Analysis of the effect of digital financial inclusion on agricultural carbon emissions in China

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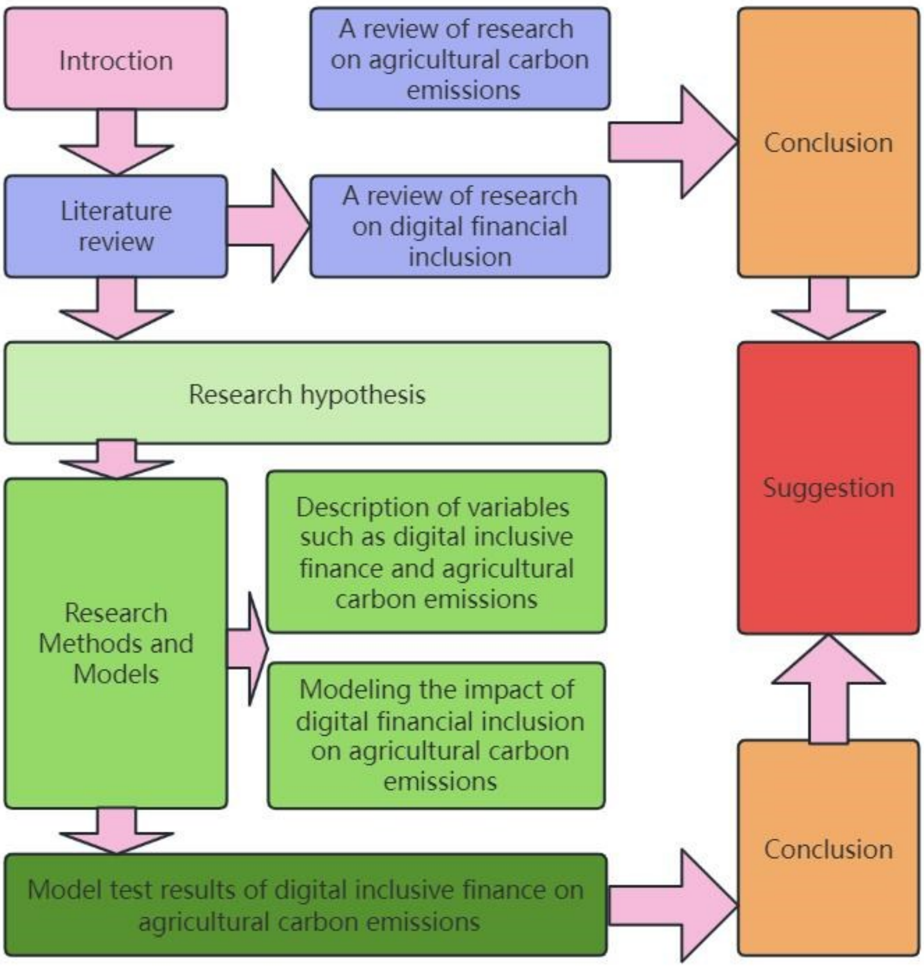
GRAPHICAL ABSTRACT



ABSTRACT: In the context of China's "dual-carbon" goal, digital financial inclusion plays an important role in agricultural carbon emission reduction. This paper analyzes the effect of digital financial inclusion on agricultural carbon emissions and its transmission mechanism based on provincial panel data of 31 provinces in China from 2012 to 2022. The results show that digital financial inclusion has a significant inhibitory effect on agricultural carbon emissions. In terms of the mechanism of action, digital financial inclusion can reduce agricultural carbon emissions through the upgrading of agricultural industrial structure. In addition, in the mechanism of digital financial inclusion affecting agricultural carbon emissions, there is a threshold effect, and only when rural human capital is higher than a certain threshold, digital financial inclusion can show the inhibiting effect on agricultural carbon emissions. Therefore, it should strengthen the multi-dimensional development of digital technology facilities, digital financial inclusion development and agricultural industrial structure upgrading to promote the green and low-carbon transformation of agriculture and comprehensively reduce agricultural carbon emissions, with a view to realizing the low-carbon and sustainable development of Chinese agriculture.

Keywords: digital financial inclusion; agricultural carbon emissions; low-carbon agriculture

1. Introduction

In recent years, global temperature change has become an important issue that all mankind needs to address urgently, in which carbon emissions, as a key factor in global warming, and how to reduce carbon emissions have become a key task for the world to realize sustainable development. As a large agricultural country, China's traditional agricultural development model has contributed to the rapid growth of food production and farmers' incomes, as well as the waste of resources and a sharp increase in pollutants. According to data related to the Zero Growth Action Plan for Chemical Fertilizer Use by 2020 issued by China's Ministry of Agriculture and Rural Development, China's total use of chemical fertilizers accounts for about 33% of the world's total fertilizer use, ranking first in the world, of which the amount used per acre of arable land is about 21.9 kilograms, which is much higher than the standard of 8 kilograms in developed countries. In addition, agricultural water consumption accounts for 61.5% of the total water consumption of the whole society, but the coefficient of water consumption efficiency is only 0.5, which is far lower than that of developed countries, which is 0.8. The agricultural development model of over-investment of agricultural resources and inefficient use of agricultural resources has resulted in a large amount of agricultural carbon emissions, which accounts for 17% of China's total carbon emissions. According to statistics, agricultural carbon emissions account for 17% of China's total carbon emissions. How to promote the promotion of agricultural carbon emission reduction has become an important part of the promotion of China's high-quality economic development and agricultural green development.

At the same time, with the booming development of China's digital economy, the deep integration of traditional inclusive finance with new-generation information technologies such as the Internet, big data and cloud computing has given rise to digital financial inclusion. Digital financial inclusion has both digital and inclusive characteristics, relying on digital network platforms, not only can enhance the efficiency of financial resource allocation, make up for the shortcomings of traditional finance, but also effectively reduce the threshold and cost of use in the agricultural sector, promote digitalization and intelligent new production model wide coverage, for agricultural carbon emission reduction is of great significance. On the one hand, digital financial inclusion can help effectively enhance the service efficiency of traditional finance, improve the level of rural financial supply, provide more comprehensive and diversified financial services for agricultural production, and effectively alleviate the problem of credit constraints in the agricultural sector. On the other hand, digital financial inclusion can promote the flow of environmental protection technology to the agricultural sector by supporting the industrialization of digital technology and the digitization of industries, giving full play to the positive role of digital technology in agricultural green energy saving and emission reduction, effectively reducing agricultural carbon dioxide emissions and agricultural pollution, and improving agricultural green output.

2. Literature review

With regard to the study of agricultural carbon emissions, Chinese and international scholars have gradually formed a more systematic research system by conducting research on the measurement of agricultural carbon emissions and the factors affecting agricultural carbon emissions, mainly in the following aspects: (1) In terms of the measurement of agricultural carbon emissions, the early research was mainly focused on the measurement of a single index of agricultural carbon emissions, such as crop carbon emissions, livestock and poultry farming, land use, etc. However, scholars have noted that the measurement of a single index has certain limitations. Johnson, an American scientist, proposed that agricultural carbon emissions should include agricultural waste, intestinal fermentation, manure management, agricultural energy utilization, rice fields and bio-burning. In related studies, crops (variety, yield and interplanting mode), climate (temperature, precipitation and evaporation) and soil (carbon storage and water content) are also taken as important factors to analyze and evaluate the carbon transfer amount of farmland soil. With the increasing research content, a more systematic and comprehensive agricultural carbon emissions measurement system was gradually formed, including agricultural inputs such as fertilizers, agricultural films and pesticides, livestock and seeding and irrigation. scholars use this as the basis for agricultural carbon emission measurement research, such as Zhang et al (2024) through the measurement of China's agricultural carbon emission intensity, and found that there are obvious provincial differences in the intensity of agricultural carbon emissions, with the overall characteristic of "high in the west and low in the east". Cui et al (2024) used the IPCC carbon accounting method to measure the total amount of agricultural carbon emissions and carbon emission intensity of 30 provinces in China, and found that the total amount of agricultural carbon emissions and carbon emission intensity in China showed a decreasing trend. (2) In terms of research on factors influencing agricultural carbon emissions, the scope of research by scholars is relatively wide, and mainly divided into three main categories: the first category is to explore the impact of digital development such as digital economy and digital agriculture construction on agricultural carbon emissions; the second category is to explore the impact of the level of agricultural development, such as agricultural socialization services, agricultural industry agglomeration, and the level of modernization of agriculture, on agricultural carbon emissions; and the third category is to take the province or geographical area as the research unit, further analyzes the decoupling relationship between agricultural carbon emissions and economic growth on the basis of analyzing the total amount of agricultural carbon emissions and carbon emission intensity. For example, Zhao (2023) takes Henan Province as the object of his research, and finds that the relationship between agricultural carbon emissions and economic growth in Henan Province has gradually changed from a weak decoupling to a strong decoupling, and that agricultural carbon emissions are gradually decreasing in Henan Province at the same time as the economy grows. Ma (2024) studied the decoupling relationship between agricultural carbon emissions and economic growth in nine provinces in the Yellow River Basin, and found that the overall state of favorable decoupling is dominated by weak decoupling and strong decoupling, presenting an ideal state in which the growth of the agricultural economy is much higher than the agricultural carbon emissions.

The concept of inclusive finance was first proposed by the United Nations in 2005, and its basic meaning is to provide appropriate and effective financial services at affordable costs to all sectors of society with financial needs, based on the requirements of equal opportunity and the principle of sustainable business development, by increasing policy guidance and support, strengthening the construction of the financial system and improving the financial infrastructure. On this basis, the White Paper on the Development of Digital financial inclusion (2019) released by the China Academy of Information and Communication Research defines digital financial inclusion as the provision of equal, effective, and comprehensive financial products and services to all segments of the society, especially low-income groups in urban areas, special groups of the rural population, and small and micro enterprises not yet covered by the existing financial system, through various digital technologies. As a product of the fourth stage of the financial revolution following microlending, microcredit and inclusive finance (Wang et al.,2020), digital financial inclusion attaches more importance to the accessibility of financial services brought about by the popularization of digital technologies, and encourages individuals to participate in and benefit from financial services provided by financial institutions. It therefore plays an important role in achieving sustainable development Goals across countries and industries (Tay et al., 2022). Digital financial inclusion breaks the service supply barriers of traditional financial services focusing only on economic benefits, and can effectively solve the problem of rural financial inclusion, improve the level of rural financial supply, provide more convenient, efficient and flexible financial services for agricultural production, and effectively alleviate the problem of credit constraints in the agricultural sector (Jin et al.,2023).

While digital financial inclusion promotes agricultural development and improves the financial support environment in rural areas, academics have begun to pay attention to its important role in agricultural carbon emission reduction. First, digital financial inclusion realizes carbon emission reduction by boosting agricultural green technology innovation. Feng et al (2023) pointed out that digital financial inclusion can provide financial support for the R&D sector, reduce the marketization limitations of enterprise scientific research results, accelerate the transformation and application of R&D results, and thus promote the innovation of agricultural production technology and promote the green development of agriculture. Pan et al (2023) argue that the inclusive nature of digital financial inclusion eases the financing constraints of farmers, making it possible for more R&D funds to be invested in the agricultural sector, thus improving the level of regional agricultural technology innovation. Second, digital financial inclusion establishes an agricultural green industrial system by promoting the integrated development of the agricultural industry. Huang et al (2022) pointed out that the development of digital financial inclusion with the help of digital technology can accurately capture the financing needs of agricultural business subjects, overcome the defects of the monotonization of financial services under the traditional financial system, and provide diversified financial services for various types of emerging business in agriculture, which contributes to the integrated development of the agricultural industry. Pang et al (2023) believe that digital financial inclusion can combine the modern green financial development concept with the development of ecological agriculture, establish the corresponding financial system, and combine with the current green development of environmental regulations continue to strengthen and realize the green transformation of agricultural production. In addition, some scholars have also included e-commerce participation (Shen et al.,2023), rural financial institutions (Zhang et al.,2024), land transfer (Gao et al.,2024), etc. as key factors in the study of the impact of digital financial inclusion on agricultural carbon emissions, and empirical illustrations. In summary, existing studies have made some useful explorations on the role of digital financial inclusion in influencing agricultural carbon emissions, but there are still shortcomings, one is that most of the current studies are based on traditional finance to explore the relationship between financial development and carbon emissions, and there are fewer studies on the impact of digital financial inclusion on agricultural carbon emissions; the second is that the literature on how digital financial inclusion affects agricultural carbon emissions and explores the influence mechanism is relatively small, and how digital financial inclusion affects agricultural carbon emissions and its transmission mechanism must be further expanded. Therefore, The possible contributions of this paper are as follows: (1) Establish the evaluation index system of digital financial inclusionand explore the mechanism of digital financial inclusionon agricultural carbon emissions; (2) Take the upgrading of agricultural industrial structure as a mediating variable to explore whether it plays a mediating role in the influencing mechanism; (3) This paper takes rural human capital as the threshold variable to explore whether different levels of rural human capital will have different effects on the impact of digital financial inclusionon agricultural carbon emissions, so as to provide certain theoretical references for the realization of low-carbon transformation in agriculture.

3. Research hypothesis

3.1 The direct impact of digital financial inclusion on agricultural carbon emissions

Digital financial inclusion can promote carbon emission reduction in agriculture, as reflected in the following: first, digital financial inclusion can alleviate agricultural financing problems. Traditional finance takes economic benefit as the service goal, and produces “financial exclusion” to the vulnerable groups such as farmers, which makes the financial service in rural areas in a state of absence for a long time. Relying on the Internet, big data and other information technology, digital financial inclusion can reduce the cost of information search and matching of financial institutions, expand the scope of financial services, improve the coverage and penetration of inclusive finance, maximize the demand for agricultural financing, and provide financial support for the green and low-carbon development of agriculture. Second, digital financial inclusion helps optimize the allocation of agricultural resources. By playing the function of resource allocation, digital financial inclusion breaks the time and space limitations of financing, improves the allocation efficiency of the use of funds in the agricultural sector, enhances the green total factor productivity of agriculture, and reduces the intensity of agricultural carbon emissions. Third, the diversified environmental protection service platform built by digital financial inclusion can not only give full play to the “network effect” and “connectivity economy” of the Internet, promote the dissemination and exchange of agricultural technology, and enhance the application rate of low-carbon technology in agricultural production, but also give rise to a new generation of low-carbon technology under the development of e-commerce. It will expand more low-carbon development modes in agriculture and promoting green agricultural development. Based on this, this paper puts forward the following hypotheses:

Hypothesis 1 (H1): Digital financial inclusion can directly reduce the carbon intensity of agriculture.

3.2 Indirect impacts of digital financial inclusion on agricultural carbon emissions

The impact of digital financial inclusion on agricultural carbon emissions can play an indirect role through the upgrading of the agricultural industrial structure, as shown in the following: First, digital financial inclusion can realize the precise docking of the supply chain and demand chain of agricultural products, form a win-win chain of consumption upgrading and agricultural transformation and upgrading, promote the evolution of the agricultural chain to the direction of deep processing, extend the agricultural industry chain, and realize the transformation and upgrading of the traditional agricultural industry. The transformation and upgrading of the agricultural industry will abandon the high-pollution and high-energy consumption production methods and production technologies that are inconsistent with the concept of modern industrial development, thus reducing agricultural carbon emissions. Second, digital financial inclusion collects agricultural production information of all kinds of agricultural business subjects through big data technology, builds an agricultural credit system (Li et al., 2024), analyzes and screens high-quality customers by taking the behavioral data of agricultural operators as the evaluation element, increases financial credit supply in a targeted manner, and better meets the multi-level and diversified financing needs in rural areas. Therefore, the agricultural credit system established by digital financial inclusion optimizes the risk management of agricultural credit, enhances the breadth of financial coverage in the agricultural sector, and then accelerates the agglomeration of agricultural industry resource elements to a more reasonable and advanced industrial form, forming a new industry in the agricultural industry. Accordingly, this paper puts forward the hypothesis:

Hypothesis 2 (H2): digital financial inclusion can reduce agricultural carbon emission intensity through structural upgrading of agricultural industry.

3.3 Threshold effects of digital financial inclusion on agricultural carbon emissions

Rural human capital refers to the intangible capital formed through education and training, health investment, migration investment and other forms, condensed in rural workers, expressed in the quantity and appropriate amount of rural labor force (Xu, 2005). Zhang et al (2019) pointed out that the promotion and application of digital financial inclusion in rural areas puts higher demands on farmers' financial knowledge and financial education. Therefore the impact of digital financial inclusion on agricultural carbon emissions may be nonlinear and will be constrained by rural human capital. Specifically, in areas with lower levels of rural human capital, affected by literacy levels and financial cognitive ability, the progress of farmers in accepting the concept of digital financial inclusion and learning digital technology is relatively slow, thus restricting the penetration of digital financial inclusion in rural areas, which is not conducive to the rapid application of advanced technology in agriculture and hinders the process of low-carbon development in agriculture. For areas with higher levels of rural human capital, farmers are not only more likely to accept new concepts such as digital financial inclusion and realize the rapid application of advanced technology, enhance the breadth of coverage and depth of use of digital financial inclusion in the region, and give better play to the role of digital financial inclusion, but also more comprehensively understand and analyze the important role of digital financial inclusion for agricultural production, and then choose a more conducive to low-carbon and environmentally friendly agricultural production mode and promote the green development of agriculture. Accordingly, this paper puts forward the following hypotheses:

Hypothesis 3 (H3): the impact of digital financial inclusion on agricultural carbon emissions has a significant threshold character and is constrained by the rural human capital

4.Research Methods and Models

4.1 Description of variables

4.1.1 Explained Variables

Carbon intensity of agriculture (InTQ_{it}). In this paper, the agricultural carbon emission intensity is chosen to measure the level of agricultural carbon emission of each province in China, which is expressed by the ratio of total agricultural carbon emission to agricultural output value, and the specific calculation formula is as follows:

$$\text{InTQ}_{it}=\frac{TZ}{ArgGDP} \qquad (1)$$

TZ in Equation (1) is the total agricultural carbon emissions and *ArgGDP* is the gross agricultural product based on the value added of the primary sector.

This paper draws on the methodology of Li Bo et al. to measure agricultural carbon emissions from six aspects, such as diesel, fertilizer and pesticide, and the carbon emission calculation formula is as follows:

$$TZ = \Sigma TZ_i = \sum T_i \times \sum \sigma_i \quad (2)$$

In Equation (2): TZ_i denotes the total amount of carbon emissions from carbon sources of category i; T_i denotes the absolute amount of carbon sources of category i. σ_i denotes the carbon emission coefficient of carbon sources in category i. Specific carbon sources and carbon emission coefficients are shown in Table 1.

Table 1. Agricultural carbon sources and emission factors

Carbon Source	Carbon Emission Factor	Reference Source
Diesel fuel	0.59 kg/kg	IPCC 2013
Fertilizers	0.89 kg/kg	Oak Ridge National Laboratory, USA
Pesticide	4.93 kg/kg	Oak Ridge National Laboratory, USA
Agricultural film	5.18 kg/kg	Institute of Agricultural Resources and Ecological Environment, Nanjing Agricultural University
Irrigated	266.48 kg/hm^2	Duan et al (2011)
Sowing	312.6 kg/km^2	Li et al (2011)

4.1.2 Core explanatory variables

Digital Financial Inclusion (DFI_{it}). Referring to the research results of Guo et al (2020), this paper establishes a digital financial inclusion indicator system based on the existing traditional financial inclusion indicators, combining the new features of digital financial services and data availability, from the three dimensions of breadth of coverage, depth of use and degree of digitization, as shown in Table 2.

Table 2. Digital financial inclusion indicator system

The First Dimension	The Second Dimension	Specific Indicators
breadth of coverage	Account coverage	Number of Alipay accounts per million people Proportion of Alipay card users Average number of bank cards tied to each Alipay
Depth of use	payment business	Number of payments per capita Amount paid per capita

	Money fund operations	Ratio of high-frequency (50 or more annual activities) active users to annual activities of 1 or more times
		Number of balance purchase transactions per capita
		Amount of balance purchase per capita
		Number of balance purchases per 10,000 Alipay users
	credit business	Number of Internet consumer loans per 10,000 adult Alipay users
		Number of loans per capita
		Loan amount per capita
		Internet micro business loans per 10,000 adult Alipay users
		Average number of loans per household for micro and small operators
		Average loan amount for micro and small operators
	insurance business	Number of insured users per 10,000 Alipay users
		Number of insurance strokes per capita
		Amount of insurance per capita
	Investment business	Number of people involved in Internet investment and wealth management per 10,000 Alipay users
		Number of investments per capita
		Amount of investment per capita
	credit business	Number of calls per capita for natural person credit
		Number of users using credit-based services per 10,000 Alipay users
Degree of digitization	mobility	Percentage of mobile payment transactions
		Percentage of mobile payment amount
	materialization	Average lending rate for micro and small operators
		Average personal loan interest rate
	creditization	Percentage of Chanting Payments
		Chanting Payment Amount Percentage
		Sesame Credit Pawnless Transactions as a Percentage
		Sesame Credit Pledge Free Amount Percentage
	facilitation	Percentage of payments made by users using QR codes
		Percentage of amount paid by users on QR code

4.1.3 Intermediate variables

Agricultural industrial structure upgrading (TL). In this paper, we draw on the measurement method of Kuang et al (2016), and use the Terrell index (TL) to represent agricultural structure upgrading, with the following specific measurement formula:

$$\text{TL} = \sum_{i=1}^{n} \frac{M_i}{M} \ln\left(\frac{M_i}{M_i} / \frac{M}{L}\right) \quad (3)$$

In equation (3), M_i is the total output value of each industry (agriculture, forestry, livestock, fishery); L is the number of people employed in each industry; $\frac{M_i}{M}$ is the structure of output; $\frac{M}{L}$ is the production efficiency. Since data on the number of people employed in agriculture, forestry, animal husbandry and fisheries are not currently available, the ratio of value added to intermediate consumption in each industry is used to express production efficiency.

4.1.4 Threshold variables

Rural human capital level (AHU). Considering that the number of years of education can reflect the cultural level of the rural labor force, which is closely related to its cultural quality, learning ability and technical application ability, this paper uses the average number of years of education of the rural labor force in each province to represent the level of rural human capital.

4.1.5 Control variables

In order to reduce the errors caused by omitted variables and ensure the accuracy of the research results, this paper selects the following control variables: urbanization rate (UR), expressed as the proportion of non-agricultural population to the total population; level of economic development (GDP), measured by regional gross domestic product per capita; the ratio of governmental support for agriculture (GOV), expressed as the proportion of the governmental expenditures on agriculture to the governmental total expenditures of funds; and environmental regulation (ER), expressed as the proportion of the investment in pollution control projects to the regional GDP of each region.

Table 3. Results of descriptive statistics for the main variables

Variables	Obs	Mean	Sd	Min	Max
InTQ_{it}	341	325.3577	230.9994	12.7235	995.7285
DFI	341	261.3188	92.3012	61.4700	460.6909

TL	341	2.3933	0.1239	2.1820	2.8359
AHU	341	9.2061	1.1288	4.2219	12.7820
UR	341	0.5980	0.1262	0.2287	0.8960
GOV	341	11.5680	3.4537	4.0404	20.3840
GDP	341	26266.45	12489.19	8568	79610
ER	341	0.2503	0.2761	0	2.4510

4.2 Data sources

This paper uses 31 provinces (autonomous regions and municipalities directly under the central government) in mainland China from 2012 to 2022, excluding Hong Kong, Macau and Taiwan. The data come from China Statistical Yearbook, China Agricultural Statistical Yearbook, National Bureau of Statistics, Provincial Statistical Yearbook, EPS data platform, and Peking University Digital financial inclusion Index. For some missing data, this paper uses linear interpolation to supplement.

4.3 Model design

4.3.1 double fixed-effects model

In order to explore the direct impact of digital financial inclusion on agricultural carbon emissions, this paper constructs the following double fixed effects model:

$$\ln\mathrm{TQ}_{it} = \partial_0 + \partial_1 \mathrm{DFI}_{it} + \partial_2 X_{it} + \delta_i + \tau_t + \mu_{it} \qquad (4)$$

In equation (4), $\ln\ \mathrm{TQ}_{it}$ is the explanatory variable agricultural carbon emission intensity, and DFI_{it} is the core explanatory variable digital financial inclusion, and X_{it} is the set of control variables, δ_i and τ_t denote area and time fixed effects, respectively, and μ_{it} denotes the random perturbation term.

4.3.2 mediation effects model

In order to verify whether the upgrading of agricultural industrial structure plays a mediating effect in digital financial inclusion affecting agricultural carbon emissions, this paper draws on the research results of Wen et al (2005) and Deng et al (2021) to construct a mediating effect model for panel data. Based on equation (4), the mediation effect model is:

$$\mathrm{TL}_{it} = \beta_0 + \beta_1 \mathrm{DFI}_{it} + \beta_2 X_{it} + \delta_i + \tau_t + \mu_{it} \quad (5)$$

$$\ln\ \mathrm{TQ}_{it} = \gamma_0 + \gamma_1 \mathrm{DFI}_{it} + \gamma_2 \mathrm{TL}_{it} + \gamma_3 X_{it} + \delta_i + \tau_t + \mu_{it} \quad (6)$$

In equations (5) (6), TL_{it} is the mediating variable agricultural industry structure upgrading, other symbols and variables are the same as in equation (4).

4.3.3 threshold effect model

In order to further figure out whether there is a threshold effect of financial inclusion in the process of influencing agricultural carbon emissions, this paper constructs the following panel threshold model on the basis of equation (4) and with reference to Hansen (1999), taking the level of rural human capital as a threshold variable:

$$\ln\ \mathrm{TQ}_{it} = \alpha_0 + \alpha_1\ \mathrm{DFI}_{it}\, I(AHU_{it} \leqslant \gamma) + \alpha_2\ \mathrm{DFI}_{it}\, I(AHU_{it} > \gamma) + \alpha_3 X_{it} + \delta_i + \tau_t + \mu_{it} \quad (7)$$

In formula (7), AHU represents rural human capital, γ is the threshold value, I(·) represents the indicator function, when the conditions in parentheses are true, I(·)=1, and vice versa I(·)=0. Other symbols and variables are the same as in Equation (4).

5. Results and discussion

5.1 Benchmark regression results

Table 4 reports the base model regression results. In Column (1), this paper did not add any control variables, and only the core explanatory variables and the explanatory variables were regressed, and the results show that the regression coefficient of digital financial inclusion is -0.751 and significant at 1% statistical level, indicating that for every 1% increase in the development level of digital financial inclusion, the intensity of agricultural carbon emissions will be reduced by 0.751%, which initially proves that digital financial inclusion has a inhibitory effect. The reason lies in that the convenience and inclusiveness of digital financial inclusion reduces the threshold of farmers' access to financial support, increases the possibility of agricultural technology application and green production and management, and thus reduces the intensity of agricultural carbon emissions. Thereafter, in columns (2) to (5), the control variables are gradually added for regression, and it is found that the positivity, negativity and significance of digital financial inclusion are not changed, and the regression coefficients of digital financial inclusion are significantly increased after adding control variables, which further verifies that the role of digital financial inclusion in influencing the carbon emission in agriculture, and that hypothesis (1) is valid. In Column (5), the control variable environmental regulation shows a significant inhibitory effect, which may be attributed to the fact that under the government's leadership, the intensity of agricultural carbon emissions is suppressed by stopping improper agricultural production behaviors such as farmers' burning of wastes and overuse of chemical fertilizers. Whereas economic development and the proportion of support to agriculture will increase financial support in the agricultural sector, farmers may choose to increase the use of fertilizers, pesticides and other items, while increasing agricultural carbon emissions.

Table 4. Benchmark regression results

Variables	ln TQ_{it} (1)	(2)	(3)	(4)	(5)
DFI	-0.751***	-0.911***	-1.108***	-1.019***	-0.961***
	(-4.147)	(-4.984)	(-4.772)	(-4.568)	(-4.307)
URB		-3.179***	-1.932	-1.194	-1.368
		(-3.665)	(-1.540)	(-0.988)	(-1.137)
GDP			0.126	0.200**	0.203**
			(1.374)	(2.249)	(2.300)
GOV				0.584***	0.582***
				(5.309)	(5.323)
ER					-1.504**
					(-2.193)
_cons	16.401***	45.424***	32.212**	18.157	18.825
	(5.161)	(5.338)	(2.511)	(1.445)	(1.508)
year	Yes	Yes	Yes	Yes	Yes
area	Yes	Yes	Yes	Yes	Yes
N	341	341	341	341	341
R^2	0.991	0.991	0.991	0.992	0.992

Note: *, ** and *** are statistically significant at 10%, 5% and 1%, respectively. The values in parentheses are the test Z-values, the same below.

5.2 Robustness Tests

The above benchmark regression results show that digital financial inclusion can significantly suppress the intensity of agricultural carbon emissions. In order to test the robustness of the regression results, this paper adopts the following methods to conduct the robustness test: Column (1) is to replace the core explanatory variables. replacing the core explanatory variables from digital financial inclusion to the digital economy index; Column (2) is to shrink the tails. Under the condition of ensuring that the sample data are not excluded, the outliers that are less than 1% and greater than 99% are replaced; Column (3) is the selection of sub-samples, and after excluding the four municipalities of Beijing, Shanghai, Tianjin, Chongqing, etc., the regression treatment is carried out again on the rest of the provinces; and Columns (4) (5) is the instrumental variable method, which replaces the digital financial inclusion index with the digital financial inclusion index lagged one-period and lagged two-period data. The results are shown in Table 5. Through the robustness test of the benchmark regression results, the sign and significance of the regression coefficient of digital financial inclusion have not changed, and they are significant at the statistical level of 1% and 5%, indicating that digital financial inclusion still has an inhibitory effect on agricultural carbon emissions, so it can be verified that the baseline regression model has strong robustness.

Table 5. Robustness test results

Variables	$\ln TQ_{it}$				
	(1)	(2)	(3)	(4)	(5)
DIG	-1.073** (-2.465)				
DFI		-0.912*** (-4.041)	-1.034*** (-4.010)		
$DFI_{i(t-1)}$				-0.807*** (-3.522)	
$DFI_{i(t-2)}$					-0.852*** (-3.719)
Controls	Yes	Yes	Yes	Yes	Yes
_cons	21.789* (1.707)	56.987*** (8.254)	65.889*** (8.465)	42.650*** (5.351)	49.100*** (5.385)
year	Yes	Yes	Yes	Yes	Yes
area	Yes	Yes	Yes	Yes	Yes
N	341	341	297	310	279
R^2	0.991	0.992	0.990	0.479	0.504

5.3 Heterogeneity test

5.3.1 Heterogeneity analysis of different geographical areas in the provinces

Considering that there are some differences in regional temperature and soil conditions among different regions in China due to different geographical locations, which in turn have an impact on agricultural carbon emissions. In order to explore the regional heterogeneity of the impact of digital financial inclusion on agricultural carbon emissions, this paper divides China into eastern, central, western and northeastern regions, and analyzes the results using a fixed-effects model. As shown in Table 6, compared with the regression coefficients of digital financial inclusion in Column (3) western region and Column (4) northeastern region, the regression coefficients of digital financial inclusion in Column (1) eastern region and Column (2) central region are larger in absolute value, and the regression coefficients are significant at the 5% statistical level. The possible reason for this is that the eastern and central regions have a better foundation for low-carbon development in agriculture, a relatively developed agricultural economy, a complete digital infrastructure, and a higher level of financial development in general, which establishes the pattern of development of digital financial inclusion in the eastern and central regions, making the effect of digital financial inclusion in boosting carbon emission reduction in agriculture better (Shen et al., 2023).

Table 6. Heterogeneity analysis in different regions

Variables	In TQ_{it}			
	(1)	(2)	(3)	(4)
DFI_{it}	-0.768**	-2.368**	-0.193	-0.117
	(-2.217)	(-2.301)	(-0.763)	(-0.644)
Controls	Yes	Yes	Yes	Yes
_cons	69.439***	163.045***	22.327***	204.913***
	(3.141)	(4.918)	(3.731)	(5.225)
year	Yes	Yes	Yes	Yes
area	Yes	Yes	Yes	Yes
N	110	66	132	33
R^2	0.989	0.986	0.996	0.999

5.3.2 Heterogeneity analysis of different food production in the provinces

Considering the probable relationship that exists between the intensity of agricultural carbon emissions and regional grain production, this paper classifies 31 provinces into high grain-producing, medium grain-producing and low grain-producing regions based on the grain production of each province in China in 2022 and conducts regression analysis. The results are shown in Table 7, where the regression coefficients of digital financial inclusion in columns (1) (2) (3) are significantly negative. The absolute value of the regression coefficients in column (1) in the grain high-producing area, (2) in the grain-medium-producing area and column (3) in the grain-low-producing area decreases in turn, indicating that the suppression effect of digital financial inclusion on the intensity of agricultural carbon emissions is more obvious within the grain high-producing area, followed by the grain-medium-producing area, and lastly by the grain-low-producing area. The possible reason is that the inhibiting effect of digital financial inclusion on agricultural carbon emissions may have a certain scale effect, and its role in reducing agricultural carbon emissions becomes more obvious with the increase in the area of food cultivation and food output. At the same time, farmers in high-grain-producing areas are more receptive to digital financial inclusion, which can effectively alleviate the problem of financing constraints, and then apply advanced agricultural production technology and agricultural planting concepts to reduce agricultural carbon emissions.

Table 7. Inhibitory analysis of different grain yields

Variables		$\ln\ TQ_{it}$	
	(1)	(2)	(3)
DFI	-1.083**	-1.069***	-0.406*
	(-2.167)	(-3.638)	(-1.775)
Controls	YES	YES	YES
_cons	96.089***	25.571*	42.396***
	(6.193)	(1.720)	(2.672)
year	Yes	Yes	Yes
area	Yes	Yes	Yes
N	121	132	88

R^2	0.989	0.993	0.995

5.4 Mediated effects test

In order to study whether the upgrading of agricultural industrial structure can play a mediating role in the process of digital financial inclusion affecting agricultural carbon emissions, this paper carries out the mediating effect test of upgrading of agricultural industrial structure, and the results are shown in Table 8. Column (1) proves that digital financial inclusion has a significant inhibitory effect on agricultural carbon emissions. The impact coefficient of digital financial inclusion on agricultural industrial structure upgrading in Column (2) is positive, indicating that digital financial inclusion can promote agricultural industrial structure upgrading. The coefficient of digital financial inclusion is 0.018, indicating that every 1% increase in digital financial inclusion will promote the upgrading of agricultural industrial structure by 0.018%. Column (3) adds the mediating variable upgrading of agricultural industry structure into the double fixed regression model, and its impact coefficient is significantly positive, and the impact coefficient of digital financial inclusion is -0.613, but the absolute value is decreased compared with that in Column (1), which indicates that the digital financial inclusion can reduce the carbon emission in agriculture through the mechanism of upgrading the structure of the agricultural industry, and Hypothesis 2 is confirmed. In order to fully confirm the validity of the results in column (3), the double-fixed model is changed to the time and province are not fixed in column (4), and the positive and negative and the significance of the impact coefficients of the digital financial inclusion and the upgrading of the structure of the agricultural industry have not changed, thus proving hypothesis 2 again.

Table 8. Results of the mediation effect test

Variables	$\ln\ TQ_{it}$ (1)	TL (2)	$\ln\ TQ_{it}$ (3)	$\ln\ TQ_{it}$ (4)
DFI	-0.961***	0.018***	-0.613***	-0.613***
	(-4.307)	(5.427)	(-2.732)	(-2.693)
TL			-19.667***	-0.914*
			(-5.138)	(-1.716)
Controls	Yes	Yes	Yes	Yes
_cons	18.825	33.994***	85.680***	93.404***
	(1.508)	(18.654)	(4.844)	(7.073)
year	Yes	Yes	Yes	No
area	Yes	Yes	Yes	No
N	341	341	341	341
R^2	0.992	0.999	0.992	0.992

5.5 Threshold effect regression results

From the theoretical analysis, it can be seen that when the rural human capital is at different levels, the impact of digital financial inclusion on agricultural carbon emissions is different, and there may be a nonlinear relationship between the two. In order to further verify this nonlinear relationship, this paper uses the panel threshold effect to reveal whether the impact of digital financial inclusion on agricultural carbon emissions is constrained by the rural human capital. First, the threshold effect of the level of rural human capital is tested by using Bootstrap to repeatedly sample 300 times, and the results are shown in Table 9. As shown in Table 9, the p-value of single threshold is less than 0.01 and significant at the 1% level, while the p-value of double and triple thresholds is greater than 0.1 and fails the significance test. It shows that there is a threshold effect of the level of agricultural human capital in the impact of digital financial inclusion on agricultural emissions, and hypothesis (3) is verified.

Table 9. Threshold model test results

Threshold Variable	Threshold Value	F	P	1% threshold	5% threshold	10% threshold
AHU	single threshold	57.32	0.0067	44.4424	32.4713	24.4570
	double threshold	11.56	0.5433	48.0210	34.7935	25.3774
	triple threshold	13.93	0.6167	56.1712	39.8719	32.0358

By observing the distribution of the confidence interval of the estimate of the single threshold, it can be seen that the estimate of the single threshold is 7.097, and the 95% confidence interval is [7.087, 7.100]. This paper further combines the regression results of the panel threshold model to analyze the impact mechanism of digital financial inclusion on agricultural carbon emissions, and the results are shown in Table 10. As shown in Table 10, when rural human capital is lower than the threshold (7.097), the coefficient of the impact of digital financial inclusion on agricultural carbon emissions is 1.176 and is significant at the 10% statistical level, indicating that every 1% increase in digital financial inclusion, agricultural carbon emissions will be raised by 1.176%. When rural human capital exceeds the threshold (7.097), the coefficient of digital financial inclusion is -1.446 and is significant at the 1% statistical level, and the sign of the coefficient of digital financial inclusion changes from positive to negative, indicating that at this time, digital financial inclusion is able to significantly inhibit the agricultural carbon emissions, and the probable reason for this is that when rural human capital is at a lower level, due to the lack of digital financial inclusion and digital technology, farmers are more inclined to rely on traditional agricultural production methods and are unable to fully utilize the carbon reduction effect of digital financial inclusion, thus increasing agricultural carbon emissions. As the level of rural human capital rises, farmers have stronger learning ability and technology application ability, and can effectively utilize the financial services provided by digital financial inclusion to provide financial support for the development of low-carbon agriculture, and they can also better master and apply green agricultural technologies such as precision agriculture and smart irrigation, thus improving agricultural production efficiency and reducing agricultural carbon emissions.

Among the control variables, urbanization rate and the ratio of governmental support for agriculture support are significant at the statistical levels of 5% and 1%, respectively, but the sign of the coefficient of the level of urbanization is negative, indicating that urbanization rate has an inhibitory effect on agricultural carbon emissions, while the sign of the coefficient of the ratio of governmental support for agriculture is positive, indicating that it has a promotional effect on agricultural carbon emissions, the possible reason is that the increase of urbanization rate will accelerate the flow of funds, technologies and advanced production concepts to the agricultural field, promote the low-carbon transformation of traditional agriculture, and then reduce agricultural carbon emissions, while the increase of the proportion of agricultural support will increase fertilizer. Resource inputs such as pesticides and agricultural machinery, and the use of these agricultural resources will produce a large amount of greenhouse gases, and therefore increase agricultural carbon emissions. The level of economic development and environmental regulation did not pass the significance test, indicating that the promotion effect of the two on agricultural carbon emissions has not yet appeared.

Table 10. Threshold model regression analysis results

Variables	Ratio	T	P	95% confidence

				interval	
DFI (≤7.097)	1.176*	1.870	0.071	-0.108	
DFI (≥7.097)	-1.446***	-2.997	0.005	-2.431	
URB	-2.180**	-2.622	0.014	-3.878	-0.481
GDP	0.029	0.744	0.463	-0.050	0.107
GOV	0.751***	4.064	0.000	3.737	11.288
ER	0.366	0.462	0.647	-1.251	1.984
_cons	37.009***	7.811	0.000	273.328	466.858
N		341			
R^2		0.477			

6. Conclusions and recommendations

Using the panel data of 31 provinces in China from 2012 to 2022, this paper incorporates digital financial inclusion and agricultural carbon emissions into a unified research framework, systematically analyzes the mechanism of digital financial inclusion on agricultural carbon emissions, and then empirically analyzes the intermediary and threshold effects of digital financial inclusion on agricultural carbon emissions based on the intermediary model and the threshold model. The results are found:

(1) From the baseline regression results, it can be seen that digital financial inclusion helps to curb agricultural carbon emissions, and for every 1% increase in digital financial inclusion, agricultural carbon intensity will be reduced by 0.75%. The conclusion still holds after the robustness test.

(2) The results of the heterogeneity analysis show that the inhibiting effect of digital financial inclusion on agricultural carbon emissions has some regional heterogeneity. When analyzing the geographic location of provinces, digital financial inclusion shows significant inhibitory effect on agricultural carbon emissions in the eastern and western regions, but not in the western region and the northeastern region;

and when analyzing the grain production of provinces digital financial inclusion shows significant inhibition of high-, medium-, and low-yielding regions.

(3) From the results of the mediation effect test, it can be seen that the upgrading of the agricultural industry plays a mediating role in the suppression of agricultural carbon emissions by digital financial inclusion, and can significantly reduce agricultural carbon emissions.

(4) From the results of the threshold effect test, it can be seen that the impact of digital financial inclusion on agricultural carbon emissions has a nonlinear, when the threshold variable rural human capital level is lower than the threshold, digital financial inclusion promotes agricultural carbon emissions, when the value of the threshold variable exceeds the threshold, the impact of digital financial inclusion on agricultural carbon emissions turns from positive to negative, and is able to inhibit agricultural carbon emissions.

Based on the above findings, the paper makes the following recommendations:

(1) The development of digital financial inclusion should be continuously promoted. Under the government's policy support and supervision, encouraging relevant financial institutions to sink into rural areas, and while improving the level of coverage of digital financial inclusion in rural areas and meeting the demand for agricultural loans, the digital service level of digital financial inclusion should be improved, the supply of agricultural special services should be increased, digital financial inclusion system should be built to support the development of low-carbon agriculture and provide financial support for the low-carbon development of agriculture.

(2) Increasing the construction of digital infrastructure systems in rural areas, especially in the western and northeastern regions. On the one hand, it is necessary to promote in-depth coverage of rural networks and continue to enhance the breadth and depth of coverage of fiber optic and 4G networks in rural areas. On the other hand, it is necessary to guide the high-quality development of rural networks, and encourage basic telecommunication regions to carry out high-quality network construction in rural areas, such as 5G and gigabit fiber optics, to gradually expand coverage and improve network quality. To reduce the cost of access to digital financial inclusion by improving digital connectivity in rural areas, and contribute to agricultural carbon emissions.

(3) Promoting in-depth structural upgrading of the agricultural industry, and giving full play to the inhibiting effect of high-level agricultural industries on agricultural carbon emissions.Modern agriculture should be guided by the development of comprehensive agriculture, rationally allocate agricultural resources, optimize agricultural industrial structure, and enhance the overall economic and comprehensive benefits of agriculture. We should strengthen the basic research and development capacity of agricultural science and technology, and build an agricultural technology research and development platform guided by the actual needs of agricultural industry development. It is also important to increase the promotion of agricultural science and technology, and realize the full application of digital technologies such as drones and remote sensing technology and renewable energy such as solar energy and wind energy. so as to promote the integration and development of the agricultural industry and agricultural low-carbon technology, and to promote the advanced structure of the

agricultural industry and its rationalization.

(4) Upgrading human capital in rural areas. The government should increase the support for education in rural areas and improve the supply capacity of rural education resources, and set up special rural education funds to ensure the equal right to education in rural areas. . In addition, the government should set up a digital agricultural technology research and application promotion center to carry out training activities on artificial intelligence, big data and other digital skills needed in agricultural production activities, to strengthen the construction of agricultural technology promotion teams in rural areas, intensify green technology training and practical guidance for farmers, and enhance their knowledge and production skills in green agriculture, so as to provide human resources support for the low-carbon transformation of agriculture.

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