Can Financial Development Curb Carbon Emissions? —Empirical Test Based on Spatial Perspective

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——Empirical Test Based on Spatial Perspective

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Abstract: To respond to global climate change and achieve "carbon peak" and "carbon neutrality" as soon as possible has become a common goal around the world. Economic growth relies heavily on financial development; indeed, low-carbon economic development is inseparable from financial support. This paper studies the impact of financial development on carbon emission intensity and its mechanism from both theoretical and empirical aspects. Based on the 2005-2018 data on Chinese cities and the Spatial Durbin Model (SDM) research results, this paper finds: (1) Financial development has significantly reduced China's carbon emission intensity overall. After considering spatial effects, financial development increased local carbon emission intensity, although it may lead to a more significant decrease in the surrounding area. (2) The analysis of heterogeneity shows that only the financial development in the eastern region has a substantial detrimental impact on total carbon emission intensity and the carbon emission intensity of neighboring cities. The financial development in the central and western regions has no significant effect on carbon emission intensity. (3) The mechanism test shows that financial development mainly reduces carbon emission intensity through technological innovation and structural optimization, with the effect of technological innovation 9.5%, and the effect of structural optimization 12.15%. The expansion of the consumption effects of financial development has no significant impact on carbon emission intensity. Accordingly, this article believes that it is necessary to further support financial development, build large-scale financial centers, continue to optimize the structure of financial products and encourage the development of green finance.

Keywords: financial development; carbon emissions; spatial effects

1. Introduction

Climate changes and natural disasters such as global warming, drought and floods brought about by carbon dioxide emissions will have a major impact on the development of both human society and economies (Strzepek et al. 2010; Williams et al. 2017; Kulp and Strauss, 2019). Statistics show that, since 1880, CO_2 in the atmosphere has now reached 413 ppm; over the last 100 years, this has increased the global temperature by 1.9 F and the sea level by 178mm (NASA, 2020). How to reduce carbon emissions has become a pressing issue worldwide. BP World Energy Statistics¹ shows that China's carbon emissions reached 9.825 billion tons in 2019, an increase of 7.5% compared to 2016, an increase of 5.6% compared to 2017 and an increase of 3.4% compared to 2018. Although the annual growth rate of China's carbon emissions is decreasing year by year, the total emissions have far exceeded those of developed countries such as the United Kingdom and the United States. The United Kingdom, which was the first to industrialize in the world, had a historical peak in CO_2 emissions as early as around 1973. Similarly, the United States has also gradually reduced its carbon emissions after reaching a carbon peak of 6.6 billion tons in 2005 (Figure 1). Faced with various climate problems caused by carbon emissions, China, as the world's largest CO_2 emitter and energy consumer (Al-Arkawazi, 2018), is undoubtedly facing huge pressure to save energy and reduce emissions. The Chinese government places a high priority on reducing carbon emissions as part of the country's economic growth. In the 2014 Sino-US Joint Declaration

¹ Data Sources: Dudley B. BP statistical review of world energy[J]. BP Statistical Review, London, UK, accessed Aug, 2019, 6(2019): 00116. <https://www.bp.com/en/global/corporate.html>.

on Climate Change, China first proposed a plan to achieve a “carbon peak” in 2030. In 2020, China once again announced at the United Nations General Assembly that it will strive to achieve a "carbon peak" by 2030 and "carbon neutrality" by 2060. Therefore, whether it is developing countries such as China and India, or developed countries such as the United States, the United Kingdom or Japan, all hope to reduce carbon emissions while, at the same time, maintaining economic development, and achieve a "carbon peak" and "carbon neutrality" at an early date. This has become an important goal for the government in formulating development policies and in improving the quality of economic development.

Figure 1 Carbon emissions of typical countries from 1965 to 2019 (unit: million tons)

Financial development is seen as an important driving force for economic growth ([Calderón and Liu, 2003](#); [Pradhan et al. 2021](#)) and has a significant impact on promoting the transformation of economic development models and in promoting a low-carbon economy ([Muganyizi et al. 2021](#)). Financial development can promote technological innovation and reduce energy consumption per unit of GDP, thereby reducing carbon dioxide emissions ([Wang et al. 2020](#)). Financial development can also improve both the financing environment and consumer credit services, prompt companies to expand production scale and increase consumer consumption of household appliances, automobiles and other commodities, all of which will also increase carbon dioxide emissions ([Dogan and Turkekul, 2016](#); [Shen et al. 2021](#)). In view of the above, to promote the low-carbon transformation of the economy it will necessary to allocate and guide the direction of the flow of financial resources ([Zhou and Li, 2019](#)). With the development of China's financial industry and the continuous improvement of internationalization, new financial forms such as green finance and digital finance continue to emerge and exert economic effects. According to data from the Global Financial Centers Index, among the world's top 10 international financial centers, China occupies 4, namely Shanghai, Hong Kong, Beijing and Shenzhen. At the same time, "IDC Financial Insights FinTech Rankings Top 100" data shows that 14% of the top 50 fintech companies in the world are owned by China. The level of China's financial development continues to improve, which is consistent with the trend of continuous growth in carbon emissions. An interesting topic is then whether financial development promotes China's carbon emissions or curbs its carbon emissions intensity? What is the mechanism behind it? Furthermore, is the impact of financial development on carbon emissions affected by geospatial factors? The possible innovations in this paper are as follows: (1) Explain the impact mechanism of financial development on carbon emissions from three aspects: a consumption effect, an innovation effect and a structural effect. (2) This paper uses

Chinese city data from 2005 to 2018, rather than provincial data, to provide more microscopic evidence for the impact of financial development on carbon emissions. (3) Empirically test the impact of financial development on carbon emission intensity, and consider the role of geospatial factors on the impact of financial development on carbon emission intensity. Further test whether this role exists in the heterogeneity of urban areas, so as to provide a theoretical basis for evaluating the emission reduction effects of financial development.

2. Literature review

The following three categories can be used to categorize studies on the influence of financial development on carbon emissions.

The first view is that financial development reduces carbon emissions ([Tamazian et al. 2009](#), [Jalil and Feridun, 2011](#)). Based on the panel data of APEC countries from 1990 to 2016, [Zaidi et al. \(2019\)](#) studied the relationship between globalization, financial development and carbon emissions and found that financial development significantly reduced carbon emissions. [Liu and Song \(2020\)](#) investigated the influence of China's financial development on carbon intensity, with the results showing that financial development curbed carbon emissions as a whole. This is mainly due to the fact that financial development can both provide companies with lower-cost funds for investment in environmentally friendly projects and increase financial support for the development and application of cleaner production technologies and energy-saving technologies, thereby improving corporate energy efficiency and reducing carbon emission ([Shahbaz et al. 2013](#)). At the same time, financial development is conducive to promoting technology spillovers and expanding the scope of use of new environmentally friendly technologies, thereby further reducing carbon emissions ([Dogan and Seker, 2016](#)). The second view is that financial development has increased carbon emissions, mainly because financial development will increase the consumption of high-emission commodities in sectors such as production and transportation ([Sadorsky, 2010](#)). [Zhang \(2011\)](#) found not only that financial development is a major contributor to the increase in carbon emissions, but also that different financial development indicators have different effects on carbon emissions. Among them, the scale of financial intermediation has a greater impact on carbon emissions than other financial development indicators such as the efficiency of financial intermediation, the size and efficiency of the stock market and so on. [Boutabba \(2014\)](#) used 1971-2008 time series data to study the relationship between India's carbon emissions, financial development, economic growth, trade openness and energy consumption. The results found that financial development has a long-term positive impact on per capita carbon emissions. [Adams and Klobodu \(2018\)](#) found that financial development is a key factor leading to an increase in carbon emissions when considering the political system. [Paramati et al. \(2021\)](#) studied the impact of financial deepening on carbon emissions based on panel data from 25 OECD economies from 1991 to 2016, and found that financial deepening significantly increased carbon emissions. [Shen et al. \(2021\)](#) believe that a well-developed financial system reduces information asymmetry, making it easier for companies to finance; this is conducive to expanding the scale of production by companies, leading to increased carbon emissions. On the other hand, however, financial development has led to an increase in carbon emissions through the increase in consumer energy demand.

The third view is that there is a non-linear relationship between financial development and carbon emissions such as the "inverted U-shaped" or "U-shaped" curve ([Charfeddine and Khediri, 2016](#); [Katircioğlu and Taşpınar, 2017](#)). [Hao et al. \(2016\)](#) took 29 provinces in China as examples and found that the influence of financial development on CO₂ emissions is different at different stages of economic development. In the initial stage of economic growth, financial development

reduced CO₂ emissions, but when the degree of economic development increased, financial development increased CO₂ emissions. [Shahbaz et al. \(2020a\)](#) studied the relationship between economic growth, R&D expenditure, energy consumption, financial development and carbon dioxide emissions based on historical data of the British economy from 1870 to 2017. It also concluded that there was a U-shaped relationship between financial development and carbon dioxide emissions. [Acheampong et al. \(2020\)](#) used panel data from 83 countries from 1980 to 2015 and found that in both independent financial economies and emerging financial economies, there is an inverted U-shaped relationship between financial market development and carbon emission intensity.

In summary, research on the influence of financial development on carbon emissions has shown certain results, but no consistent research conclusion has yet been established. At the same time, the mechanism by which the impact of financial development affects carbon emissions is still unclear. Not only does the existing literature rarely incorporate spatial factors into the study of financial development and carbon emissions, but it also lacks micro-level evidence at the city level which, ultimately, will bias the estimation results. Based on this, this paper uses Chinese city-level data to integrate spatial factors into the analysis of the influence of financial development on carbon emission intensity and then analyzes and tests its mechanism of action.

3. Influence mechanism

From a theoretical point of view, financial development may reduce carbon emissions both by promoting technological innovation to achieve cleaner production and by adjusting industrial structure. It is also possible to increase energy consumption and promote carbon emissions by the expansion of consumer demand and economic scale. As a result, the influence of financial growth on carbon emissions remains uncertain, depending on the contrast between the positive and negative effects of carbon emissions.

3.1 The effect of technological innovation

Technological innovations such as renewable energy technologies and cleaner production technologies are important factors in reducing carbon emissions ([Lin and Zhu, 2019](#); [Shahbaz et al. 2020](#)). Through research and development, innovation and the application of green technology to actual production, emissions of CO₂ can be effectively reduced. Financial development will promote technological innovation by three means and so reduce carbon emissions. The first is to reduce financing costs and promote technological innovation. Enterprise technological innovation is a complex and special input-output process with high risk and high input characteristics. Whether it can obtain sufficient external financial support is the key to the success or failure of innovation ([Brown and Petersen, 2011](#)). A developed financial market can provide diversified financing tools and channels for corporate green innovation activities. Special financial products such as green bonds and innovation and entrepreneurship bonds can continuously enrich the market investment and financial product system, reduce corporate financing costs, improve financing constraints, and promote green technological innovation. At the same time, the development of new financial forms such as digital finance will also help break the administrative barriers of traditional finance, promote the cross-regional flow of financial resources, reduce the information and matching costs of capital cross-regional flows, promote green technological innovation and reduce carbon emission intensity. The second is to optimize the efficiency of financial resource allocation and promote technological innovation. An increase in the level of financial development, to a certain extent, means not only that the level of financial marketization has also increased, but also that the government's direct

interference in the allocation of financial resources has decreased; this will help to change the distortion of traditional financial resource allocation ([Wu, 2018](#)). Financial institutions can transfer more financial resources from state-owned enterprises with low innovation efficiency ([Lin et al. 2010](#); [Tang et al. 2020](#)) to the more efficient and dynamic private sector based on the principles of risk and return, facilitate new technological innovation, and reduce carbon emissions by promoting technological innovation. The third is to promote the diffusion and spillover of knowledge and promote technological innovation. Regional innovation activities are susceptible to the dual influence of input factors and innovation environment. In addition to reducing financing costs and increasing R&D capital investment, financial development can also both promote knowledge diffusion and spillover and promote technological innovation. Cities with a high level of financial development usually have a high level of internationalization, which helps to accelerate the introduction of foreign capital. By driving the flow of R&D personnel and the spillover of technological elements, the level of energy-saving and emission-reduction technologies and green production technologies will be improved, thereby encouraging regional innovation and reducing carbon emissions. Based on this, Hypothesis 1 is proposed.

Hypothesis 1: Financial development reduces carbon emissions by promoting technological innovation.

3.2 Structural effects

Industrial structure is closely related to the spatial distribution of regional energy consumption and carbon emissions ([Zhang and Qin, 2018](#)) and plays an important role in achieving low-carbon economic development in China ([Chen et al. 2017](#)). Financial development has achieved resource conservation and reduction of carbon emissions by promoting optimization of the industrial structure. On the one hand, financial development can optimize the capital allocation structure, and then by guiding the flow of capital, promote the optimization and upgrading of industrial structure, so reducing carbon emissions. First of all, at the policy level, national policy banks specifically support high-tech industries that are needed for future development through loan subsidies and credit rationing. This high-end industry usually has the characteristics of high technology, low energy consumption and low emissions. Secondly, at the market level, as China's requirements for carbon emission reduction work continue to increase, the financial system will continuously optimize the capital allocation structure by controlling the flow of capital. Financial institutions will strengthen the review of capital flows, consciously restrict the flow of capital to high-emission and high-energy-consuming industries and actively guide financial capital to increase its tilt toward both green and clean industries and smart high-end industries. This will help optimize the industrial structure and reduce carbon emissions. On the other hand, financial development can optimize the structure of financial products. With the improvement of the level of financial development, there is an obvious green trend, with new financial forms such as green credit and green bonds becoming more abundant. For example, carbon neutral bonds are a sub-type of green bonds, and the funds raised by them will be earmarked for green projects with carbon emission reduction benefits. The optimization of this kind of financial structure can effectively reduce the financing difficulty and capital borrowing cost of green projects and green industries, provide positive incentives for enterprises to carry out both green technology research and development and industrial upgrading activities as well as reduce carbon emissions. Based on this, Hypothesis 2 is proposed.

Hypothesis 2: Financial development reduces carbon emissions by optimizing industrial structure.

3.3 Consumption effect

Financial development can increase the breadth and depth of financial services, make financial services more convenient, and reduce transaction costs. This allows consumers who are constrained by liquidity to conveniently use the financial market to achieve inter-temporal smoothing of consumption and release potential consumer demand. It will mainly promote carbon emissions from both consumption and production. First, from the perspective of the household sector, when a country develops financial services, consumers will expand consumption due to the availability of loans and increase the purchase and use of large commodities such as houses, cars, and air conditioners, which will directly increase energy demand and increase carbon emissions in the household sector ([Sadorsky, 2011](#)). From a corporate perspective, financial development can make corporate financing more convenient and reduce corporate friction costs and transaction costs. Stock market financing has also reduced corporate financing costs to a certain extent, which will promote enterprises to expand production. At the same time, as the consumer demand for various commodities in the household sector increases, it will further promote the expansion of scale production and the expansion of business activities by enterprises, which will increase the demand for energy consumption such as coal and electricity. This in turn causes an increase in carbon emissions from the industrial production sector. In addition, financial development helps attract more foreign direct investment, thereby further increasing energy consumption from production and economic development ([Shahbaz et al. 2017](#)). In particular, the current imperfect environmental regulatory system in China and the low level of energy-saving and emission-reduction technologies will further increase carbon emissions. Based on this, Hypothesis 3 is proposed.

Hypothesis 3: Financial development increases carbon emissions by promoting consumption.

4. Model setting and variable description

4.1 Model setting

This article first establishes a common fixed effects model (Model 1) to investigate the influence of financial development on carbon emission intensity. Consider that carbon emissions will show a certain degree of auto-correlation when their spatial locations are correlated. To explore the spatial effect of financial development on carbon emission intensity, this article draws on the work of [Liu and Song \(2020\)](#) and use the spatial econometric model to further test and judge the possible direct and indirect effects. This is done in order to better interpret the spatial dependence between regions due to the increasing economic exchanges. Based on this, we establish three spatial measurement models: Spatial Autoregressive Model (SAR), Spatial Error Model (SEM), and Spatial Durbin Model (SDM):

$$ln ci_{it} = \beta_1 ln fin_{it} + \beta_2 ln pop_{it} + \beta_3 ln gov_{it} + \beta_4 ln fdi_{it} + \beta_5 ln edu_{it} + \beta_6 ln cy_{it} + \beta_7 ln jt_{it} + u_i + \varepsilon_{it}, \quad (1)$$

$$ln ci_{it} = \beta_1 ln fin_{it} + \beta_2 ln pop_{it} + \beta_3 ln gov_{it} + \beta_4 ln fdi_{it} + \beta_5 ln edu_{it} + \beta_6 ln cy_{it} + \beta_7 ln jt_{it} + u_i + \varepsilon_{it}, \quad \varepsilon_{it} = \lambda \sum_{j=1}^n W_{ij} \varepsilon_{it} + \mu_{it} \quad (2)$$

$$ln ci_{it} = \rho \sum_{j=1}^n W_{ij} ln ci_{it} + \beta_1 ln fin_{it} + \beta_2 ln pop_{it} + \beta_3 ln gov_{it} + \beta_4 ln fdi_{it} + \beta_5 ln edu_{it} + \beta_6 ln cy_{it} + \beta_7 ln jt_{it} + u_i + \varepsilon_{it} + \mu_{it}, \quad \mu_{it} = \lambda \sum_{j=1}^n W_{ij} \varepsilon_{it} + \varepsilon_{it} \quad (3)$$

$$ln ci_{it} = \alpha_i + \rho \sum_{j=1}^N W_{ij} ln ci_{it} + \beta_1 ln ci_{it} + \beta X_{it} + \varphi_1 W * ln ci_{it} + \varphi \sum_{j=1}^N W_{ij} X_{it} + U_{it}, U_{it} = \lambda W \mu_{it} + \varepsilon_{it} \quad (4)$$

where $ln ci_{it}$ represents carbon emission intensity, which is an explained variable;

$lnfin_{it}$ represents the level of financial development and is the core explanatory variable; $lnpop_{it}$, $lngov_{it}$, $lnfdi_{it}$, $lnedu_{it}$, $lncy_{it}$, $lnjt_{it}$ are control variables, which respectively represent population density, government expenditure, foreign direct investment, human capital, industrial structure and transportation development; ρ , λ , φ are the space lag coefficient, the space error coefficient and the space coefficient of the explanatory variable respectively; W_{ij} is the spatial weight matrix. This paper selects the geographical adjacent distance to establish the weight matrix.

$$W_{ij} = \begin{cases} 1, & \text{When the space unit } i \text{ and } j \text{ have a common boundary} \\ 0, & \text{When the space unit } i \text{ and } j \text{ do not have a common boundary} \end{cases} \quad (5)$$

4.2 Variable description

4.2.1 Explained variable: Carbon emission intensity (CI).

Because China has no official carbon emissions data, this article draws on the practices of [Hao et al. \(2020\)](#) and [Wang et al. \(2020\)](#) to measure carbon emissions and uses the calculation methods published by the IPCC to measure carbon dioxide emissions in the various cities. Carbon dioxide emissions in Chinese cities between 2005 and 2018 are measured by taking coal, coke, crude oil, gasoline, kerosene, diesel, natural gas, and fuel oil as the terminal consumption of 8 types of energy in each city and multiplying the consumption of the 8 types of energy by their respective carbon emission coefficients. The carbon dioxide emissions of each city are divided by the GDP of each city as the carbon emissions per unit of GDP. The specific calculation formula and steps are as follows:

$$CO_{2it} = \sum_{k=1}^8 CO_{2tik} = \sum_{k=1}^8 E_{tik} \times NCV_k \times CEF_k \times COF_k \times \frac{44}{12} = \sum_{k=1}^8 \frac{44}{12} \rho_k E_{tik} \quad (6)$$

where t represents the year and i represents the city; CO_{2tik} represents the emission of CO_2 of the k -th energy in city i in year t ; E_{tik} represents the consumption of the k -th energy in city i in year t ; NCV_k represents the low calorific value of the k -th energy; CEF_k represents the carbon emission factor of the k -th energy; COF_k represents the carbon oxidation rate of the k -th energy; $44/12$ means that carbon is oxidized to CO_2 with the molecular weight changing from 12 to 44. When calculating the emissions of CO_2 , you need to multiply 44 and divide by 12. ρ_k is the carbon emission coefficient. Formula (7) is then used to calculate the carbon emission intensity of each city.

$$CI_{it} = \frac{EC_{it}}{GDP_{it}} \quad (7)$$

4.2.2 Core explanatory variables

Financial development level (FD). Drawing on the research of [Yan et al. \(2016\)](#), [Liu and Song \(2020\)](#), the ratio of total credit of financial institutions to GDP is used to express financial development. The higher the ratio of total credit to GDP, the easier it is for companies to finance, which means the higher the level of financial development.

4.2.3 Control variables

① Population density ($lnpop$). Low population density will lead to an increase in commuting distance and increase carbon emission levels. An increase in population density is conducive to saving space, improving compactness, and reducing the energy cost of urban operation by sharing infrastructure reduces carbon emissions ([Timmons et al. 2016](#)). It is measured by the proportion of the population in the city area at the end of the year in the city jurisdiction.

② Government expenditure ($lngov$). With the continuous enhancement of the Chinese

government's requirements for "carbon peak" and "carbon neutrality", carbon emission reduction has been included as an important indicator in the evaluation system for government officials. Local governments will increase regulation of, and expenditure on, carbon emissions reduction in order to meet the central government's "carbon peak" requirement as soon as possible. Using the ratio of government fiscal expenditure to GDP as a proxy variable, it is expected that government expenditure will have a positive effect on carbon emission reduction.

③ Direct investment (*lnfdi*). Foreign direct investment has two effects on carbon emissions. FDI companies often relocate some polluting companies to countries with lower environmental standards for production, thereby increasing the CO_2 emissions of the host country. That said, foreign direct investment may also bring advanced and clean technology and management experience to host country enterprises and so lead to a reduction in CO_2 emissions ([Mahadevan and Sun, 2020](#)).

④ Human capital (*lnedu*). Human capital is a manifestation of labor force knowledge and skill levels. The higher the level of human capital, the more conducive it is to promoting technological innovation, carrying out related clean production activities and reducing carbon emissions caused by production activities ([Bano et al. 2018](#)). In general, people with higher human capital have stronger environmental awareness and pay more attention to low-carbon life. This article uses per capita education level as a proxy variable. $Edu = \text{number of primary school students}/\text{total population} \times 6 + \text{number of middle school students}/\text{total population} \times 12 + \text{number of college students}/\text{total population} \times 16$.

⑤ Industrial structure (*lnicy*). Industrial activity is an important cause of carbon emissions. The higher the proportion of urban industry, the higher the proportion of enterprises using fossil energy. This will lead to an increase in total carbon emissions. This article uses the ratio of the added value of the city's secondary industry to GDP to measure industrial structure.

⑥ Public transportation (*lnjt*). In their paper, [Grazi and Bergh \(2008\)](#) maintained that energy-related carbon emissions brought about by the transportation sector accounted for 21% of total emissions; this makes it an important sector causing increased carbon emissions. This paper therefore selects the number of publicly operated vehicles in the city as a proxy variable to control for the impact of the transportation sector on carbon emissions.

4.3 Data sources and descriptive statistics

This paper selects the panel data of 223 cities in China from 2005 to 2018 as the sample data. Data sources include the "China City Statistical Yearbook" (2006-2019) and the "China Energy Statistical Yearbook" (2006-2019). We made descriptive statistics on the data characteristics of the main variables (see [Table 1](#)). In order to investigate the multicollinearity of the model, correlation coefficients between the explanatory variables were calculated. The correlation coefficients between the variables were mostly less than 0.5. We further investigated the variance expansion factor, and found that they are all around 2, which is lower than the empirical criterion 10. Therefore, there is no multicollinearity problem.

Table 1 Descriptive statistics and correlation analysis

Variables	<i>lnci</i>	<i>lnfin</i>	<i>lnpop</i>	<i>lngov</i>	<i>lnfdi</i>	<i>lnedu</i>	<i>lnicy</i>	<i>lnjt</i>
<i>Obs</i>	3122	3122	3122	3122	3122	3122	3122	3122
<i>Mean</i>	-8.499	-0.021	5.857	-1.952	10.025	2.242	3.861	6.746
<i>Std. Dev.</i>	0.829	0.502	0.919	0.424	1.79	0.09	0.232	1.269
<i>Min</i>	-10.709	-2.187	0.3	-4.176	1.099	1.931	2.705	2.303

<i>Max</i>	-3.817	1.67	7.887	0.396	14.941	2.587	4.453	13.172
<i>lnci</i>	1.000							
<i>lnfin</i>	-0.190***	1.000						
<i>lnpop</i>	-0.060***	0.113***	1.000					
<i>lngov</i>	-0.062***	0.361***	-0.365***	1.000				
<i>lnfdi</i>	-0.349***	0.331***	0.444***	-0.283***	1.000			
<i>lnedu</i>	-0.013	0.398***	0.099***	-0.202***	0.406***	1.000		
<i>lncy</i>	0.148***	-0.221***	0.243***	-0.395***	0.120***	-0.041**	1.000	
<i>lnjt</i>	-0.111***	0.309***	0.374***	-0.393***	0.522***	0.513***	-0.003	1.000
<i>VIF</i>	1.77	2.01	1.48	2.25	1.71	1.65	1.28	2.00

5. Regression analysis

5.1 Spatial autocorrelation test

Before performing spatial metrological inspection, it is necessary to verify whether the object under study has spatial dependence. Drawing lessons from Moran (1950), *Moran's I* index is used for the autocorrelation test.

$$\text{Global Moran's } I = \frac{\sum_{i=1}^n \sum_{j=1}^n W_{ij} (X_i - \bar{X})(X_j - \bar{X})}{S^2 \sum_{i=1}^n \sum_{j=1}^n W_{ij}} \quad (8)$$

$$\text{Local } I_i(d) = Z_i \sum_{j \neq 1}^n W'_{ij} Z_j \quad (9)$$

where $S^2 = \frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n}$, X_i is the sample observation value of area i . n is the total number of regions. W_{ij} is the spatial weight. $\sum_{j \neq 1}^n W'_{ij} Z_j$ is the space lag vector, representing the weighted average of carbon emissions and financial development index deviations in neighboring areas.

Based on the geographical proximity matrix, we calculate the local *Moran's I* value of each city's carbon emission intensity (*CI*) and financial development (*FD*). [Table 2](#) shows the local *Moran's I* values for each city from 2008 to 2018. The estimated results are significantly positive and show a trend of increasing year on year. It can be observed that the carbon emission intensity (*CI*) and financial development (*FD*) of each region have a significant positive spatial correlation, with this geographic correlation increasing year by year over time.

Table 2 Moran index based on geographic adjacency matrix

Year	Carbon Intensity (<i>CI</i>)		Financial Development (<i>FD</i>)	
	<i>Moran's I</i> value	<i>P</i> value	<i>Moran's I</i> value	<i>P</i> value
2005	0.277***	0.000	0.086*	0.052
2006	0.282***	0.000	0.141***	0.002
2007	0.266***	0.000	0.151***	0.001
2008	0.279***	0.000	0.188***	0.000
2009	0.263***	0.000	0.243***	0.000
2010	0.254***	0.000	0.252***	0.000
2011	0.260***	0.000	0.253***	0.000
2012	0.274***	0.000	0.245***	0.000
2013	0.262***	0.001	0.247***	0.000
2014	0.330***	0.001	0.234***	0.000
2015	0.347***	0.001	0.206***	0.000
2016	0.382***	0.004	0.240***	0.000
2017	0.407***	0.000	0.227***	0.000
2018	0.417***	0.000	0.206***	0.000

To disclose the spatial agglomeration status of green economic growth and financial development in various provinces and cities, a local spatial correlation analysis of two cross-sections in 2005 and 2018 was carried out. [Figure 2-Figure 5](#) are Moran's I scatter plots of carbon emission intensity and financial development. This map divides the carbon emission intensity and financial development of each city into 4 agglomeration modes: high-high (H-H) agglomeration areas where provinces and cities with high levels of carbon emission intensity and financial development are surrounded by similarly high-level surrounding cities; low-high agglomeration areas (L-H) surrounded by low levels and high levels; low-low agglomeration areas (L-L) surrounded by low levels and high-low agglomeration (H-L) surrounded by high-level provinces and cities surrounded by low-level provinces and cities. It can be seen from the figure that the carbon emission intensity and financial development of most cities in China in 2005 and 2018 were in H-H agglomeration areas and L-L agglomeration areas, indicating a significant positive spatial autocorrelation.

Figure 2 Global Moran scatter plot of CI in 2005
FD in 2005

Figure 3 Global Moran scatter plot of

Figure 4 Global Moran scatter plot of CI in 2018

Figure 5 Global Moran scatter plot of FD in 2018

5.2 Spatial measurement model inspection and selection

Before model estimation, this article first conducts *LM*, *Wald* and *LR* tests to select the spatial model.

The results in [Table 3](#) show that, under the geographical proximity weight matrix, both the *LM – Lag* statistic and the *LM – Error* statistic are significant at the 1% significance level. The robust *LM – Lag* and robust *LM – Error* statistics are not significant, but the P value of the robust *LM – Error* is the smaller, indicating that the spatial SEM model is more suitable than the SAR model. The *Wald* and *LR* tests both rejected the null hypothesis that the SDM model cannot be reduced to the or SAR model, so the SDM model was finally chosen for interpretation.

Table 3 Spatial model test results

Test	Index	Statistics	P value
LM test	<i>LM_Error_test</i>	22.185***	0.000

	<i>R_LM_Error_test</i>	0.900	0.343
	<i>LM_Lag_test</i>	330.655***	0.000
	<i>R_LM_Lag_test</i>	0.490	0.522
Wald test	<i>Wald – SAR</i>	186.67***	0.000
	<i>Wald – SEM</i>	272.70***	0.000
LR test	<i>LR – SAR</i>	186.78***	0.000
	<i>LR – SEM</i>	355.92***	0.000

5.3 Benchmark results

In Table 4, Models 1 and 2 show the Fixed Effects (*FE*) and the Random Effects (*RE*) models respectively. According to the *Hausman* test of the model, the fixed effect model (model 1) is selected. Model 1 gives the coefficient of financial development as -0.168, which passes the 1% significance test, showing that financial development has a specific and significant inhibitory effect on the carbon emission intensity of Chinese cities. Specifically, when the level of financial development increases by 1%, the urban carbon emission intensity will decrease by 0.168%. In order to explore the impact of the level of financial development on the carbon emission intensity of the local and neighboring regions, we established SEM and SDM models to take into account the impact of geographical location on economic activities. Based on the above test results, we then choose to discuss the research findings on the basis of the SDM.

In Table 4, Models 3 and 4 respectively report the SEM and the SDM. From the results of Model 4, the coefficient of influence of financial development on the local carbon emission intensity is 0.183 and passes the significance test at 1%. This shows that a 1% increase in the level of financial development will increase local carbon emission intensity by 0.183%. At the same time, both the coefficient of the spatial spillover term ($Wx * lnfin$) of financial development, which is -0.241 and positive at the 1% significance level, and the space ρ or space λ of the two spatial measurement models, are significant. This shows that, although improvements in the financial development level are not conducive to reductions in the carbon emission intensity of the region, they can significantly reduce the carbon emission intensity of neighboring regions. Specifically, a 1% increase in the level of local financial development will reduce the carbon emission intensity of neighboring areas by 0.241%. One possible reason is that high levels of urban financial development will have a siphonic effect on neighboring areas (these areas are usually villages with low financial levels or small underdeveloped cities), and promote the migration of labor and enterprises from neighboring areas. This leads to an increase in local industrial activities and transportation demand, which in turn leads to an increase in local carbon emissions. The emigration of enterprises and people in neighboring rural or small urban areas reduces surplus labor and non-essential industrial activities, thereby reducing the intensity of carbon emissions.

Table 4 Benchmark regression

Variable	(1) <i>FE</i>	(2) <i>RE</i>	(3) <i>SEM</i>	(4) <i>SDM</i>
<i>lnfin</i>	-0.168*** (-4.37)	-0.169*** (-4.64)	0.281*** (8.98)	0.183*** (5.70)
<i>lnpop</i>	-0.155*** (-4.63)	-0.106*** (-3.31)	-0.0560* (-1.87)	-0.0521* (-1.65)
<i>lngov</i>	-0.487*** (-5.69)	-0.466*** (-6.00)	0.170*** (4.77)	-0.00243 (-0.07)

<i>lnfdi</i>	-0.107*** (-5.95)	-0.115*** (-6.83)	-0.0208*** (-3.05)	-0.0284*** (-3.96)
<i>lnedu</i>	-0.419 (-0.92)	-0.223 (-0.54)	-0.0514 (-0.31)	-0.538*** (-3.09)
<i>lncy</i>	0.107 (0.76)	0.144 (1.06)	-0.00166 (-0.03)	0.0986* (1.65)
<i>lnjt</i>	0.00340 (0.33)	0.00506 (0.49)	0.0565*** (4.20)	0.0572*** (4.25)
<hr/> <i>Wx * lnfin</i>				-0.241*** (-6.54)
<i>Wx * lnpop</i>				-0.0931 (-1.44)
<i>Wx * lngov</i>				-0.246*** (-5.03)
<i>Wx * lnfdi</i>				-0.0521*** (-4.67)
<i>Wx * lnedu</i>				0.233 (0.90)
<i>Wx * lncy</i>				0.0149 (0.18)
<i>Wx * lnjt</i>				-0.0712*** (-4.75)
<i>_cons</i>	-6.969*** (-6.01)	-7.734*** (-7.62)		
<i>Hausman</i>		70.11***		
<i>N</i>	3122	3122	3122	3122
<i>Spatial</i>			0.463*** (22.58)	0.566*** (31.60)
<i>λ/ρ</i>			0.0571*** (38.65)	0.0627*** (38.31)
<i>σ²</i>				

Note: (1) The value in parentheses is the t value; (2) ***, **, * indicate that the variable coefficient has passed the significance test at 1%, 5%, and 10%, respectively. The following table is the same.

Table 5 shows the spatial effect decomposition based on the *SDM* model. The direct effect refers to the impact of financial development on the carbon emission intensity of the region, the indirect effect refers to the impact of local financial development on the carbon emission intensity of neighboring cities, and the total effect is the sum of the two. The impact of financial development is variable; financial development significantly promoted the intensity of local carbon emissions but reduced the carbon emission intensity of neighboring regions. The total effect is -0.129 and passes the 5% significance test. This shows that, after considering the space factor, on the whole, financial development has a restraining effect on carbon emission intensity. This is consistent with the situation where the space effect is not considered. In the *SDM* model, direct effects accounted for 35.57% of the total utility and indirect effects accounted for 64.43%. This shows that financial development has obvious spatial effects, with the restraining influence on the carbon emission intensity of neighboring areas greater than the promotion effect on local carbon emission intensity. The reason why the total effect reduces the intensity of carbon emissions is that carbon emissions have the nature of economies of scale in which the marginal emissions decrease as the industrial

scale increases (Andreoni and levinson, 2001). The population and enterprises of the same size are scattered in areas with low levels of financial development and the carbon emissions caused by repeated construction such as newly built industrial areas and paved roads will be higher than their carbon emissions in areas with high levels of financial development. Pollution treatment requires equipment, and the unit cost required for treatment of concentrated pollution sources may be lower. Therefore, this agglomeration contributes to the reduction of overall emissions. This is similar to the research conclusions of Lu and Feng (2014).

Table 5 Spatial effect decomposition based on SDM model

Variable	(1) Direct effect	(2) Indirect effect	(3) Total effect
<i>lnfin</i>	0.159** (5.12)	-0.288** (-5.52)	-0.129** (-2.55)
<i>lnpop</i>	-0.0742** (-2.35)	-0.244* (-1.93)	-0.318** (-2.30)
<i>lngov</i>	-0.0430 (-1.25)	-0.510*** (-6.42)	-0.553*** (-6.47)
<i>lnfdi</i>	-0.0407*** (-5.85)	-0.143*** (-7.07)	-0.183*** (-8.26)
<i>lnedu</i>	-0.545*** (-3.16)	-0.113 (-0.21)	-0.658 (-1.12)
<i>lncy</i>	0.115* (1.93)	0.143 (1.10)	0.258* (1.76)
<i>lnjt</i>	0.0502*** (3.80)	-0.0796*** (-3.97)	-0.0294 (-1.54)

5.4 Analysis of regional heterogeneity

Taking into account the differences in the economic status, resource richness, and technological development level of different regions, for heterogeneity analysis this article further divides the sample into three major economic regions: the east, the middle, and the west of China. This article introduces regional dummy variables (set the western and central regions to 1 respectively), and cross-multiplies the financial development with the regional dummy variables (*lnfin * Dummy*), with estimates still based on the *SDM* model.

Table 6 models (1)-(3) are the direct effect, indirect effect and total effect respectively. From the estimation results of Model (1), financial development has promoted local carbon emission intensity. As the reference group in the eastern region, the influence coefficient of financial development on urban carbon emission intensity is 0.2187, the estimated coefficient of the central region is 0.1881 and the influence coefficient of the western region is 0.0036. Of these, only the central region failed the significance test. From the perspective of Models (2) and (3), the impact of financial development on carbon emission intensity is significantly heterogeneous. Not only did the financial development in the eastern region reduce the carbon intensity of neighboring regions, but it also showed a significant inhibitory effect on the overall effect. The indirect effects and the total effects in the central and western regions were not significant.

It indicates that financial development directly increases the carbon emission intensity of cities. However, among the indirect effects, it is only the financial development in the eastern region that has a significant negative effect on both neighboring cities and the total carbon emission intensity, which are -0.3461 and -0.1275, respectively. This may be due to the fact that the eastern region is

an area where various factors of production such as talents, science, technology and capital are concentrated in China. The level of financial development is relatively high. The exchange of technology and capital among cities in the eastern region is more convenient. Cities with better financial development have advantages in the financing environment for small and medium-sized enterprises in the region and the reduction of financing costs, attracting the population and enterprises from neighboring underdeveloped cities to migrate to the region, which in turn promotes increases in local carbon emission intensity and a reduction in the carbon intensity of neighboring areas. The level of financial development in the central and western regions is mostly low, and the attractiveness between cities is weak. Although some cities with better financial development in the central and western regions have attracted some enterprises and population, the effect is relatively weak, so it is difficult to have a substantial effect on the carbon intensity of neighboring areas.

Table 6 Analysis of regional heterogeneity

Variable	(1)	(2)	(3)
	Direct effect	Indirect effect	Total effect
<i>lnfin</i>	0.2187*** (4.61)	-0.3461*** (-4.59)	-0.1275** (-2.01)
<i>lnfin_west</i>	-0.2151*** (-2.91)	0.1467 (1.33)	-0.0684 (-0.67)
<i>lnfin_central</i>	-0.0306 (-0.61)	0.0644 (0.73)	0.0338 (0.43)
<i>Control</i>	YES	YES	YES
N	3122	3122	3122

5.5 Robustness test

To further verify the robustness of the estimation results, we first change the measurement method of core explanatory variables and use the proportion of the number of employees in the financial industry to the working population to measure financial development. The second is to replace the spatial weight matrix with a geographic distance matrix and an economic distance matrix for robustness testing. The results are reported in [Table 7](#). The results show that whether the measurement method of the core explanatory variables is replaced or the spatial weight matrix is replaced, the overall inhibitory effect of financial development on the city's carbon emission intensity remains steady. After the introduction of the spatial matrix, the promoting effect of financial development on the local carbon intensity and the restraining effect on the carbon intensity of neighboring areas are still significantly established, with the negative spatial effect significantly greater than the positive promotion effect on the local carbon intensity.

Table 7 Robustness test

Variable	Change measurement method		Replace the space matrix	
	FE	SDM	Geographic distance matrix	Economic distance matrix
<i>lnfin</i>	-0.0331*** (-6.44)	0.0429*** (3.20)	0.2671*** (8.00)	0.2483*** (7.89)
<i>Wx * lnfin</i>		-0.0443*** (-3.27)	-0.6082*** (-2.87)	-0.2573*** (-6.54)
<i>Spatial</i>		0.2321***	0.7004***	0.2351***

ρ		(7.89)	(10.45)	(8.05)
Control	YES	YES	YES	YES
N	3122	3122	3122	3122

5.6 Mechanism inspection

According to the previous mechanism analysis, the impact of financial development on carbon emissions mainly comes from innovation effects, structural effects and consumption effects. This article will test the above-mentioned influence mechanism by constructing an intermediary effect model. Drawing on research by [Hayes \(2009\)](#), a step-wise regression is performed on Models 10-12 to test whether there is such a transmission pathway.

$$ln ci_{it} = \beta ln fin_{it} + X'_{it} \gamma + \varepsilon_{it} \quad (10)$$

$$ln M_{it} = \psi ln fin_{it} + X'_{it} \gamma + \varepsilon_{it} \quad (11)$$

$$ln ci_{it} = \beta' ln fin_{it} + \phi ln M_{it} + X'_{it} \gamma + \varepsilon_{it} \quad (12)$$

In the formula, $ln ci_{it}$ is the logarithm of the carbon emission intensity of city i at time t , $ln fin_{it}$ is the level of financial development, X'_{it} is the control variable, and ε_{it} is the random disturbance term. $ln M_{it}$ is an intermediate variable, including technological innovation (*inno*), industrial structure (*is*) and consumption level (*consmue*). Technological innovation (*inno*) is characterized by the amount of urban green patents granted; industrial structure (*is*) is measured by the proportion of tertiary industry in GDP; consumption level (*consmue*) is measured by the fraction of total retail sales of social consumer goods in GDP.

(1) The mediating effect of technological innovation. We use the number of urban patent grants as an intermediary indicator of technological innovation. Judging from the estimated results in the first column of Table 8, the estimated coefficient of financial development is -0.1685 and is significant at the 1% level; this means that the influence of financial development on carbon emission intensity has a mediating effect (the same below). Looking at the estimated results in the second column of Table 9, the estimated coefficient of financial development on technological innovation is 0.1068, which is significant at the 5% level. This means that financial development has a significant effect on promoting the improvement of technological level, which is manifested as an increase in financial development. A 1% increase in financial development will increase the level of technological innovation by 0.1068%. In the third column, both technological innovation and financial development are included in the model. The coefficient of influence of technological innovation on carbon emission intensity is -0.1502, which is significant at the 1% level. It shows that improvements in the level of technological innovation are conducive to reducing the intensity of carbon emissions. The results of both financial development and technological innovation show significantly that there is a partial mediation effect. The mediation effect accounts for 9.5% of the total effect. This means that financial development reduces carbon emission intensity by increasing the level of technological innovation, which validates Hypothesis 1.

Table 8 Mechanism Test: Promoting Innovation

Variable	(1) <i>ln ci</i>	(2) <i>inno</i>	(3) <i>ln ci</i>
<i>ln fin</i>	-0.1685*** (0.0385)	0.1068** (0.0432)	-0.1524*** (0.0347)
<i>inno</i>			-0.1502*** (0.0291)
<i>_cons</i>	-6.9686***	7.2717***	-5.8763***

	(1.1597)	(1.0300)	(1.1187)
<i>N</i>	3122	3122	3122
<i>R</i> ²	0.3436	0.0924	0.3899

(2) The mediating effect of structural optimization. We use the ratio of tertiary industry to GDP as an intermediary indicator for structural optimization. Judging from the estimated leads to the second column of Table 9, the estimated coefficient of financial development on the proportion of tertiary industry in GDP is 0.0533, which is significant at the 1% level. This means that financial development has a significant effect on increasing the ratio of tertiary industry. Specifically, if the level of financial development increases by 1%, the proportion of tertiary industry will increase by 0.0533%. Incorporating the proportion of tertiary industry and financial development into the model at the same time, it is found that the coefficient of influence of the proportion of tertiary industry on carbon emission intensity is -0.3840, indicating that the increase in the proportion of tertiary industry has promoted a reduction in carbon emission intensity. Meanwhile, the results of financial development and the proportion of tertiary industry both clearly indicate that there is a partial mediation effect. The mediation effect accounts for 12.15% of the total effect, indicating that financial development can reduce the carbon emission intensity by optimizing the industrial structure. Hypothesis 2 is verified.

Table 9 Mechanism Test: Optimizing Industrial Structure

Variable	(1) <i>lnci</i>	(2) <i>is3</i>	(3) <i>lnci</i>
<i>lnfin</i>	-0.1685*** (0.0385)	0.0533*** (0.0135)	-0.1480*** (0.0360)
<i>is3</i>			-0.3840*** (0.1380)
<i>_cons</i>	-6.9686*** (1.1597)	7.0446*** (0.4115)	-4.2634*** (1.5943)
<i>N</i>	3122	3122	3122
<i>R</i> ²	0.3436	0.3145	0.3659

(3) The mediating effect of promoting consumption. We use the ratio of the total retail sales of consumer goods to GDP to represent the intermediate indicator of consumption effects. From the sequential test in the second column of Table 10, it is found that the coefficient of financial development on social consumption is 0.4527, and significant at the 1% level; this indicates that financial development can significantly promote social consumption. Then in the third section, financial development and social consumption are included in the model at the same time, but the results are not significant, indicating that there is no mediating effect. This means that financial development cannot increase carbon emissions by promoting social consumption; Hypothesis 3 is not supported.

Table 10 Mechanism Test: Expansion of Consumption

Variable	(1) <i>lnci</i>	(2) <i>consmue</i>	(3) <i>lnci</i>
<i>lnfin</i>	-0.1685*** (0.0385)	0.4527*** (0.0628)	0.0302 (0.0467)
<i>consmue</i>			-0.0626 (0.1314)
<i>_cons</i>	-6.9686***	15.8351***	-0.0917

	(1.1597)	(1.1531)	(1.7281)
<i>N</i>	3122	3117	3117
<i>R</i> ²	0.3436	0.6553	0.4985

6. Conclusions and policy recommendations

Based on the panel data of 223 prefecture-level cities in China from 2005 to 2018, this paper studies the impact of financial development on China's carbon emission intensity and its mechanism from both theoretical and empirical aspects. Studies have shown that financial development has significantly reduced China's carbon emission intensity overall. After considering the spatial effect, financial development has significantly promoted the intensity of local carbon emissions, while reducing the intensity of carbon emissions in neighboring areas. Among them, the direct effects of financial development on the local area accounted for 35.57% of the total utility, and the indirect effects on neighbors accounted for 64.43%. After a series of robustness tests, the conclusion is still clearly established; heterogeneity analysis shows that financial development has directly increased the carbon emission intensity of cities. However, among the indirect effects, only the urban financial development in the eastern region has a substantial detrimental impact on neighboring cities and the total carbon emission intensity, while in the central and western regions it has no significant impact. Finally, this paper examines the mechanism between financial development and carbon emission intensity. The results show that financial development mainly reduces carbon emission intensity through technological innovation and industrial structure optimization. Among them, the effect of technological innovation is 9.5%, and the effect of industrial structure optimization is 12.15%; thus industrial structure optimization has a greater impact on reducing carbon emissions. The conclusion of this article is consistent with the research of [Liu and Song, \(2020\)](#). However, this article uses city-level data to provide microscopic evidence for the impact of financial development on carbon emissions. At the same time, this paper further examines its influence mechanism and analyzes for possible heterogeneity.

Accordingly, this article proposes the following policy implications: (1) Further support for financial development and the building of a large financial center. It is found that, after adding spatial factors, financial development has a significant spatial spillover effect on carbon emissions reduction. Financial centers are conducive to achieving the scale effect of emissions reduction and reducing the overall carbon intensity. Therefore, further support is needed for financial development and the building of large financial centers. Strengthen the construction of financial infrastructure, especially fintech facilities, attach importance to the introduction of fintech talents, strengthen supervision of financial development, and develop a new type of financial center through the benign integration of finance and technology. This will give play to the important role of financial development in reducing carbon emission intensity. (2) Build a financial service system that supports green technological innovation, and further use the role of financial development in promoting green technological innovation. Encourage banking and financial institutions to provide professional investment services for green technology innovations such as renewable energy technologies and cleaner production technologies. Vigorously support and cultivate private equity and venture capital institutions that focus on investing in green technologies and build a multi-level financing and risk management mechanism. (3) Optimize the capital allocation structure and financial product structure. In terms of optimizing the capital allocation structure, it is critical to perform a good job in guiding the flow of capital in the capital market. Restrict the flow of financial capital to high-emission and high-energy-consuming industries, and actively guide financial capital to invest in high-tech, low-energy, low-emission green and clean industries and smart high-end

industries. In terms of optimizing the structure of financial products, it is necessary to further encourage financial innovation. Vigorously develop new financial formats such as digital finance and green finance, and enrich the types of green credit, green bonds, green stock indexes and related products.

Owing to data limitations, this article only uses the proportion of total financial institution loans to GDP to measure financial development, and fails to further consider the breadth and depth of financial development and the impact of its internal structure on carbon emissions. All these may bring differences in the impact of financial development on carbon emission intensity. In this regard, it is crucial to further refine our research to summarize more targeted financial development proposals.

Authorship contribution

Xueyang Liu: Methodology, Data curation, Formal analysis, Writing - original draft, Writing-review & editing. Xiaoxing Liu: Conceptualization, Methodology, Funding acquisition, Supervision.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate I am free to contact any of the people involved in the research to seek further clarification and information.

Consent for publication Not applicable.

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