution are inevitable. As of 2020, the evaluation results of the Environmental Performance Index (EPI) released by a global authority reveal that China’s worldwide EPI ranking is still low. Meanwhile, the world is facing extreme weather conditions, which means that it is very important to improve energy utilisation, accelerate technological progress, reduce hydrocarbon emissions, and achieve carbon peak as soon as possible. In the outline of China’s 2035 long-term plan, economic development, scientific and technological progress, and ecological civilisation construction are given equal importance. Developing a low-carbon economy is the only way to achieve energy conservation and emission reduction, and economic development is inseparable from financial development. Finance plays an important part in optimising the allocation of funds, guiding the adjustment of industrial structure, and improving the marginal productivity of capital in the modern economic system. The Chinese government has also been committed to integrating regional financial development with a low-carbon economy and achieving carbon emission reduction targets in the socio-economic environment through continuous improvement of technological progress. In view of this, the relationship between financial development and carbon emissions has been constantly explored. Can financial development reduce the intensity of carbon emissions? Is technological progress an intermediary path for financial development that affects carbon emissions? Do different types of technological progress have different effects on the financial development and carbon emission transmission paths? Is there any difference in the impact of financial development on carbon emissions between different regions in China?

Based on the above problems, this study selects provincial panel data of 30 provinces, cities, and autonomous regions from 2006 to 2018. Using the intermediary effect model, this study compares the impact of financial development on carbon emissions across the country and among different regions and compares the impact, path and effect of heterogeneous technological progress on the relationship between financial development and carbon emissions among different regions in China. This analysis can enrich the theoretical basis for the development of a low-carbon economy in different regions and provide relevant reference suggestions.

Literature review

Several studies show that financial development has impact on carbon emissions. Grossman and Krueger (1991) combined economic problems with environmental problems in their early stages, proposed the Environmental Kuznets Curve (EKC) and believed that the direct relationship between economic development and environmental pollution was an inverted U-shaped one. Financial development and economic development promote each other. At the same time, financial development will also bring technological progress and improve the total output level of domestic goods and services (Wang and Sun, 2006; Fan, 2006). Levine (1997) believes that 'market failure' is inevitable. Finance plays an intermediary role in the market economy, which can make resource allocation more efficient. Industrial enterprises benefit from financial development, and if financing conditions are more convenient, the production scale can be expanded, and the consumption of raw materials, mainly coal, carbon, and crude oil, increases (Zhang, 2011). One view is that financial development is accompanied by an improvement in energy consumption level, and the consumer credit market will see an upsurge as consumer demand for cars and houses increases, which will lead to an increase in carbon emissions (Mahalik, 2016;Sadorsky, 2010). Another view is that financial development can facilitate industrial enterprises to obtain loans and increase R&D investment to alleviate the financing difficulties encountered by industrial enterprises to a certain extent. Thus, the technical level of industrial enterprises and the resource utilization rate can be improved, and the unit energy consumption can be reduced, to achieve the purpose of reducing the carbon emission level (Tamazian, 2009; Shahbaz et al., 2013). Xu and Song (2010) concluded through empirical research and analysis that the relationship between economic growth and carbon emissions is nonlinear, and there is a time inflexion point. Some regions comply with the inverted U-shaped characteristics of the Kuznets curve of carbon emissions, and the trend of the relationship between economic growth and carbon emissions is different among different regions in China. Hu et al. (2018) analysed the relationship between China's financial development and carbon dioxide emissions to verify whether the relationship between financial development and carbon emissions has the characteristics of the Kuznets curve. In the empirical model design, the square term of the financial development proxy variable is added. Finally, it is concluded that the relationship between financial development level and carbon emissions first rises and then restrains, which is consistent with the concept of the environmental Kuznets curve.

The development of a low-carbon economy and the realisation of carbon emission reduction cannot be separated from technological progress. In a special report made by the Intergovernmental Panel on Climate Change (IPCC) in 2018, it was proposed that global warming should be controlled within 1.5°C, and carbon emission reduction through technological progress was the consensus reached by all countries. Zhu et al. (2010) applied STIRPAT model to investigate the impacts of population, wealth and technology on carbon emissions.It concluded that the impact of technological progress on carbon emission is not great in the sample time interval in the empirical study, but the potential of technological progress on carbon emission reduction is still unlimited in the future. Wei and Yang(2010) applied endogenous growth theory to an empirical analysis of the impact of technological progress on carbon dioxide emissions and found that technological progress was conducive to carbon emission reduction and further concluded that there were regional differences in the impact of technological progress on carbon emissions in the analysis of sub-samples in different regions. Owing to the time lag in technological progress, more attention should be paid to encouraging technological innovation in assisting carbon emission reduction with technological progress (Li et al.,2014). Jaffe et al.(2002) studied the relationship between environmental development and technological change and found that the relationship between technological progress and carbon emission reduction could not be treated in a general way. Technological progress may increase or reduce carbon emissions. The types of technological progress includes pollution and clean, and the effect on carbon emissions is heterogeneous (Acemoglu et al., 2012). Technological progress is also divided into many types and is not represented just by a single indicator. After dividing technological progress into energy use technology, CO_2 emission technology, and broad technological innovation, it has been found that CO_2 emission technological progress has the most significant inhibitory effect on carbon emission reduction (Xu et al., 2020). The effects of technological progress on carbon emissions differ between industries. Zhang et al.(2017) selected 37 industries as samples for analysis and found that technological progress has a more obvious inhibition effect on carbon emissions in industries with high energy efficiency. Since the economic reform and opening-up, China's economy has been undergoing industrial structure adjustment and speed shift, and the influencing factors of carbon emissions at different stages are different. Lu et al.(2013) divided economic growth into five stages, investigated the influencing factors of carbon emissions in different economic development stages, and indirectly explained that the carbon emission reduction effect of technological progress is different in different stages of economic development.

In recent years, financial development, technological progress, and carbon emissions have been brought into the same framework as the research elements. Research on the development of a regional low-carbon economy by analysing these three elements has attracted increasing attention within academic circles. Ma et al. (2018) constructed a spatial panel data model and adopted the spatial econometric method to decompose financial development indicators into the financial development scale and financial development structure. Multiple indicators were selected as the representative variables of technological progress. They found that financial development structure indicators and the number of patent grants representing technological progress and technology spillover from foreign investment have a positive impact on low-carbon economic development. Chen et al. (2020) believe that pure financial development or technological progress cannot effectively promote carbon emission reduction, and it requires the synergy of financial development and technological progress to promote carbon emission reduction. In addition, they believe that the technological progress that contributes to carbon emission reduction is not universal, but biased, such as green technological progress and technological innovation. Yan et al. (2016) believed that financial development contributes to technological progress and innovation by building an endogenous growth model, to promote the transformation of economic development to low-carbon and energy conservation. However, in terms of analysing the impact of financial development and technological progress on carbon emissions by combining the characterisation of various technological progress, there are still few studies that incorporate technological progress into the transmission path of financial development on carbon emissions and further analyse the impact of heterogeneity of technological progress on carbon emission reduction.

The possible marginal contributions of this study are as follows: (1) Combining the financial development theory and the concept of the environmental Kuznets curve and constructing a mediating effect model that uses technological progress as a transmission path for financial development and carbon emissions. (2) Decomposing technical progress indicators from multiple perspectives, such as the energy utilisation rate, capital utilisation rate, and foreign investment conversion rate, can reduce the defects of a single indicator. (3) Combined with the reality of China's vast territory, it is necessary to explore what kind of technological progress can better promote carbon emission reduction through financial development in some regions of the east, middle, and west, which is helpful in formulating green financial policies according to local conditions.

Methodology and data

Brief introduction of intermediary variable method

This study draws from MacKinnon et al. (2002) and Zhonglin Wen et al. (2005) on the empirical test method of mediation effect, as shown in Figure 1. If the independent variable X can affect the dependent variable Y, but its transmission path is that the independent variable X first affects the variable M, and then, through the variable M to affect the dependent variable Y, then M is called an intermediate variable. According to the mediation effect theory, the method of sequentially testing the regression coefficients is as follows: if the coefficient c in equation (1) is significant, the independent variable X has a significant influence on the dependent variable Y; if a in equation (2) is significant, the independent variable X significantly affects the intermediate variable M; if the coefficient c' in equation (3) is completely insignificant and the coefficient b is significant, it indicates that the influence of the independent variable X on the dependent variable Y is completely realised by the intermediary variable M. At this time, the intermediary variable M is called a complete intermediary variable, that is, a complete mediation effect exists. If both the coefficient c' and the coefficient b in equation (3) are significant, it indicates that there is an incomplete mediating effect, and the variable M is a partial mediating variable of the independent variable X affecting the dependent variable Y.

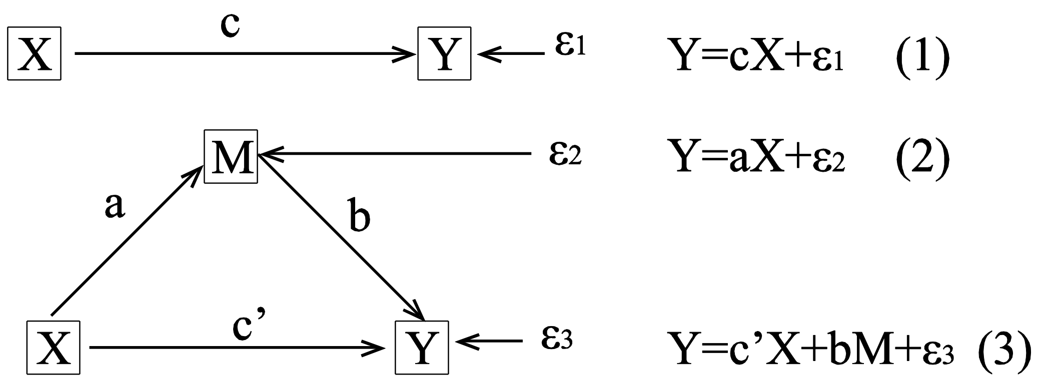

Figure 1 Test Path Diagram of Intermediate Variables

Source: Zhonglin Wen, Lei Zhang, Jieqin Hou, and Hongyun Liu. Testing and application of mediating effects. Acta Psychologica Sinica. 2004,36(5):614-620

Empirical model

According to the test theory of intermediary variables, as shown in Figure 1, first, an econometric model of financial development and carbon emissions is constructed to test the relationship between financial development and carbon emissions.

$$CI_{it} = \alpha_0 + \alpha_1 FD_{i,t-1} + \alpha_2 FD^2{}_{i,t-1} + \sum \alpha_j Z_{it} + v_i + v_{t+} \varepsilon_{it} \quad (4)$$

Then, the mediation effect model of financial development and technological progress, as well as financial development, technological progress, and carbon emissions, is constructed as follows:

$$T_{it} = \beta_0 + \beta_1 FD_{i,t-1} + \sum \beta_j Z_{it} + v_i + v_t + \varepsilon_{it} \quad (5)$$

$$CI_{it} = \gamma_0 + \gamma_1 FD_{i,t-1} + \gamma_2 FD^2{}_{i,t-1} + \gamma_3 T_{i,t-1} + \sum \gamma_j Z_{it} + v_i + v_t + \varepsilon_{it} \quad (6)$$

Where i represents the province, t represents the year, and the dependent variable CI represents the carbon emission intensity, which is the explained variable; The independent variable FD represents financial development, and is the core explanatory variable; T represents technological progress; Z is the control variable, including regional openness ($Open$), human capital (Hc), infrastructure level ($Infr$), industrial structure ($Stru$), and urbanisation level (Urb); V_i represents the individual effect, V_t represents the time effect, ε represents the random error term, and a_0 is the constant term of model (3). The square term of financial development (FD^2) is added to the model to verify whether there is an inverted U-shaped relationship between financial development and carbon emissions. If the coefficient a_2 of the square term (FD^2) of financial development is negative, it indicates that there is an inverted U-shaped relationship between financial development and carbon emissions, which is consistent with the concept of the relationship between economic development and pollutant emissions emphasised by the Environmental Kuznets curve (EKC). To enhance the robustness of the model results and prevent reverse causality, the core explanatory variable FD is selected to lag for one period. β_0 and γ_0 are the constant terms of models (5) and (6) respectively. If, a_1 β_1, γ_1 and γ_3 are all significant in the regression results of models (4) , (5) , and (6), it indicates that financial development can indirectly affect carbon emissions by influencing the path of technological progress. At this time, technological progress, as a mediator variable, has a partial mediation effect. If, a_1 β_1, and γ_3 are significant but γ_1 is no longer significant, it means that the conduction path of financial development to carbon emissions is completely realised through technological progress, and technological progress has a completely mediating effect at this time.

Data sources

This study selects provincial panel data of 30 provinces and cities in China from 2006 to 2018. Owing to the lack of numerical values in the statistical data of Hong Kong, Macao and Taiwan, they were excluded from the sample. The various energy consumption data involved in the carbon emission calculation are all from the 'China Energy Statistical Yearbook' and the information data published by the IPCC. The deposit and loan balance data of financial institutions were obtained from the official website of the People's Bank of China. The statistical data of domestic patent application authorisation comes from the 'China Science and Technology Statistical Yearbook'. The relevant data on fixed asset investment comes from the 'Statistical Yearbook of China's Fixed Asset Investment'. Foreign direct investment data are obtained from the Wind database and the 'China Foreign Economic Statistics Yearbook'. Regional GDP figures and other data are from the 'China Statistical Yearbook'.

Variable selection

(1) Explained variables

In this study, the ratio of total carbon emissions to GDP was calculated as the index of carbon emission intensity, to quantify the degree of carbon emissions. The larger the value, the more CO_2 per unit output, which means that it is imperative to develop a low-carbon economy and take the intensive economic growth route. The estimation of carbon emissions refers to the formulation method of the IPCC, and the specific calculation method is as follows:

$$CO_2 = \sum_{i=1}^{14} E_i \times NCV_i \times CEF_i \qquad (7)$$

$$CEF_i = CC_i \times COF_i \times (44/12) \qquad (8)$$

Where CO_2 represents the amount of carbon dioxide emissions to be estimated, i represents various energy fuels, E_i represents the burning consumption of the various energy sources, NCV_i represents the average low calorific value of various energy sources, CEF_i represents the carbon dioxide emission factor of various energy sources, CC_i is the carbon content of various energy sources and COF_i represents the carbon oxidation factor of the various energy sources. $(44/12)$ is the molecular weight ratio of carbon dioxide to carbon. The indicators involved in the carbon emission calculation method are listed in Table 1.

Table 1 Average low calorific value and carbon dioxide emission factor of various energy sources

Energy name	Coal	Coke	Coke oven gas	Blast furnace gas	Converter gas	Other gas	Crude oil
NCV (kj/kg)	20908	28435	17981	3855	8585	18273.6	41816
CEF (Kg/TJ)	95977	105996	44367	259600	181867	44367	73333
Energy name	Gasoline	kerosene	Diesel oil	Fuel oil	Liquefied petroleum gas	Natural gas	Liquefied natural gas
NCV (kj/kg)	43070	43070	42652	41816	50179	38931	44200
CEF (Kg/TJ)	70033	71500	74067	77367	63067	56100	64167

Source: China Energy Statistical Yearbook and IPCC

(2) Explanatory variables

The core explanatory variable of this study was financial development. Financial development not only refers to the change in financial transaction flow in successive stages but also includes the relative change in financial structure at each time point. Many quantitative indicators measure financial development. This study refers to the financial correlation ratio (FIR) selected by Liang Chen et al. (2020) as the financial development indicator. The deposit and loan balance of financial institutions represents the total amount of financial transaction activities, and regional GDP represents the total amount of economic activities in the region. Since FIR is the ratio of the total amount of financial activities to the total amount of economic activities in a certain period, this study sets the proxy variable of financial development as the ratio of the balance of deposits and loans of financial institutions to GDP, which is directly proportional to the development of monetary and financial markets.

(3) Heterogeneous technological progress indicators

To analyse the difference between different types of technological progress for financial development and carbon emission transmission paths, this study selects five variables to represent technological progress (T) and constructs heterogeneous technological progress indicators, including generalised technological progress ($Tech$), environmental technological progress (ET), energy technology progress (IE), capital embodied technology progress (KE), and FDI technology spillover ($TFDI$).Among them, generalised technological progress ($Tech$) is represented by the number of domestic patent applications granted. To ensure the stability and convergence of the data, the logarithmic form of this variable was adopted. The value is proportional to the technological level; that is, the larger the value, the more technological innovation achievements, higher production efficiency and higher technical level. Environmental technology progress (ET) is expressed as the ratio of carbon emissions to energy consumption. The larger the value, the higher the carbon emission per unit energy consumption and the lower the technological level. Energy technology progress (IE) is expressed in terms of energy consumption per unit of GDP. The larger the value, the more energy is consumed to create a unit of GDP, which means at lower level of technology. Capital embodied technological progress (KE) is expressed as the ratio of GDP to physical capital stock. The calculation method of physical capital stock refers to the calculation method of Shan (2008) and Zhang (2015) using the perpetual inventory method (PIM). The larger the value of capital-embodied technological progress (KE), the higher the GDP per unit of physical capital stock, while at the same time, the utilisation rate of material capital is high, and the level of technological progress is also high. FDI technology spillover ($TFDI$) is expressed as the ratio of the actual foreign direct investment of each province converted into RMB at the standard exchange rate to the GDP of each province. This indicator reflects the development of low-carbon technology, while the introduction of external technology promotes the updating of corporate management concepts. The higher the value of this indicator, the higher the level of technological progress. According to the above analysis, the variable of technological progress (T) is represented by the following formula:

$$T = T(Tech, ET, IE, KE, TFDI) \quad (9)$$

(4) Control variables.

To make the research results more convincing, this study selects the degree of regional openness ($Open$), human capital (Hc), infrastructure level ($Infr$), industrial structure ($Stru$) and urbanisation level (Urb) as control variables. The degree of regional openness ($Open$) is expressed as the ratio of the total import and export volumes of each province to GDP. Human capital (Hc) is expressed as the average years of education of employees in each province. The infrastructure level ($Infr$) is measured by the total mileage of roads and railways per square kilometre in each province. The industrial structure ($Stru$) is expressed as the ratio of the added value of the secondary industry in each province to the GDP of the year (Hu et al., 2018). The urbanisation level (Urb) is expressed as the ratio of the urban population of each province to the total population.

Research results and analysis

Descriptive statistics and correlation analysis

In this study, the mean, standard deviation, and Pearson correlation analysis results for the main variables are listed in Table 2. In the correlation coefficient matrix of Table 2, the core explanatory variable FD significantly affects the CI variable negatively, and the specific value is -0.273, which means that for every unit increase in the level of financial development, the carbon emission intensity will decrease by 0.273 units. Among heterogeneous technological progress indicators, $Tech$ KE, $TFDI$ and CI are significantly negatively correlated, indicating that the improvement of generalised technological progress, capital embodied technological progress and FDI technology spillover level will reduce carbon emission intensity. ET IE and CI are significantly positively correlated, and their correlation coefficient values are 0.592 and 0.848, respectively. This indicates that when the value of the environmental technology progress variable and energy technology progress variable increases by one unit, the carbon emission intensity increases by 0.592 and 0.848 units, respectively. Since the variables of environmental technological progress and energy technological progress are reverse variables, an improvement in the level of environmental technological progress and energy technological progress will lead to a decline in carbon emission intensity in the correlation analysis. Among the control variables, *Stru* and *CI* show a positive correlation, indicating that the increase in the ratio of the added value of the secondary industry to GDP will lead to an increase in carbon emission intensity; the other control variables are all negatively correlated with carbon emission intensity to varying degrees.

Table 2 Mean value, standard deviation and correlation coefficient matrix of each variable

Variable	CI	FD	Tech	ET	IE	KE	TFDI
CI	1.000						
FD	-0.273***	1.000					
Tech	-0.655***	0.237***	1.000				
ET	0.592***	-0.332***	-0.247***	1.000			
IE	0.848***	-0.233***	-0.741***	0.200***	1.000		
KE	-0.310***	-0.044	0.345***	-0.171***	-0.276***	1.000	
TFDI	-0.304***	0.120**	0.273***	0.018	-0.411***	0.324***	1.000
Open	-0.361***	0.520***	0.440***	-0.215***	-0.399***	0.441***	0.505***
Hc	-0.361***	0.620***	0.502***	-0.092*	-0.528***	0.013	0.429***
Infr	-0.105**	-0.450***	0.339***	-0.018	-0.134***	0.113***	-0.315***
Stru	0.273***	-0.670***	-0.065	0.206***	0.262***	0.045	-0.025
Urb	-0.414***	0.631***	0.545***	-0.171***	-0.524***	0.075	0.561***
MEAN	2.454	2.928	9.397	2.357	1.115	0.543	0.022
SD	1.668	1.092	1.590	0.580	0.633	0.118	0.017

Variable	Open	Hc	Infr	Stru	Urb
Open	1.000				
Hc	0.564***	1.000			
Infr	-0.382***	-0.325***	1.000		
Stru	-0.252***	-0.415***	0.259***	1.000	
Urb	0.737***	0.875***	-0.445***	-0.326***	1.000
MEAN	0.367	8.841	14.131	0.458	54.088
SD	0.311	0.986	7.494	0.083	13.596

Note: * represents significance at the 10% level, ** represents significance at the 5% level and *** represents significance at the 1% level.

China has a vast territory under its control. To analyse the differences in carbon emission intensity and heterogeneous technology levels in different regions, it is necessary to conduct a descriptive analysis of the carbon emission intensity and technological progress levels of different regions. The sample data were divided into eastern, central and western regions according to their geographical locations. Figure 2 shows the mean values of carbon emission intensity variables for the whole country, the east, the middle and the west. It can be seen that the carbon emission intensity increases in the east, middle and west, one by one, that is, the carbon emissions required to create unit GDP increases in the east, middle and west. This may be due to the vigorous development of the tertiary industry in the eastern region in recent years. The added value of high-tech industries is higher than that of the central and western regions, and the total economic output value of the central and western regions mainly depends on the secondary industry. In particular, the economic growth mode of the western region is relatively extensive, and the proportion of energy consumption is always high. Figure 3 shows the mean values of heterogeneous technological progress variables for the whole country, the east, the middle and the west. It can be seen that different levels of technological progress are different in each region. Among them, the regional difference in generalised technological progress is the most obvious. Its value is higher in the eastern region than in the middle and western regions. This shows that the number of domestic patents granted in the eastern region is relatively large. This may be due to the continuous improvement of infrastructure construction and economic development in eastern China in recent years, as well as the increasing attraction of scientific and technological talents and strong independent innovation ability. Among the heterogeneous technological progress variables, the value of the proxy variable of energy technology progress shows a trend of increasing from east to west. This shows that the energy consumption per unit of GDP is the lowest in the east and highest in the west. This may be because the production efficiency of the eastern region is higher, and the results of the production mode to intensive change gradually. In the regional descriptive analysis of environmental technology progress, it was found that its average value was the highest in the middle region. This shows that the middle region has the highest carbon emissions per unit of energy consumption, which may be determined by the characteristics of the coal-based energy structure and the dependence on resource-intensive economic development in the central region. All the other technological progress variables show the characteristics of ‘high in the east and low in the west’, which is consistent with the characteristics of China’s regional economic development, that is, the east is developed, the middle is second, and the west is backward.

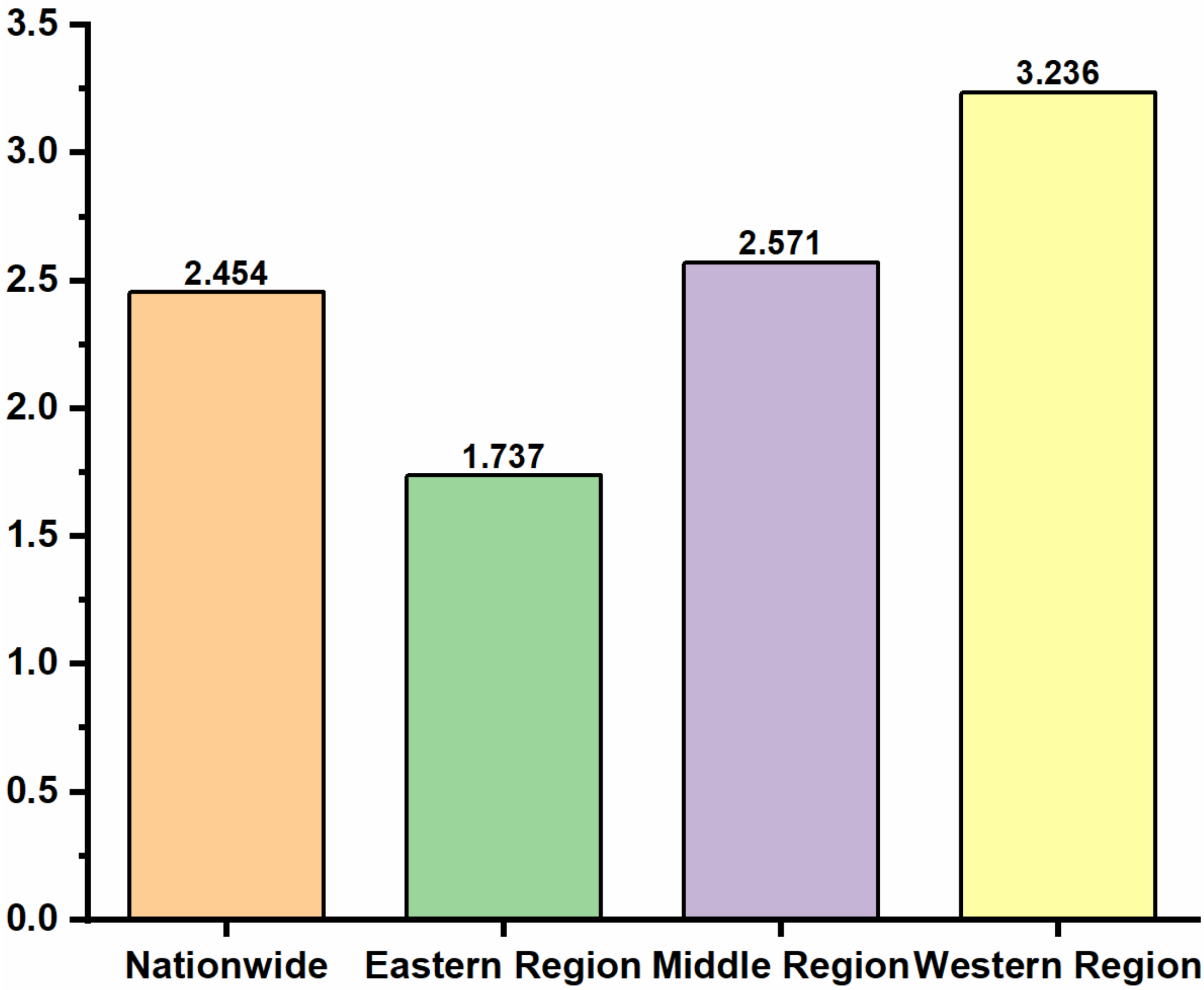

Figure 2 Regional description of the mean value of carbon emission intensity

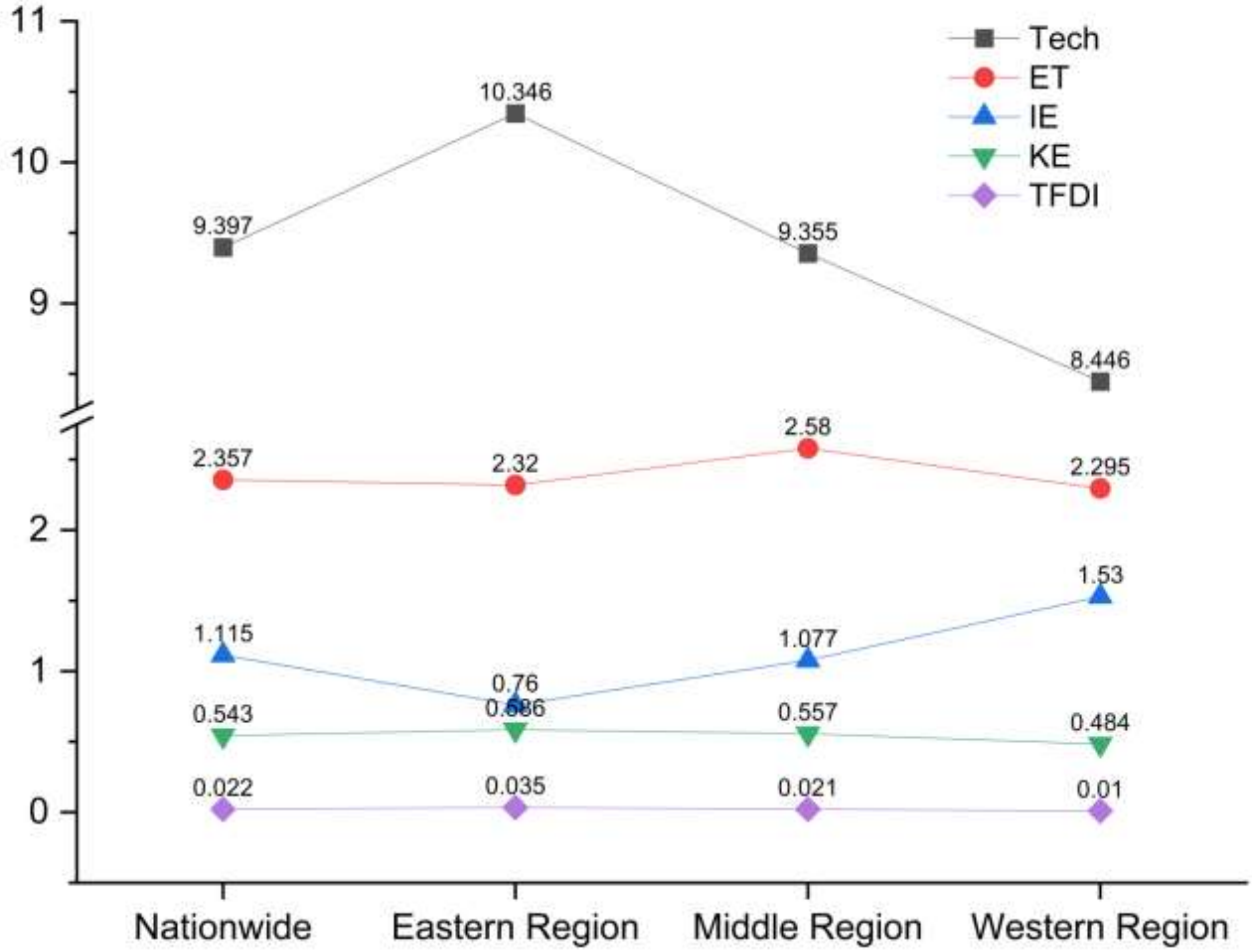

Figure 3 Regional description of the mean value of heterogeneous technological progress

Principal effect test

Before regression analysis, the variance expansion factor $VIF = 4.10$ (less than 10) of each variable was measured, indicating that the problem of multicollinearity between variables did not exist. Then, through the Hausman test, the result significantly rejects the null hypothesis of random effects, so this study chooses the fixed effects model.

Table 3 reports the impact of financial development on carbon emissions and the regression results of principal effect model (4). To further analyse the impact of financial development on carbon emissions among different regions, the sample data are divided into regions. Columns (1), (2), (3) and (4) are the principal effect regression results of the impact of financial development on carbon emissions in the whole country, the east, the middle and the west, respectively. From a national perspective, the first-order coefficient $\alpha_1 = 0.321(p < 0.05)$ of the lagging first-order core variable $L.FD$ is significantly positive, and the coefficient $\alpha_2 = -0.048(p < 0.01)$ of the quadratic term $L.FD^2$ is significantly negative. This conforms to the inverted U-shaped characteristic of the environmental Kuznets curve, indicating that in the short-term financial development promotes carbon emissions and reduces carbon emissions in the long-term. The reason is mainly the result of the interaction between the expansion effect of financial development on carbon emissions and the technological effect. At the short-term national level, the expansion effect of financial development on carbon emissions is greater than the technological effect. That is, the energy consumption caused by the increase of economic scale and production scale caused by financial development is greater than the reduction of carbon emissions per unit GDP brought about by the improvement of financial development and technological level. In the regional regression results of the main effects model, the coefficient $\alpha_{2east} = -0.041(p < 0.1)$ of the quadratic term $L.FD^2$ of the lagging first-order core variable in the eastern region is negative, indicating that the relationship between financial development and carbon emissions in the eastern region also conforms to the environmental Kuznets curve's inverted U Type characteristics. And the coefficient of the first term $L.FD$ is $\alpha_{1east} = -0.849(p < 0.05)$, which indicates that the financial development in the eastern region plays a role in reducing carbon emissions, and its technical effect is greater than the expansion effect. The coefficient of the quadratic term $L.FD^2$ of the lagging first-order core variable in the middle region is $\alpha_{2middle} = -0.450(p < 0.05)$, and the coefficient of the primary term $L.FD$ is $\alpha_{1middle} = 2.165(p < 0.05)$, which indicates that the relationship between financial development and carbon emission in the central region conforms to the inverted U-shaped characteristics of the environmental Kuznets curve. However, at this stage(i.e. in the short term), financial development has not yet achieved carbon emission reduction. The current financial development has promoted the increase of carbon emission intensity, and the long-term financial development will reduce carbon emission intensity. The regression results of the quadratic $L.FD^2$ coefficient of the lagging first-order core variables in the western region are not significant, and the first-order $L.FD$ coefficient $\alpha_{1west} = 0.127(p < 0.1)$ is significantly positive, indicating that financial development and carbon emissions are linearly positively correlated, and financial development leads to an increase in carbon emission intensity. In the principal effect, regression results of model(4), the financial development and carbon emissions of the whole country, eastern, middle and western regions all show a significant correlation, indicating that financial development in each region significantly affects carbon emissions.

Table 3 Principal effect regression results of the impact of financial development on carbon emissions

Variable	Nationwide	Eastern Region	Middle Region	Western Region
	（1）	（2）	（3）	（4）
L.FD	0.321**	-0.849**	2.156**	0.217*
	（2.53）	（-2.02）	（2.31）	（1.66）
$L.FD^2$	-0.048***	-0.041*	-0.450**	0.005
	（-3.59）	（-1.81）	（-2.57）	（0.05）
Constant	6.405**	14.73***	7.651***	12.186***
	（2.43）	（7.71）	（3.99）	（9.57）
Control variables	Yes	Yes	Yes	Yes
Individual fixed effect	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes
R-squared	0.731	0.596	0.601	0.750
Number of obs	360	132	96	132

Note: * represents significance at the 10% level, ** represents significance at the 5% level, *** represents significance at the 1% level, and the value in parentheses is the t statistic. The same below.

Mediating effect test

After completing the principal effect test on the relationship between financial development and carbon emissions, according to the mediation effect test path theory, Table 4 shows the regression results of the mediation effect of models(5) and (6) on the national level of heterogeneous technological progress. It can be seen that in column (5), the regression coefficient of $L.FD$ is $\beta_1 = 0.258$, and it is significant at the 1% level, indicating that financial development can promote the improvement of general technological progress. Then, it further analyses the intermediary effect mechanism of financial development affecting carbon emission intensity through the generalised path of technological progress. In column (6), after the variable $Tech$ is controlled, the regression coefficient of $L.FD$ on CI is significant at the 5% level, and γ_1=0.292 p 0.321 is lower than that of LFD on CI in the main effect model(4). This shows that there is an indirect transmission path for financial development that affects carbon emissions through generalized technological progress. At this time, the intermediary effect coefficient is about 0.070(0.271*0.258) and the interpretation strength is approximately 21.78%(0.070/0.321), indicating that generalised technological progress is part of the intermediary variable of the impact of financial development on carbon emissions and has some intermediary effects. This result is consistent with China's overall national conditions, mainly because financial development has facilitated enterprises to obtain financing, which helps increase scientific research funding, promote scientific research output and increase the number of domestic patent applications granted. However, because the economic growth mode is still in the transformation from extensive to intensive, environmental awareness is insufficient; therefore, financial development does not support low-carbon economic development through the generalised path of technological progress. In column (7), the proxy variable $L.FD$ of financial development is negative and significantly affects the environmental technology progress variable ET at the 1% level, because environmental technology progress represents the level of carbon emissions per unit of energy consumption, which is an inverse variable. This shows that financial development at the national level has led to an increase in the level of environmental technology progress, which helps to reduce carbon emissions per unit of energy consumption. In column (8), after controlling for the proxy variable ET of environmental technological progress, the regression coefficient of the impact of financial development on carbon emissions is 0.070 and not significant, which indicates that environmental technological progress is a complete intermediary variable and has a complete intermediary effect; that is, the impact of financial development on carbon emissions is completely realised through environmental technological progress. In column (9), the regression coefficient of $L.FD$ to IE is significantly negative; that is, financial development reduces energy consumption per unit of GDP. After the proxy variable IE of energy technology progress is controlled in column (10), the regression coefficient of financial development on carbon emissions is 0.319, which is significant at the 10% level, indicating that energy technology progress is the intermediary variable of financial development on carbon emission transmission, and its mediating effect is about -0.087 (-0.107*0.812). The sign is opposite to the main effect regression coefficient (0.321), which means that the progress of energy technology plays a role in diluting the total effect as the transmission path of financial development on carbon emissions. Columns (11) and (13) are the regression coefficients of the LFD for KE and TFDI, respectively. The values are 0.013 and 0.011 and both show 1% significance, indicating that capital-embodied technological progress and FDI technological spillover are mediating variables in the relationship between financial development and carbon emissions. The mediating effects are -0.002 (-0.189*0.013) and -0.041 (-3.696*0.011), respectively, which is opposite to the main effect regression coefficient (0.321). This means that the capital utilisation rate increases and making full use of the advanced production technology brought by foreign investment can alleviate the increase in carbon emissions caused by financial development at the national level.

Table 4 Regression results of the mediating effect of heterogeneous technological progress at the national level

Variable	Tech	CI_1	ET	CI_2	IE	CI_3	KE	CI_4	TFDI	CI_5
	（5）	（6）	（7）	（8）	（9）	（10）	（11）	（12）	（13）	（14）
L.FD	0.258***	0.292**	-0.320***	0.070	-0.107***	0.319*	0.013*	0.267**	0.011*	0.280*
	（5.11）	（2.32）	（-4.34）	（0.21）	（-3.13）	（1.68）	（1.67）	（2.49）	（1.68）	(1.66)
L.FD^2		-0.048*		-0.001		-0.045		-0.042		-0.045
		（-1.67）		（-0.01）		（-1.06）		(-0.79)		（-1.03）
Tech		0.271*								
		（1.91）								
ET				0.742***						
				（6.96）						
IE						0.812**				
						（2.29）				
KE								-0.189*		
								（-1.65）		
TFDI										-3.696*
										（-1.66）
Constant	-0.325	6.136**	3.950***	6.008**	5.830***	4.226*	0.636***	7.202***	0.025	7.123***
	（-0.73）	（2.57）	（6.04）	（2.57）	（19.13）	（1.66）	（7.67）	（2.87）	（1.64）	（2.89）
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.897	0.733	0.134	0.774	0.733	0.756	0.555	0.728	0.117	0.731
Number of obs	360	360	360	360	360	360	360	360	360	360

Subsample mediation effect test

Combining the differences in the environment, energy resources, climate, and economic development levels in different regions of China, we will further investigate the regression results of the mediation effect of heterogeneous technological progress in different regions. In the subsample, the regression results of the mediating effect of heterogeneous technological progress in the eastern region is shown in Table 5. The regression results of financial development to heterogeneous technological progress are all significant, indicating that in eastern China, generalised technological progress, environmental technological progress, energy technological progress, capital embodied technological progress and FDI technology spillover are all mediating variables of financial development on the transmission path of carbon emissions, with a mediating effect. It is noteworthy that the mediating effect of ET is about -0.553 (-0.642*0.861), and its explanatory power is approximately 65.11% (-0.553/-0.849). This shows that the technological progress path of carbon emission reduction driven by financial development in the eastern region mainly comes from the improvement of environmental technology progress level because the eastern region has always been the economic pilot zone of green development, which is basically consistent with the evaluation result of the ‘China Green Economic Development Report’.

Table 5 Regression results of the mediating effect of heterogeneous technological progress in the eastern region

Variable	Tech	CI_1	ET	CI_2	IE	CI_3	KE	CI_4	TFDI	CI_5
	（15）	（16）	（17）	（18）	（19）	（20）	（21）	（22）	（23）	（24）
L.FD	0.233***	-0.739*	-0.642***	-0.252**	-0.040*	-0.797**	0.006*	-0.786*	0.013*	-0.802**
	（3.48）	（-1.75）	（-4.86）	（-2.19）	（-1.68）	（-2.05）	（1.66）	（-1.81）	（1.71）	（-2.14）
$L.FD^2$		0.037		-0.012		-0.045		0.033		0.049
		（0.88）		(-0.59)		(1.15)		(0.74)		(1.14)
Tech		-0.434**								
		（-2.26）								
ET				0.861***						
				（18.68）						
IE						2.112***				
						（4.46）				
KE								0.633*		
								（1.76）		
TFDI										-4.509*
										（-1.66）
Constant	-0.467	13.478***	10.043***	8.075***	3.666***	8.476***	0.688***	14.019***	0.062	15.104***
	（-0.49）	（7.19）	（5.30）	（4.37）	（10.74）	（3.65）	（4.19）	（6.76）	（1.38）	（8.16）
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.891	0.609	0.334	0.707	0.836	0.640	0.575	0.593	0.368	0.731
Number of obs	132	132	132	132	132	132	132	132	132	132

Table 6 shows the regression results for the mediating effect of heterogeneous technological progress in the middle region. In the middle region, the regression coefficient of the variable $L.FD$ to ET is 0.314, and it is significant at the 5% level, which means that $L.FD$ increases by one unit and ET increases by 0.314 units. However, after controlling for the variable ET, financial development is no longer significant to carbon emissions, indicating that financial development in the middle region has led to an increase in carbon emissions per unit of energy consumption. The transmission path of financial development to carbon emissions is mainly through the progress of environmental technology, where the progress of environmental technology is reflected as a completely intermediary effect. This is mainly because the central region is currently dominated by the secondary industry in the industrial structure, and the financing tends to be for the heavy industry, which is mainly dominated by fossil fuels and highly dependent on high carbon energy. The regression results of financial development on the other heterogeneous progress variables are all significant, indicating that the various technological progress indicators selected are the transmission paths of financial development to carbon emissions. Among them, the mediating effects (-2.034, -0.301) of the variables Tech and IE are opposite to the signs of the main effect (2.156). This shows that financial development plays a dilutive role in the carbon transmission effect. Financial development can increase the number of patent authorisations and reduce energy consumption per unit GDP in the central region. In other words, financial development can support the low-carbon economic development of the region by improving the general technological progress level and energy technological progress level. The mediating effect of capital embodied technological progress and FDI technology spillover in the middle region is estimated to account for only 3.61% (0.024*3.239/2.156) and 3.24% (0.002*34.875/2.156), respectively, which is consistent with the fact that the physical capital stock in the middle region is small and the utilisation rate is not high, and foreign investment is relatively small. This may be due to the unbalanced development policy implemented by the government in the late 1990s, which gave priority to the development of the eastern coastal region and supported the development strategy of the western region. Although the Central China Rise Project has sprung up in recent years, long-term practice is needed for it to be effective.

Table 6 Regression results of the mediating effect of heterogeneous technological progress in the middle region

Variable	Tech	CI_1	ET	CI_2	IE	CI_3	KE	CI_4	TFDI	CI_5
	（25）	（26）	（27）	（28）	（29）	（30）	（31）	（32）	（33）	（34）

L.FD	0.415*	0.317***	0.314**	0.601	-0.118*	1.403**	0.024**	2.066***	0.002*	1.639*
	（1.96）	（3.20）	（2.09）	（0.82）	（-1.69）	（2.25）	（2.13）	（2.72）	（1.71）	（1.70）
$L.FD^2$		-0.615***		-0.237*		-0.235**		-0.497***		-0.330*
		(-3.38)		(-1.76)		(-1.99)		(-3.04)		(-1.79)
Tech		-4.90**								
		（-2.50）								
ET				1.619***						
				（7.91）						
IE						2.551***				
						（10.24）				
KE								3.239***		
								（3.68）		
TFDI										34.875*
										（1.82）
Constant	-2.407**	9.349***	0.424	9.493***	5.397***	-1.237	0.606***	6.175***	-0.010	10.354***
	（-2.51）	（5.01）	（0.62）	（7.21）	（11.04）	（-0.68）	（4.14）	（3.63）	（-1.01）	（6.19）
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.893	0.575	0.223	0.744	0.799	0.774	0.749	0.669	0.444	0.586
Number of obs	96	96	96	96	96	96	96	96	96	96

Table 7 shows the regression results for the mediating effect of heterogeneous technological progress in the western region. Among the heterogeneous technological progress indicators, the regression results of variables *L.FD* on *IE* and *TFDI* are not significant. On the one hand, this may be because the financial market in the western region is underdeveloped, and large-scale project funds are mainly supported by the state's financial appropriations. On the other hand, the special geographical conditions of the western region are not attractive enough for foreign investment. In Table 7, the regression results of the variables *L.FD* on *Tech*, *ET* and *KE* are significant. Among them, the mediating effect of the variable *Tech* is -0.042 (-0.211*0.198), which is opposite to the sign of the main effect of 0.217, indicating that generalised technological progress has a diluting effect as a mediating variable. Since the development of the western region in China, the implementation of projects with advantageous industries in the western region, such as the West-East Gas Pipeline, Qinghai-Tibet Railway, wind power generation and alternative new energy and other projects, cannot be achieved without the development of patented technologies. Financial investment institutions are guided by national policies and carry out investment and financing activities for characteristic industries, thus contributing to the development of a low-carbon economy. In addition, environmental technological progress and capital-embodied technological progress are intermediary transmission paths of financial development to carbon emissions in the western region.

Table 7 Regression results of the mediating effect of heterogeneous technological progress in the western region

Variable	Tech	CI_1	ET	CI_2	IE	CI_3	KE	CI_4	TFDI	CI_5
	（35）	（36）	（37）	（38）	（39）	（40）	（41）	（42）	（43）	（44）
L.FD	0.198**	0.089*	0.031*	0.191*	-0.118	-0.089	0.046***	0.047*	0.001	0.123
	（2.58）	（1.73）	（1.71）	（1.65）	（-1.09）	（-0.14）	（2.98）	（1.89）	（0.05）	（0.18）
$L.FD^2$		-0.005		0.089		-0.022		0.062		-0.016
		（-0.05）		（1.07）		（0.24）		（0.68）		（-0.16）
Tech		-0.211*								
		（-1.66）								
ET				0.852***						
				（6.52）						
IE						0.525***				
						（2.68）				
KE								3.712***		
								（3.96）		
TFDI										10.264
										（0.99）
Constant	1.328**	12.271***	2.214***	11.355***	5.397***	8.148***	0.803***	14.318***	-0.008	12.268***
	（2.41）	（10.35）	（3.06）	（9.32）	（11.04）	（4.92）	（7.24）	（11.46）	（-0.75）	（10.49）
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.935	0.751	0.102	0.759	0.799	0.771	0.649	0.777	0.308	0.752
Number of obs	132	132	132	132	132	132	132	132	132	132

Conclusions and recommendations

Financial development can play a role in regulating the distribution of resources by optimising capital allocation and improving the marginal efficiency of production, thereby promoting technological progress and stimulating economic growth. This study fully considers the heterogeneity of technological progress, selects indicators representing different technological progress to introduce the mediation effect model and uses the data of 30 provinces from 2006 to 2018 to construct a provincial panel data model for empirical analysis. The study found that at the national level and in the eastern and central regions, the relationship between financial development and carbon emissions conforms to the inverted U-shaped characteristics of the environmental Kuznets curve. After a long period of financial development, a low-carbon economy will eventually be formed. However, after the regional division, the relationship between financial development and carbon emissions in the western region shows a linearly increasing trend. Different types of technological progress have different effects on the financial development and carbon emission transmission pathways. At the national level, generalised technological progress, environmental technological progress, energy technological progress, capital-embodied technological progress and FDI technology spillover are the intermediary paths of carbon emissions caused by financial development. The explanation of the intermediary effects of different technological progress is different, among which environmental technological advancement is embodied as the complete transmission path of financial development to carbon emissions. In the eastern region, the generalised technological progress, environmental technological progress, energy technological progress, capital-embodied technological progress and FDI technology spillover are all reflected as part of the mediating effect of financial development on carbon emissions, in which the mediating effect of environmental technological progress accounts for the largest proportion and has the strongest explanatory power. In the middle region, environmental technological progress is reflected in the complete transmission path of financial development to carbon emissions. Financial development can dilute the intensity of carbon emissions through the transmission channels of generalised technological progress and energy technological progress. In the western region, the transmission path of financial development to carbon emissions mainly comes from generalised technological progress, environmental technological progress and capital-embodied technological progress, and generalised technological progress can reduce the intensity of carbon emissions caused by financial development.

Based on the above analysis and conclusions, in order to develop a low-carbon economy more efficiently, this research puts forward the following recommendations: (1) Give full play to the guiding role of financial services to the real economy and strengthen the reform and innovation of green finance. For example, innovate green financial policy tools, promote financial products such as green funds, green trusts and green leases; broaden financing channels for low-carbon and environmentally friendly green economy projects and technological projects, and reduce financing costs and risks. (2) Strengthen technological progress and at the same time pay attention to the heterogeneity of technological progress, and avoid a ‘one size fits all’ policy. Based on the above empirical results, great attention should be paid to the contribution of environmental technology advancement for the development of a low-carbon economy. Policy-oriented R&D investment in science and technology tends to reduce carbon emissions per unit of energy consumption because whether it is analysed at the national level or divided by region, the progress of environmental technology is an important transmission path of financial development to carbon emissions. In terms of the technological progress path of financial development to carbon emission transmission in the middle and western regions, the types of technological progress paths affected by financial development are less than those in the eastern region. Therefore, the middle and western regions should improve the utilisation rate of resources and pay more attention to the cleanliness of energy use. The eastern region should actively take advantage of its geographical location, appropriately introduce advanced management concepts and carbon emission technologies brought about by FDI, increase the utilisation rate of human and material capital and spread advanced technologies to the middle and western regions. (3) Carry out nationwide industrial restructuring, actively develop tertiary industries and low-energy-consuming industries and control greenhouse gas emissions through market mechanisms. For example, establishing monetary policy tools to support carbon emission reduction, taking the power generation industry as a pilot, starting online trading in the national carbon emission trading market, and gradually expanding the industry coverage, to leverage more social funds to promote carbon emission reduction.

Declarations

This study was purely registry based, as no human participants were recruited or included in experiments.

Ethics Approval ethics approval is not required for this paper.

Consent to participate Not applicable.

Consent for publication Not applicable.

Authors Contributions DU and LIU developed the idea of the study and drafted the manuscript. DU and LIU contributed to the acquisition and interpretation of data. At the same time DU and LIU provided critical review and substantially revised the manuscript and approved the final manuscript.

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