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The impact of digital inclusive finance on agricultural carbon emissions in China—From spatial spillover perspective

Ningyuan Lu[1,a], Yang Luo[1,b], Xin Liao[1,c,*]

[1]School of Management, University of Shanghai for Science and Technology, Shanghai, China
[a]1640591382@qq.com, [b]1913521009@st.usst.edu.cn, [c]liaoxin2010@163.com
[*]Corresponding author

Abstract: *Based on panel data from 31 Chinese provinces from 2011 to 2020, this study empirically analyzes the mediating effects of agricultural structure and agricultural operation scale on the impact of digital inclusive finance on agricultural carbon emissions from the perspective of spatial overflow. The research findings indicate that digital inclusive finance can enhance agricultural carbon emissions by promoting the growth of neighboring provinces' agricultural structure and agricultural operation scale. The issue of greenhouse effect caused by excessive emissions of greenhouse gases, including carbon dioxide, has become increasingly prominent and is a global challenge. Agriculture is one of the significant sources of greenhouse gas emissions, with data from the Food and Agriculture Organization of the United Nations (FAO) indicating that 24% of global GHG emissions come from the agricultural sector. Furthermore, according to various studies, since the 18th century, the concentration of methane (CH4) in the atmosphere has increased by more than twofold, with approximately 70% of this increase attributed to human activities such as rice cultivation and biomass burning.*

Keywords: *Digital Inclusive Finance, Agricultural Carbon Emissions, Impact Mechanism, Spatial Overflow Effects*

1. Introduction and Literature Review

Agricultural methane and nitrous oxide emissions account for 50% and 92% of the national total, respectively *(Li Bo et al., 2011)[1]*. Therefore, analyzing and understanding the influencing factors and mechanisms of agricultural carbon emissions is of paramount importance for the scientific formulation of agricultural carbon reduction policies.

Digital inclusive finance is considered a crucial means to promote high-quality economic development and influence carbon emissions and environmental externalities. A substantial body of research has shown that digital inclusive finance is closely related to carbon emissions. For instance, *Cristian Ortiz et al. (2022)[2]* found that digital inclusive finance can achieve carbon reduction by supporting the industrialization of digital technology and enabling the digitization of industries. *Bazyli Czyżewski et al. (2020)[3]*confirmed that digital inclusive finance can increase household carbon emissions by stimulating consumption but can also reduce household carbon emissions by promoting green consumption. *Zheng et al. (2022)[4]* discovered that digital inclusive finance has a restraining effect on carbon dioxide emissions and that the development of digital financial inclusivity in terms of depth and digitalization level contributes to the reduction of carbon dioxide emissions.

Most existing research primarily focuses on the impact of digital inclusive finance on carbon emissions and its mechanisms, with limited exploration of the spatial overflow effects of digital finance on agricultural carbon emissions. Currently, only empirical studies, such as *Su Peitian et al. (2023)[5]*, have examined the spatial overflow effect of digital inclusive finance on the intensity of agricultural carbon emissions. However, these studies did not consider the impact mechanism of digital inclusive finance on agricultural carbon emissions intensity from a spatial overflow perspective. Therefore, there is a need for in-depth research on this matter. The main contribution of this study is based on panel data from 31 Chinese provinces (excluding Hong Kong, Macau, and Taiwan) from 2011 to 2020. It empirically investigates the spatial overflow effects of digital inclusive finance on the mechanism of agricultural carbon emissions, specifically the mediating role of agricultural structure and agricultural operation scale. This work theoretically enhances the transmission path of the impact of digital inclusive finance on agricultural carbon emissions. The research findings suggest that digital inclusive finance can increase agricultural carbon emissions by promoting the growth of the agricultural economy, agricultural structure, and agricultural operation scale in neighboring regions.

2. Hypotheses for Analysis and Research

2.1. Digital Inclusive Finance, Agricultural Operation Scale, and Agricultural Carbon Emissions

The development of digital inclusive finance in a province can lead to an expansion of agricultural operation scale in neighboring provinces. Due to its digital and financial attributes, digital inclusive finance relies on the internet and is less constrained by spatial boundaries, which results in spatial overflow effects *(Su Peitian et al., 2023)*[5]. The development of digital inclusive finance in a province can stimulate the development of digital inclusive finance in neighboring provinces. Digital inclusive finance in neighboring provinces can affect farmers' financing behavior and their agricultural operation scale. In a situation where agricultural funding demands and agricultural production input costs have been continuously increasing, digital inclusive finance not only reduces the cost of financial services but also enhances the accessibility and convenience of borrowing for rural low-income groups, encouraging farmers to expand their agricultural operation scale *(Fang Guanfu et al., 2022)*[6]. Furthermore, developing digital inclusive finance in neighboring provinces can accelerate the transformation and upgrading of the land transfer market, increase land transfer efficiency, expand the arable land area and agricultural operation scale, and promote large-scale land management *(Li Mingliang et al., 2023)*[7]. Referring to *Liu Qiong et al.'s (2020)*[8] research, increasing agricultural operation scale can increase agricultural carbon emissions through greater input of chemical consumables and technology input, represented by agricultural machinery. Due to the limited economic benefits of small-scale farmers and their limited knowledge of new fertilization and pesticide techniques, they mostly adhere to the traditional experience that "the more input, the higher the yield." This can lead to increased input of fertilizers, pesticides, agricultural films, and large agricultural machinery as the agricultural operation scale increases, thereby increasing agricultural carbon emissions. Furthermore, *Yao Yang (1998)*[9] argued that the indivisibility of irrigation, technical facilities such as canals, and large agricultural machinery can lead to "economies of scale" in farming. According to the research of *Lijuan Su et al. (2023)*[10], the cross-regional service of large and medium-sized agricultural machinery leads to spatial overflow effects in China's various provinces, meaning that the expansion of agricultural scale in neighboring provinces increases agricultural input, further increasing agricultural carbon emissions in the home province. Based on the above, this paper proposes the following hypothesis:

H1: Digital inclusive finance can increase agricultural carbon emissions in the home province by promoting the expansion of agricultural operation scale in neighboring provinces.

2.2. Digital Inclusive Finance, Agricultural Structure, and Agricultural Carbon Emissions

The development of digital inclusive finance in a province can alter the agricultural structure in neighboring provinces. Since the development of digital inclusive finance in a province can promote the development of digital inclusive finance in neighboring provinces, and according to the research by *Fang Guanfu et al. (2022)*[6], digital inclusive finance has a significant promoting effect on cereal crops. Additionally, with the flourishing development of existing e-commerce platforms, farmers can more efficiently and conveniently attract consumers. Developing of digital inclusive finance in neighboring provinces can lead to a steady increase in the total demand for cereals in neighboring provinces *(Olivier Joseph Abban et al., 2023)*[11]. The sowing areas in neighboring provinces gradually concentrate on the main cereal production areas, leading to a change in agricultural structure. This means that the development of digital inclusive finance in a province can not only change the agricultural structure within that province but can also promote a change in the agricultural structure in neighboring provinces by driving the development of digital inclusive finance in those areas. Research by *Li Mingliang et al. (2023)*[7] confirms the positive spatial overflow effect of digital inclusive finance on the cereal system. Moreover, research by *Wu Zhihao et al. (2020)*[12] indicates that the level of agricultural development has a significant positive spillover effect on cereal production. Agricultural carbon emissions change with changes in agricultural structure. Research by *Zhang Yang et al. (2023)*[13] shows that cereal crops' growth attributes can induce carbon emissions, such as the significant methane emissions in rice paddies. Additionally, as the cereal cultivation area in the central cereal-producing regions gradually increases, and the agricultural structure changes, applying inputs like fertilizers and machinery during the production process can lead to a gradual increase in agricultural carbon emissions. An increase in the

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proportion of cereal crop cultivation area has a noticeable enhancing effect on agricultural carbon emissions. Based on this, the paper proposes the following hypothesis:

H2: Digital inclusive finance can increase agricultural carbon emissions in the home province by promoting the growth of agricultural structures in neighboring provinces.

3. Research Design and Variable Selection

3.1. Spatial Durbin Model (SDM) Construction

The Spatial Durbin Model (SDM) can reflect both the spatial interdependence of the dependent variable among regions and the spatial influence of explanatory variables from other regions, providing unbiased estimation results. Therefore, this paper constructs the following SDM model to study the spatial overflow effects of digital inclusive finance development on agricultural carbon emissions intensity:

$$CEI_{it} = \alpha_0 + \rho_1 CEI_{it} + \alpha_1 DFI + \alpha_2 \sum X_{it} + \delta_1 WDFI + \delta_2 W \sum X_{it} + \mu_i + \lambda_i + \varepsilon_{it} \quad (1)$$

Where, i and t represent provinces and years, respectively. W represents the spatial weight matrix. CEI_{it} is the agricultural carbon emissions intensity in province i in year t. DFI_{it} is the digital inclusive finance in province i in year t. X represents control variables, including fiscal support for agriculture (X1), environmental regulatory strength (X2), and rural residents' per capita disposable income (X3). μ_i represents time effects, λ_i represents provincial fixed effects, and ε_{it} is the random error term.

To study the mediating effects of agricultural operation scale (M1) and agricultural structure (M2) on the impact of digital inclusive finance on agricultural carbon emissions, a mediation effect model is constructed, following the approach of *Wen Zhonglin et al. (2004)*[14]. In this model (1), interaction terms between the level of urbanization development and the level of digital inclusive finance development are introduced. The extended SDM model is as follows:

$$M_{it} = \alpha_0 + \rho_1 CEI_{it} + \alpha_1 DFI + \alpha_2 \sum X_{it} + \delta_1 WDFI + \delta_2 W \sum X_{it} + \mu_i + \lambda_i + \varepsilon_{it} \quad (2)$$

$$CEI_{it} = \alpha_0 + \rho_3 CEI_{it} + \alpha_1 DFI + \alpha_2 \sum X_{it} + \alpha_3 M_{it} + \delta_1 WDFI + \delta_2 W \sum X_{it} + \delta_3 W \sum M_{it} + \mu_i + \lambda_i + \varepsilon_{it} \quad (3)$$

In equations (1) to (3), M_{it} serves as the mediating variable, which includes agricultural structure and agricultural operation scale.

3.2. Variable Selection and Data Sources

(1) Dependent Variable

The dependent variable in this study is agricultural carbon emissions intensity (CEI). Initially, it is measured using indicators such as the use of agricultural fertilizers, pesticides, agricultural films, agricultural diesel, plowing, and agricultural irrigation. Emission coefficients for various carbon emission sources are calculated based on the methods recommended in the United Nations Intergovernmental Panel on Climate Change (IPCC) "2006 IPCC Guidelines for National Greenhouse Gas Inventories." The calculation formula is as follows:

$$TCE = \sum C_i = \sum S_i * \rho_i \quad (4)$$

In equation (5), TCE represents total agricultural carbon emissions (in ten thousand tons), C_i denotes the carbon emissions generated by various carbon emission sources, S_i is the quantity of various carbon sources, and ρ_i is the carbon emission coefficient for various carbon sources. The carbon emission coefficients for various sources are as follows: agricultural fertilizers are 0.896 kg/kg, pesticides are 4.934 kg/kg, agricultural films are 5.180 kg/kg, agricultural diesel is 0.593 kg/kg, plowing is 312.600 kg/km^2, and agricultural irrigation is 20.476 kg/hm^2.

Based on the calculation of carbon emissions, agricultural carbon emissions intensity for each province is determined by dividing TCE by the agricultural GDP, calculated as follows:

$$CEI = TCE/GDP \quad (5)$$

In equation (6), CEI represents agricultural carbon emissions intensity (kg per 10,000 RMB), and GDP represents agricultural output.

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(2) Key Independent Variable

The core independent variable in this study is digital inclusive finance (DFI). It is measured using the China Digital Inclusive Finance Index compiled by Peking University's Digital Finance Center *(Guo Feng et al., 2020)*[15].

(3) Mediating Variables

a) Agricultural Operation Scale (M1): This is measured as per capita crop planting area, calculated as the ratio of crop planting area to the number of people engaged in agriculture, forestry, animal husbandry, and fishing.

b) Agricultural Structure (M2): This is measured as the proportion of cultivated land dedicated to cereal crops. It is determined as the ratio of the total area of cereal crop planting to the total area of crop planting.

(4) Control Variables

Based on previous research, the study includes the following control variables:

a) Fiscal Support for Agriculture (X1): It represents the proportion of local government expenditures on agriculture, forestry, and water conservancy to the total fiscal expenditure. The indicator is adjusted to comparable values for 2011 using the Consumer Price Index (CPI).

b) Environmental Regulatory Strength (X2): It represents the ratio of environmental protection expenditures to local government expenditures.

c) Rural Per Capita Disposable Income (X3): It reflects the income received by rural households after initial and subsequent distribution.

3.3. Data Sources

To ensure the availability and completeness of data, this study utilizes data at the provincial level for 31 provinces and municipalities in China from 2011 to 2020, excluding Hong Kong, Macao, and Taiwan. Digital inclusive finance data is sourced from Peking University's Digital Finance Center, while other data is obtained from various official sources, including the "China Rural Statistical Yearbook," "China Statistical Yearbook," and the National Bureau of Statistics.

Additionally, to study regional heterogeneity in different areas, the 31 provinces are classified into three regions—East, Central, and West—based on the division standards of the National Bureau of Statistics.

To meet estimation requirements and reduce errors, the data in this study has been logarithmically transformed. Descriptive statistics for each variable are presented in Table 1.

Table 1: Descriptive Statistics.

Variable	Observation	Mean	Standard Deviation	Minimum	Maximum
CEI	310	5.254	0.34	3.831	5.939
DFI	310	5.51	0.698	2.026	6.136
X1	310	0.297	0.21	0.12	1.354
X2	310	0.116	0.034	0.041	0.204
X3	310	0.03	0.01	0.012	0.068
M1	310	7.074	3.783	2.089	27.714
M2	310	0.662	0.144	0.355	0.971

4. Empirical Analysis

4.1. Spatial Autocorrelation Test for Digital Inclusive Finance and Agricultural Carbon Emission Intensity

Using Stata software and an adjacency weight matrix, this study calculates the Moran's I index to conduct a spatial autocorrelation test for digital inclusive finance and agricultural carbon emissions. The formula for calculating Moran's I index is as follows:

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$$\text{Moran's I} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i-\bar{x})(x_j-\bar{x})}{\sum_{i=1}^{n}(x_i-\bar{x})^2} \tag{6}$$

The calculation results are shown in Table 2. From 2011 to 2020, the Moran's I for digital inclusive finance and agricultural carbon emissions intensity are mostly significantly positive. This indicates that both agricultural carbon emissions intensity and digital inclusive finance exhibit noticeable spatial clustering and positive spatial autocorrelation. Additionally, the Moran's I index shows a growing trend over time, suggesting that the spatial clustering of digital inclusive finance is gradually deepening.

Table 2: Moran's I Test Results for Digital Inclusive Finance and Agricultural Carbon Emissions.

year	DFI		CEI	
	Moron's I	Z value	Moron's I	Z value
2011	0.379***	3.753	0.082	0.979
2012	0.314***	3.015	0.123	1.323
2013	0.077	0.957	0.101	1.146
2014	0.012	0.398	0.079	0.967
2015	0.519***	4.738	0.091	1.094
2016	0.129	1.442	0.088	1.067
2017	0.073	0.912	0.18*	1.881
2018	0.632***	5.751	0.284***	2.834
2019	0.614***	5.594	0.293***	2.919
2020	0.614***	5.564	0.343***	3.343

Note: ***, **, and * represent significance levels of 1%, 5%, and 10%, respectively.

4.2. Mechanism Test of Digital Inclusive Finance's Impact on Agricultural Carbon Emissions from a Spatial Spillover Perspective

To select an appropriate model for empirical analysis, the model underwent a Hausman test, LR test, and LM test. The results indicated that the spatial Durbin model with double fixed effects is more suitable. The test results for the main effects, mediation effects, and moderating effects of digital inclusive finance (DFI) on agricultural carbon emissions are shown in Table 3. Columns (1) and (2) of Table 3 show that the coefficient of DFI is significantly positive. This means that, from a nationwide perspective, an increase in the level of digital inclusive finance in a province leads to an increase in the intensity of agricultural carbon emissions in that province. This may be due to the widespread existence of a high-input, high-emission development pattern in China *(Li et al., 2011)*[1]. Although China's agricultural development has made significant progress, and traditional high-carbon emission production methods are gradually being replaced with the advancement of agricultural modernization, China is still in a transitional period from traditional to modern agriculture and from extensive to intensive agriculture. Domestic agricultural production remains heavily reliant on fertilizers and pesticides, leading to significant carbon emissions *(Tian et al., 2012)*[16]. This aligns with the pattern exhibited by the Environmental Kuznets Curve (EKC): when a country has a relatively low level of economic development, environmental degradation worsens as the economy grows. The non-significant coefficient for WDFI may be due to the varying levels of economic development and differences in technological advancement among different regions in China. Additionally, from a holistic perspective, China's digital economic development is still in its early stages. The increased resource consumption in the initial stage of digital economic development offsets the effects of digital empowerment *(Xu et al., 2022*). Therefore, spatial spillover effects are not significant at the national level.

To explore the mechanism of how digital inclusive finance impacts agricultural carbon emission intensity, a spatial Durbin model with double fixed effects was used to regress equations (1) to (3), and the results are shown in Table 3.

In column (3), the coefficient for WDFI is significantly positive, indicating that as the level of digital inclusive finance development in neighboring provinces increases, the agricultural operating scale of the local province can also increase. In column (4), the coefficient for WM1 is significantly positive, suggesting that as the agricultural operating scale of neighboring provinces continues to increase, the agricultural carbon emission intensity of the local province will also increase. This indicates the significant mediating effect of agricultural operating scale (M1). An increase in the level of digital inclusive finance in one province can lead to an increase in the agricultural carbon emission intensity of the local province by expanding the agricultural operating scale of neighboring provinces, thus validating hypothesis H1.

In column (5), the coefficient for WDFI is significantly positive, indicating that an increase in the level of digital inclusive finance development in neighboring provinces leads to an increase in the local province's agricultural structure. In column (6), the coefficient for WM2 is significantly positive, indicating that an increase in the agricultural structure of neighboring provinces results in an increase in the agricultural carbon emission intensity of the local province. This validates hypothesis H2, showing that the level of digital inclusive finance in one province can increase the local province's agricultural carbon emission intensity by promoting the improvement of the agricultural structure in neighboring provinces.

Table 3: Baseline Regression and Mediation Analysis.

variable	FE		M1	CEI	M2	CEI
	(1)	(2)	(3)	(4)	(5)	(6)
DFI	0.124**	0.128***	-1.192	0.14***	-0.023**	0.092*
	(0.06)	(0.05)	(0.88)	(0.04)	(0.01)	(0.05)
M1				0		
				(0.01)		
M2						0.193
						(0.52)
Control variables	control	control	control	control	control	control
WDFI	-0.002	0.01	0.936**	-0.042	0.058***	0.017
	(0.09)	(0.05)	(0.40)	(0.04)	(0.02)	(0.07)
WM1				0.053**		
				(0.02)		
WM2						0.017***
						(0.07)
W*Control variables	control	control	control	control	control	control
rho	0.176	-0.115	-0.13	-0.123	-0.145	-0.217
	(0.13)	(0.13)	(0.14)	(0.12)	(0.27)	(0.14)
sigma2_e	0.011***	0.01***	0.843***	0.009***	0***	0.009***
	(0.00)	(0.00)	(0.19)	(0.00)	0.00	(0.00)
loglikelyhood	249.1697	283.1224	- 415.4193	292.4072	755.6085	289.541
R^2	0.3962	0.1595	0.0024	0.3098	0.0024	0.0491
observations	310	311	310	310	310	310
Province Fixed Effects	YES	YES	YES	YES	YES	YES
Year Fixed Effects	YES	YES	YES	YES	YES	YES

4.3. Robustness Tests

Referring to the study by *Ma Jiujie (2021)*, population size was added as a control variable for robustness tests of the mediating and moderating effects. The results of the regression after adding the new control variable showed that the promotional effect of digital inclusive finance on agricultural carbon emissions remained unchanged. The mediating effect model, the moderating effect model, and the heterogeneity analysis results all remained robust. Due to space limitations, the test results are not presented here.

5. Conclusions

To investigate the impact mechanism of digital inclusive finance on agricultural carbon emissions from a spatial spillover perspective, this study used panel data from 31 provinces and cities in China (excluding Hong Kong, Macao, and Taiwan) for the years 2011-2020. Firstly, based on the dynamic Durbin model, we analyzed the influence of digital inclusive finance on agricultural carbon emissions. Then, we explored the mediating effects of agricultural structure and agricultural operation scale using the dynamic Durbin model in combination with the mediating and moderating effect models. The following conclusions were drawn: (1) Digital inclusive finance can increase agricultural carbon emissions in the province by promoting the growth of neighboring provinces' agricultural structure. (2) Digital inclusive finance can increase agricultural carbon emissions in the province by promoting the expansion of neighboring provinces' agricultural operation scale. Based on these conclusions and to promote carbon reduction in agriculture more effectively, the following recommendations are made:

First, relevant departments should strengthen policy guidance, provide subsidies for the purchase of energy-saving large agricultural machinery, implement the concept of energy conservation and carbon reduction in agricultural production and life, change the traditional idea of "high input, high output," and achieve scientific low-carbon food production through the cultivation and improvement of excellent crop varieties, the use of carbon sequestration technologies such as conservation tillage, and crop straw returning technology.

Second, different regions should adopt appropriate measures according to local conditions. In areas with better economic development, provinces should strengthen low-carbon mutual assistance and resource sharing and impose target constraints during the development of digital inclusive finance to avoid excessive investments leading to increased agricultural carbon emissions. In regions with insufficient self-development, there is still a need to vigorously develop digital inclusive finance, improve the construction of the digital inclusive finance system, and reduce regional development disparities.

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