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A System GMM Empirical Analysis of the Impact of Agricultural Carbon Finance Innovation on Carbon Emissions Reduction

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Abstract Agricultural carbon financial innovation provides a new path to promote the development of low-carbon agriculture, which is of great significance in realizing the goals of sustainable agricultural development and carbon emission reduction. This study explores the impact mechanism of agricultural carbon financial innovation on agricultural carbon emission reduction. Based on the ternary cycle theory, a panel data model is constructed, and the data of 90 prefecture-level cities in five major agricultural provinces in China from 2014 to 2024 are selected for empirical analysis. The results show that agricultural carbon financial innovation has a significant inhibitory effect on agricultural carbon emissions, with a regression coefficient of -0.177 and significant at 1% confidence level. Agricultural carbon financial innovation promotes agricultural carbon emission reduction through the three paths of small cycle of farmers, medium cycle of industry and large cycle of society, in which the regression coefficient of small cycle of farmers is 0.003, which is significant at 5% statistical level; the regression coefficients of medium cycle of industry and large cycle of society are 0.068 and 0.042 respectively, which are both significant at 10% statistical level. In addition, the level of urbanization development plays a significant moderating role in the agricultural carbon emission reduction effect of agricultural carbon financial innovation, with an interaction term coefficient of -0.633 and significant at the 1% level. Regional heterogeneity analysis found that the coefficient of the effect of agricultural carbon financial innovation on carbon emissions in the western region is -1.0836, with the strongest inhibitory effect. The findings of the study have important policy implications for improving the agricultural carbon financial system and promoting the green and low-carbon transformation of agriculture.

Index Terms Agricultural carbon financial innovation, carbon emission reduction, ternary cycle, panel data model, urbanization, regional heterogeneity

I. Introduction

Since the Industrial Revolution, rapid economic growth and industrialization have led to increasingly serious atmospheric pollution, which has become one of the major constraints to sustainable development. Although this transformation has contributed to the rapid development of human society, it has also brought about the aggravation of atmospheric pollution, the deterioration of the global greenhouse effect, and the frequent occurrence of vicious environmental phenomena such as rising temperatures and extreme climatic events, which have led to a great dilemma for human survival [1]-[3]. For this reason, countries have taken a series of measures to reduce greenhouse gas emissions over the years, with the aim of preventing uncontrollable greenhouse gas emissions and thus further damage to the global ecological environment [4].

Agriculture is an important component of carbon emissions, and the World Resources Institute has shown that emissions from agricultural activities alone accounted for 11.8% of overall emissions in 2017 and are growing dramatically. Without strong measures, greenhouse gases from agricultural activities will increase by another 30% in 2050 [5], [6]. Agricultural production activities are the third largest source of GHG emissions after energy activities and industrial processes. Low-carbon agriculture is a production activity that follows the principle of unification of ecological, economic and social benefits, and is also an important part of the low-carbon economy and an important model for realizing sustainable agricultural development [7], [8]. Compared with traditional agriculture, this low-carbon agriculture has higher technical requirements and greater capital investment, so it cannot be separated from financial support. From the perspective of agriculture, carbon finance is a financial activity aimed at reducing greenhouse gas emissions, which promotes low-carbon economic development through financial instruments and market mechanisms [9]. Carbon finance, as an emerging financial instrument, provides financial and market support for the development of agriculture, and the study of how it promotes the high-quality development of agriculture is of great practical significance [10].

Carbon finance originated from “environmental finance”, which is a kind of eco-finance derived from carbon emissions in order to reduce carbon emissions and solve the problem of carbon emissions [11]. In recent years, with the deepening of global concern about climate change and the strategic goal of “carbon neutrality” put forward by governments, carbon finance has become a new development direction in the financial field [12]. Carbon financial innovation is mainly reflected in, first, the construction bank, the mechanical and electrical chamber of commerce, carbon balance technology and other formal signing of carbon financial innovation memorandum of cooperation, the use of resources and advantages of multiple parties to innovate carbon financial products, to promote the development of the carbon market, and to help Chinese enterprises green low-carbon transformation. The second is the prediction of carbon financial market size, new model analysis [13]-[15]. In fact, in the field of agriculture, the practice of carbon finance is far less than that of electric power, industry, transportation and other industries, because traditional agricultural production relies only on manpower and common tools, agricultural production activities are characterized by long production cycles and regional dispersion, and it is difficult to carry out carbon emission monitoring, which makes it extremely difficult for agriculture to enter the carbon market [16]-[18]. With the input of Internet of Things (IoT), big data, artificial intelligence (AI), drones and remote sensing in agricultural production, the convenience of agricultural carbon emission monitoring has increased, providing partial support for agricultural carbon finance innovation [19], [20]. However, the cost of monitoring is not affordable for small-scale farmers, the carbon trading system in agriculture is not perfect, and the long payback cycle of low-carbon agricultural production reduces the low willingness of farmers [21], [22].

Since the industrial revolution, rapid global economic development and accelerated industrialization have led to increasingly serious pollution of the atmospheric environment, which has become a major obstacle to sustainable development. Malignant environmental phenomena such as rising temperatures and frequent occurrence of extreme climatic events have posed great challenges to human survival. Agriculture, as an important component of carbon emissions, accounted for 11.8% of total global emissions in 2017, according to the World Resources Institute, and shows a sharp growth trend, and greenhouse gases from agricultural activities are expected to increase by another 30% by 2050. The implementation of low-carbon agriculture is an important way to realize the sustainable development of agriculture, and compared with traditional agriculture, low-carbon agriculture has higher technical requirements and greater capital investment, which requires effective financial support. Carbon finance, as an emerging financial instrument, provides financial and market support for the low-carbon transformation of agriculture. This study will explore the impact mechanism of agricultural carbon financial innovation on agricultural carbon emission reduction from the perspective of ternary cycle theory. First, a panel data model is constructed to test the overall impact of agricultural carbon financial innovation on agricultural carbon emission reduction; second, the role mechanisms of the three intermediary paths of the small cycle of farmers, the medium cycle of industry and the large cycle of society are analyzed; third, the moderating effect of the level of urbanization in the promotion of agricultural carbon financial innovation for agricultural carbon emission reduction is explored; and lastly, the heterogeneous impact of agricultural carbon financial innovation on agricultural carbon emission reduction in different regions is examined. To this end, this study selects the panel data of 90 prefecture-level cities in China's five major agricultural provinces (Shandong, Henan, Sichuan, Guangdong, and Hubei) for the period of 2014-2024 for empirical analysis. By analyzing the impacts of the three dimensions of coverage breadth, use depth, and digitization degree of agricultural carbon financial innovation on agricultural carbon emissions, it provides theoretical basis and policy recommendations for improving the agricultural carbon financial system and promoting the green and low-carbon transformation of agriculture. This study not only enriches the theoretical system of carbon financial innovation and carbon emission reduction research, but also has important practical significance in promoting the high-quality development of agriculture and helping the national “carbon neutral” strategic goal to be realized. By promoting the improvement of the agricultural carbon financial system, it will facilitate the transformation of agriculture into a low-carbon and sustainable direction, and realize the coordination and unification of economic and environmental benefits.

II. Theoretical analysis and research hypotheses

*II. A. **Analysis of the direct impact of rural carbon finance innovation on carbon emission reduction***

For agriculture, the development of agricultural green enterprises requires capital financing, and agricultural carbon financial innovation can provide convenient financing channels for agricultural green enterprises by enhancing resource allocation efficiency and financial product innovation. For rural areas, the universality of agricultural carbon financial innovation makes economic resources tilted to agricultural and rural areas, which will help the construction and improvement of green infrastructure in rural areas. For farmers, agricultural carbon financial innovation can serve the long-tail users more conveniently by relying on its inclusive characteristics, and broaden the channels for farmers to participate in the green low-carbon cause [23]. Based on this, the following research hypotheses are proposed:

H1: The development of agricultural carbon financial innovation helps promote agricultural carbon emission reduction.

II. B. ***Analysis of the Indirect Impact of Rural Carbon Financial Innovation on Carbon Emission Reduction***

The "ternary cycle" can be defined as three dimensions: the small cycle of farmers, the medium cycle of industry and the large cycle of society. First, the small cycle of farmers, i.e., the behavioral choice of farmers for the circular economy model. Through the recycling of waste resources and the reduction and resourcing of domestic garbage, it promotes resource conservation, intensification and circular development. Secondly, the industry in the cycle, that is, the endogenous extension and industrial linkage between the agricultural industry chain. Through industrial structure adjustment and upgrading, agriculture, forestry, animal husbandry and fishery can exchange wastes with each other and realize the whole process of resource development and utilization. Third, the social cycle, that is, the redistribution and transformation of social resources between agriculture and secondary and tertiary industries, this paper mainly studies the circular flow of economic capital among the three.

(1) Agricultural Carbon Financial Innovation, Farmers' Small Cycle and Agricultural Carbon Emission Reduction

As a micro-driver of economic green development, the small farm household cycle can realize the efficient use of rural waste and promote the positive interaction between economic performance and environmental performance. The first important way in which carbon financial innovation affects agricultural carbon emission reduction is through the operation mechanism of small farm household cycle. First, carbon financial innovation with big data can realize the fixed-point push and precise transmission of information, and transmit green low-carbon development concepts and policies to farmers, which can stimulate the motivation of green production and consumption of farmers. Second, the digital transformation of financial institutions has created a huge employment gap, which in turn has led to the cultivation of local composite innovation talents. Third, the development of carbon financial innovation contributes to the research and development of agricultural and rural waste reduction and resource utilization technologies. Based on this, the following research hypotheses are proposed:

H2: Agricultural carbon financial innovation can promote agricultural carbon emission reduction through the small cycle of farmers.

(2) Agricultural carbon financial innovation, industry medium cycle and agricultural carbon emission reduction

Industrial green transformation is an important support to promote economic quality and efficiency, and to realize ecological economy and economic ecology. By exerting the structural adjustment effect of industry-medium cycle, it helps to cultivate a number of high-tech, high-quality and high value-added industries in rural areas, and to realize the exchange and utilization of waste among agriculture, forestry, animal husbandry and fishery. The second important way for carbon financial innovation to influence agricultural carbon emission reduction is the operation mechanism of the industry-in-industry cycle. Carbon financial innovation can promote the green transformation of traditional agriculture with its own efficient resource allocation function, and promote farmers' consumption upgrading by giving full play to its advantages of networking and de-mediatization, thus forcing industrial upgrading from the consumption side. At the same time, the development of carbon financial innovation also provides technical and financial support for the improvement of production processes and the development of clean energy. Based on this, the following research hypotheses are proposed:

H3: Agricultural carbon financial innovation can promote agricultural carbon emission reduction through the mid-industry cycle.

(3) Rural carbon financial innovation, social macrocycle and agricultural carbon emission reduction

With the help of the social grand cycle, more financial capital can be pried into the green low-carbon field, changing the investment scale and investment structure of rural enterprises. The third important way for carbon financial innovation to influence agricultural carbon emission reduction is the operation mechanism of the social grand cycle. Carbon financial innovation can alleviate agricultural underinvestment by expanding the scale of investment, incentivize farmers to start their own businesses, and increase investment in environmental protection and pollution control equipment by adjusting the investment structure. Based on this, the following research hypotheses are proposed:

H4: Carbon financial innovation can promote agricultural carbon emission reduction through the social cycle.

The three levels of the cycle is not completely independent, but a unified whole of organic connection. The low-level cycle is catalyzed by coupling to influence the middle and high-level cycles, and the middle and high-level cycles will also act on the low-level cycle, and the coupling relationship is shown in Figure 1. With the efficient recycling of resources as the core, along with the flow of material flow, information flow, capital flow and energy flow, the three constitute a unified economic unit and form a development synergy.

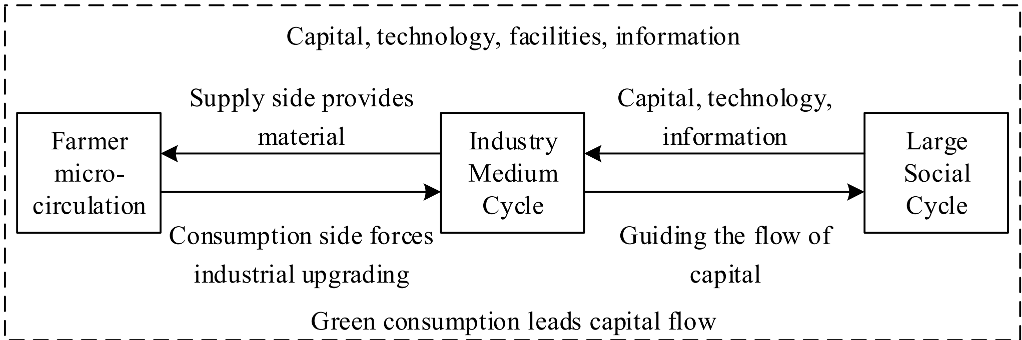

Figure 1: Ternary cyclic coupling

III. Study design

III. A. Selection of variables

III. A. 1) Explained variables

According to the main pathways of agricultural carbon emissions, six carbon sources, namely, fertilizers, pesticides, agricultural films, agricultural diesel, agricultural sown area, and agricultural irrigated area, were selected to construct an indicator system to measure the data of carbon emissions generated in the process of agricultural production in each prefecture-level city.

According to the basic carbon accounting method recommended by the Intergovernmental Panel on Climate Change IPCC (2006) [24], the formula for calculating carbon emissions is:

$$ACE = \sum \left(E_i * \theta_i \right) \tag{1}$$

In Equation (1), i denotes the source category, ACE is the carbon emissions from each type of activity in agricultural production, E_i is the number of each type of source, and θ_i is the emission coefficient of each source.

III. A. 2) Explanatory variables

In this paper, the rural carbon financial innovation index (DFI) from 2014 to 2024 is selected as an explanatory variable for empirical analysis. The index is based on Ant Financial Services' micro big data, with mobile payment as the main representative, and establishes a geographic indicator system covering three levels of provinces, prefectures and counties within China, and contains three sub-dimensions of breadth of coverage, depth of use, and digitization degree of agricultural carbon financial innovation, which further reflects the development of agricultural carbon financial innovation at different levels.

III. A. 3) Intermediate variables

The mechanism effect test under the ternary cycle (INNO) perspective was conducted with the rate of harmless treatment of domestic waste, the optimization and transformation of industry, and the circulation of economic capital as the mediating variables.

III. A. 4) Moderating variables

Urbanization Level (CITY). With China's vast geographical scope and large differences in the degree of regional development, the level of urbanization is an important reference indicator of the country's development situation, and the national policy level has injected strength into the process of promoting urbanization in the long term. Therefore, this paper adopts the urbanization rate as an indicator to reflect the urbanization level of prefecture-level cities, and measures the urbanization rate as the proportion of urban population to the total population.

III. A. 5) Control variables

The following control variables are selected in this paper:

(1) Strength of financial support for agriculture (FINAN). The size of national support for agriculture will fundamentally affect the development direction of rural carbon financial innovation and the intensity of its support for low-carbon agriculture, and thus the strength of financial support for agriculture is taken as a control variable.

Since the statistical data rarely disclose the data of purely financial expenditure in the agricultural field, this paper chooses to cover the primary industry of agriculture, forestry and water affairs, and adopts the proportion of financial expenditure in agriculture, forestry and water affairs to the general public budget expenditure to express.

(2) Agricultural industrial structure (ISTRU). China has been focusing on the development of modern and efficient agriculture, so it is very important to rationalize the agricultural industrial structure. And there are great differences in the carbon emissions generated by different agricultural structures, which directly affect the amount of carbon emissions from agricultural production. Therefore, this paper adopts the proportion of agriculture in the total output value of agriculture, forestry, animal husbandry and fishery to measure the variable of agricultural industrial structure.

(3) Transportation infrastructure (TRAN). The construction of transportation infrastructure is an effective contributor to reducing agricultural carbon emissions. Therefore, this paper chooses to use the ratio of total highway mileage to regional area to measure the construction of transportation infrastructure in a certain city.

(4) Cultivation structure (PSTRU). With the development of the process of agricultural modernization, the range of food crops planted is constantly adjusted, and the use of agricultural fertilizers and other means of production required for crop growth shows dynamic changes, which have an impact on the carbon emissions in agricultural production. Therefore, this paper adopts the proportion of the sown area of food crops to the total sown area of crops to indicate the planting structure as a control variable.

III. B. 3.2 Modeling

III. B. 1) Fixed effects model

In this paper, we intend to use a fixed-effects model [25] to investigate whether rural carbon financial innovation has a significant positive impact on agricultural carbon emission reduction. In order to eliminate heteroskedasticity to make the data smoother, some variables are logarithmic, and the model is constructed as follows:

$$\ln ACE_{i,t} = \alpha_0 + \alpha_1 \ln DFI_{i,t} + \alpha_2 Control_{i,t} + \mu_i + \varepsilon_{i,t} \tag{2}$$

In Equation (2), i denotes cities, t denotes time, $ACE_{i,t}$ is agricultural carbon emissions, $DFI_{i,t}$ is rural carbon and financial innovation index, and $control_{i,t}$ is a control variable covering the structure of the agricultural industry (ISTRU), transportation infrastructure (TRAN), planting structure (PSTRU), financial support for agriculture (FINAN), etc. μ_i is an individual fixed effect that does not vary over time. $\varepsilon_{i,t}$ is a random perturbation term, which obeys a normal distribution with mean 0, i.e. $\varepsilon_{i,t} \sim (0,\sigma^2)$.

III. B. 2) Mediated effects model

In order to test the indirect path effect of rural carbon financial innovation affecting agricultural carbon emission reduction, this paper proposes a mediating effect model to further explore whether the mediating variable of ternary circular effect plays a mediating effect in the process of rural carbon financial innovation affecting agricultural carbon emission reduction. The model is constructed as follows:

$$\ln ACE_{i,t} = \alpha_0 + \alpha_1 \ln DFI_{i,t} + \alpha_2 Control_{i,t} + \mu_i + \varepsilon_{i,t} \tag{3}$$

$$INNO_{i,t} = \beta_0 + \beta_1 \ln DFI_{i,t} + \beta_2 Control_{i,t} + \mu_i + \varphi_{i,t} \tag{4}$$

$$\ln ACE_{i,t} = \gamma_0 + \gamma_1 \ln DFI_{i,t} + \gamma_2 INNO_{i,t} + \gamma_3 Control_{i,t} + \mu_i + \delta_{i,t} \tag{5}$$

In Eqs. (3) to (5), $INNO$ is the mediating variable, representing the ternary loop effect. α , β and γ are the regression coefficients, and $\varepsilon_{i,t}$, $\varphi_{i,t}$, $\delta_{i,t}$ are the random disturbance terms. The first regression of equation (3) is performed to obtain the overall impact of rural carbon financial innovation on agricultural carbon emissions (α_1) . Secondly, regression is performed on Eq. (4) to obtain the impact of rural carbon financial innovation on the ternary cycle effect (β_1) . Finally, regression of Equation (5) is conducted to test the direct effect of rural carbon financial innovation on agricultural carbon emissions (γ_1) and the mediating effect of ternary loop effect (γ_2) . Under the precondition that α_1 is significant, if β_1 and γ_2 are significant, the mediating effect is proved to be significant. On this basis, if γ_1 is significant, it indicates a partial mediation effect. If γ_1 is not significant, it is a full mediation effect.

III. B. 3) Moderating effects model

In order to verify the moderating effect of urbanization level in rural carbon financial innovation affecting agricultural carbon emission reduction, the model is constructed as follows:

$$\ln ACE_{i,t} = \lambda_0 + \lambda_1 \ln DFI_{i,t} + \lambda_2 Control_{i,t} + \lambda_3 \ln CITY_{i,t} + \lambda_4 \left(\ln DFI_{i,t} * \ln CITY_{i,t}\right) + \mu_i + \theta_{i,t} \tag{6}$$

In Equation (6), $CITY_{i,t}$ denotes the level of urbanization, and $\ln DFI_{i,t} * \ln CITY_{i,t}$ denotes the interaction term between rural carbon financial innovation and urbanization rate. Since there is a high degree of covariance between the interaction term and the explanatory and moderating variables, which can cause the estimation bias of the model, in order to mitigate the high degree of covariance, the model is centered in this paper:

$$\ln ACE_{i,t} = \lambda_0 + \lambda_1 \ln DFI_{i,t} + \lambda_2 Control_{i,t} + \lambda_3 \ln CITY_{i,t} + \lambda_4 \left(\ln DFI_{i,t} - \overline{\ln DFI_{i,t}}\right) * \left(\ln CITY_{i,t} - \overline{\ln CITY_{i,t}}\right) + \mu_i + \theta_{i,t} \tag{7}$$

III. C. Data sources

In this paper, with reference to the ranking of the gross output value of agriculture, forestry, animal husbandry and fishery of each province in China, five provinces, namely Lu, Henan, Sichuan, Guangdong and Ezhou, are taken as the major agricultural provinces, and the panel data of prefecture-level cities in all the provinces for the period of 2014-2024 are selected for empirical research. Among them, due to too much missing data can not be collected in Ezhou city of Hubei province, this paper chooses to exclude the city, so a total of 90 prefecture-level cities related data are collected and counted. The data in this paper mainly come from the statistical yearbooks of five major agricultural provinces, China Statistical Yearbook, China Rural Statistical Yearbook, China Urban Statistical Yearbook, etc., for the period of 2014-2024, a total of eleven years, for some of the missing data, we choose to adopt the telephone consultation of the Bureau of Statistics or the method of linear interpolation to deal with it. The descriptive statistics of the relevant variables are shown in Table 1. A total of 1000 sample sizes were selected. Among them, the minimum and maximum values of agricultural carbon emissions (lnACE) are 0.759 and 19.58, respectively, both of which have a large difference, indicating that there are significant differences in the agricultural carbon emissions of different prefectural-level cities. Similarly the maximum and minimum values of other variables also have large differences, indicating that the data selected in this paper are suitable for empirical analysis.

Table 1: Variable descriptive statistics

Variable	Symbol	Sample size	M	SD	Min	Max
Agricultural carbon emissions	lnACE	1000	9.34	6.666	0.759	19.58
Digital puhui financial index	lnDFI	1000	5.093	0.534	3.189	5.834
Coverage index	lnBREATH	1000	5.017	0.594	1.484	5.897
Use depth index	lnDEPTH	1000	5.084	0.504	3.239	5.796
Digital index	lnDIG	1000	5.229	0.6	2.377	5.824
Regional innovation level	INNO	1000	0.123	0.401	0.014	4.452
Level of urbanization	CITY	1000	0.49	0.212	-0.625	1
Agricultural industrial structure	lnISTRU	1000	-0.712	0.287	-2.108	1.546
Transportation infrastructure	lnTRAN	1000	3.137	2.289	-3.393	5.979
Planting structure	lnPSTRU	1000	-0.561	0.626	-8.893	-0.107
Financial support	FINAN	1000	0.13	0.049	-0.002	0.592

IV. Empirical analysis

IV. A. Tests of the nature of the model residuals

The study utilizes the DW statistic to validate the independence of the residuals of the regression model.DW takes values ranging from 0 to 4. As DW gets closer to 2, the more uncorrelated the residual terms are. The closer to 0, the stronger the positive correlation. The closer to 4, the stronger the negative correlation:

$$DW = \frac{\sum (U_t - U_{t-3})^2}{\sum U_t^2} \approx 2 * (1 - \rho) \tag{8}$$

The value of the DW statistic was calculated to be 2.323, which falls within the interval of no serial correlation, indicating that the residuals are independent.

The regression standardized residual plot and cumulative probability plot are shown in Figures 2 and 3, respectively. The standardized residuals approximately obey the normal distribution, and the scatter points are basically scattered around the diagonal of the first quadrant, so it can be assumed that the residuals basically obey the normal distribution.

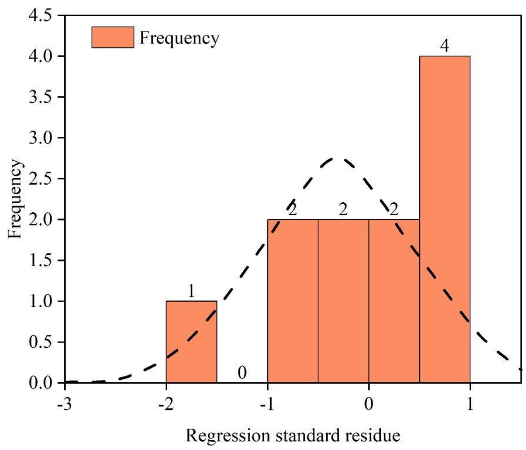

Figure 2: Regression map

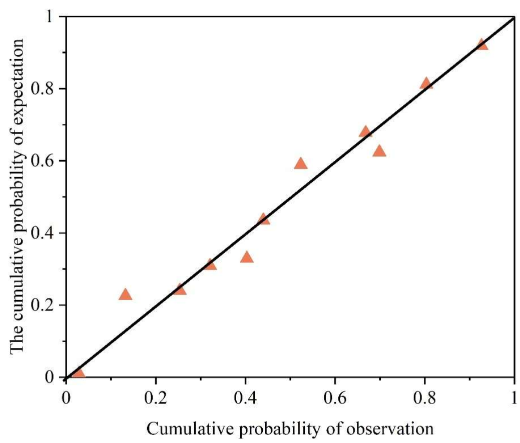

Figure 3: Cumulative probability diagram

Since multicollinearity increases the variance of the parameter estimates, the larger the variance inflation factor value VIF, the stronger the covariance. The results of the model solution are shown in Table 2, where *** denotes p<0.01, ** denotes p<0.05, and * denotes p<0.1 (below). As can be seen in the last column of the table, the VIF of rural carbon and financial innovation index (lnDFI), agricultural industry structure (lnISTRU), transportation infrastructure (lnTRAN), planting structure (lnPSTRU), and financial support for agriculture (FINAN) are all less than 5, so there is no covariance between the independent variables.

Table 2: Model solution

Model	Nonnormalized coefficient	Normalization factor		T	P	Common linear statistics	
	B	Standard error	Beta			Tolerance	VIF
Cons	-0.163	1.952	-	-0.069	0.000**	-	-
lnDFI	0.08	0.076	0.007	0.08	0.002**	0.713	1.437
lnISTRU	0.036	0.203	0.005	0.036	0.001**	0.507	1.939
lnTRAN	0.995	0.015	1.636	0.995	0.000**	0.141	2.568
lnPSTRU	1.018	0.039	0.764	1.018	0.016**	0.141	1.417
FINAN	1.023	0.042	0.035	0.763	0.021**	0.136	1.421

IV. B. Benchmark regression analysis

This study uses Stata 17.0 software to empirically analyze the impact of rural carbon financial innovation on agricultural carbon emission reduction, and the baseline regression results are shown in Table 3. Without the introduction of control variables, rural carbon financial innovation has a significant inhibitory effect on the intensity of agricultural carbon emissions, the regression coefficient is -0.236, and is significant at the 1% confidence level, while after the introduction of control variables, the significance level and the direction of the impact of rural carbon financial innovation on agricultural carbon emission reduction did not change, which indicates that rural carbon financial innovation can significantly promote agricultural carbon emission reduction, and H1 is established. From the perspective of control variables, the effect of industrial structure (lnISTRU) on agricultural carbon emission intensity is significantly negative at the 1% level. The effects of transportation infrastructure (lnTRAN) and financial support for agriculture (FINAN) on the intensity of agricultural carbon emissions are negative but not significant, indicating that the improvement of transportation conditions and the level of financial expenditure can reduce the intensity of agricultural carbon emissions to a certain extent. The influence of planting structure (lnPSTRU) on agricultural carbon emission intensity is significantly positive at the 5% level, which may be due to the fact that the food planting structure will have an impact on the production activities of farmers, who will maximize their own interests by increasing the inputs of agricultural factors of production, which will lead to an increase in the intensity of agricultural carbon emissions.

Table 3: Benchmark regression

Project	(1)	(2)
lnDFI	-0.236***	-0.177***
	(0.031)	(0.032)
lnPSTRU	-	1.322**
		(0.532)
FINAN		-0.036
		(0.136)
lnISTRU		-1.502***
		(0.569)
LnTRAN		-0.336***
		(0.123)
Provincial fixation effect	YES	YES
R2	0.569	0.672
Observed value	1000	1000

IV. C. Robustness Tests

In order to enhance the reliability of the conclusions of the benchmark model, this study conducts the robustness test of the benchmark regression model by replacing the explanatory variables method and excluding samples method, respectively, and the test results are shown in Table 4. First, the method of replacing explanatory variables, the explanatory variables are replaced with the first-order lagged term of rural carbon financial innovation (L.lnDF) for the robustness test, and the results are shown in Column (3) and Column (4). The significance level and the direction of influence after replacing the explanatory variables are basically consistent with the results of the benchmark regression, confirming that the results of the benchmark regression are credible. Secondly, considering the gap between municipalities and other provinces in the development of rural carbon finance innovation, the benchmark model is robustly tested by excluding the samples from four municipalities, namely Beijing, Tianjin, Shanghai and Chongqing, and the results are shown in columns (5) and (6). After excluding the samples, the significant level and direction of influence of rural carbon financial innovation are basically the same as those of the benchmark regression results, which further supports the accuracy of the conclusion.

IV. D. Endogeneity test

Considering that the development of rural carbon financial innovation has an impact on the intensity of agricultural carbon emissions at the same time, the reduction of agricultural carbon emission intensity will also lead to the optimization and adjustment of agricultural production methods and resource allocation, which will in turn promote the development of rural carbon financial innovation, and the endogeneity problem may arise due to the bi-directional causality between the two. In order to overcome the possible endogeneity problem, this study chooses regional Internet penetration (NET) as an instrumental variable to solve the endogeneity problem. The regional Internet penetration rate will directly affect the development of rural carbon financial innovation, and there is no direct link between it and agricultural carbon emissions, which is in line with the principle of exogeneity of instrumental variables. The endogeneity test results are shown in Table 5, and the P-value of the endogeneity test parameter is 0.003, which indicates that the baseline regression model has endogeneity problems and needs to be tested for endogeneity. The regression coefficient of the instrumental variable Internet penetration in stage 1 is 2.638 and passes the 1% confidence level, indicating that the principle of correlation is satisfied. Meanwhile, the F-statistic is greater than 10, indicating that there is no weak instrumental variable. The regression coefficient of rural carbon financial innovation in stage 2 is -0.263 and passes the 1% confidence level, which indicates that the results of the study using instrumental variables are basically the same as the baseline regression results, i.e., rural carbon financial innovation significantly promotes agricultural carbon emission reduction. Therefore, after excluding the endogeneity problem, the significance and direction of effect of the research results are basically consistent with the benchmark regression results, which further confirms the credibility of the benchmark regression results.

Table 4: Robustness test results

Project	(3)	(4)	(5)	(6)
L.lnDF	-0.189***	-0.136***	-	-
	(0.032)	(0.023)		
lnDFI	-	-	-0.226***	-0.159***
			(0.032)	(0.016)
lnPSTRU	-	1.269**	-	1.869***
		(0.523)		(0.523)
FINAN		-0.069		-0.036
		(0.125)		(0.126)
lnISTRU		-1.169**		0.045**
		(0.523)		(0.032)
LnTRAN		-306		-1.498***
		(0.163)		(-0.273)
Cons	6.325***	9.169***	6.214***	8.725***
	(0.115)	(2.136)	(0.163)	(2.362)
Provincial fixation effect	YES	YES	YES	YES
R2	0.526	0.533	0.554	0.632
Observed value	900	900	800	800

Table 5: Endogenous test results

Project	lnDFI	lnACE
lnNET	2.638***	-
	(0.162)	
lnDFI	-	-0.263***
		(0.036)
Control variable	YES	YES
Provincial fixation effect	YES	YES
Observed value	1000	1000
Endogenous test parameter P value	0.003	
F statistic	27.523	

IV. E. Heterogeneity analysis

In this paper, China is divided into three regions: east, center and west according to the standards of the National Bureau of Statistics, and the level of economic development in the east is significantly higher than that in the center and west in terms of productivity level. Based on this background, the impact of agricultural carbon financial innovation on agricultural carbon emissions may be different in different geographic regions, and the results of the empirical test are shown in Table 6. The impact coefficient of agricultural carbon financial innovation on carbon emissions in the western region is -1.0836, and it is significant at the 1% level, with a significant inhibition effect. The impact coefficient of agricultural carbon financial innovation on agricultural carbon emissions in the eastern region is positive and the result is not significant. The impact coefficient of agricultural carbon financial innovation on agricultural carbon emissions in the central region is -0.0653, and the result does not show significance. In contrast, agricultural carbon financial innovation in the western region has the strongest inhibiting effect on agricultural carbon emissions. Specifically analyzing the reasons, the western region's economic development level is relatively lagging behind that of the eastern and central regions, and it relies too much on the traditional “crude” production methods in agricultural production, while with the continuous improvement of digital infrastructure, the development of agricultural carbon financial innovation makes it possible to rapidly improve the level of productivity, and the intensive and large-scale agricultural production mode can be efficiently utilized. Efficient utilization. The central and eastern regions have higher levels of economic development and agricultural productivity, and the low-carbon and low-pollution agricultural production mode is more mature, coupled with the relatively high level of agricultural carbon financial innovation, which can bring about agricultural carbon emission reduction effect is relatively weaker than that of the western region. Therefore, the negative effect of agricultural carbon financial innovation on agricultural carbon emissions in the western region is the most significant.

Table 6: Heterogeneity analysis results

Project	(7) East	(8) Middle	(9) West
lnDFI	0.1732	-0.0653	-1.0836***
	(0.1133)	(0.2556)	(0.1586)
FINAN	0.3356	-0.0243	0.3053
	(0.2513)	(0.2286)	(0.2325)
LnTRAN	-0.1156***	0.0547	-0.063
	(0.0511)	(0.0523)	(0.0845)
lnISTRU	-0.1423*	0.019	0.0563
	(0.0786)	(0.0435)	(0.1432)
lnPSTRU	0.0075	-0.0414	-0.0375
	(0.0125)	(0.0444)	(0.0252)
Cons	3.2841***	1.5652	4.8353***
	(0.7511)	(0.9925)	(1.0886)
Provincial fixation effect	YES	YES	YES
Time fixed effect	YES	YES	YES
R2	0.512	0.534	0.559
Observed value	400	200	400

IV. F. Intermediation test

The results of the mechanism test under the ternary cycle perspective are shown in Table 7. Columns (10), (11) and (12) reflect the mechanism test results of the small cycle of farmers, the medium cycle of industry and the large cycle of society, respectively. The regression coefficient of the small cycle of farmers is positive and significant at the 5% statistical level, indicating that carbon financial innovation can enhance the carbon emission reduction capacity of farmers through measures such as enhancing the concept of green development, cultivating innovative talents and promoting green technology research and development. Verify that H2 holds. The regression coefficient of the cycle in the industry is positive and significant at the 10% statistical level, which argues that carbon financial innovation can make the green transformation of agriculture by guiding the flow of capital and at the same time integrating the green low-carbon concept into financial products and services. Verify that H3 holds. The regression coefficient of the social macrocycle is positive and significant at the 10% statistical level, indicating that carbon financial innovation can effectively alleviate agricultural underinvestment, stimulate farmers' entrepreneurial enthusiasm, and gather social idle funds for green infrastructure construction and environmental pollution control equipment investment. It is verified that H4 is valid.

Table 7: The mechanism effect test of the ternary cycle Angle

Variable	(10)	(11)	(12)
lnDFI	0.003**	0.068*	0.042*
	(2.069)	(1.865)	(1.756)
Cons	6.954*	106.365***	93.421***
	(5.632)	(3.624)	(4.331)
Individual effect	Control	Control	Control
Time effect	Control	Control	Control
R2	0.863	0.264	0.635

IV. G. Moderating effects test

The test results of the moderating effect of urbanization development level are shown in Table 8. As can be seen from column (13), the coefficient of the interaction term between agricultural carbon financial innovation and urbanization development level is -0.633, and it is significant at the 1% level, indicating that the urbanization development level plays a significant moderating role in the agricultural carbon emission reduction effect of agricultural carbon financial innovation. From model (14)-(15), the regression coefficient of the interaction term between agricultural carbon financial innovation and urbanization development level in the East region is -0.731 and significant at 1% level of significance, indicating that the moderating effect of urbanization development level in the East region is significant. Overall, the level of urbanization development has an enhancing effect on the agricultural carbon emission reduction effect of agricultural carbon financial innovation, i.e., the higher the level of urbanization development, the greater the agricultural carbon emission reduction effect of agricultural carbon financial innovation. The advancement of urbanization makes agricultural activities constrained in the process of transforming rural areas into towns and cities, and agricultural carbon emissions are subsequently reduced. At the same time, urbanization also implies the improvement of regional infrastructure level, which lays the foundation for the deep development of agricultural carbon financial innovation. With financial support, limited agricultural activities will pay more attention to energy conservation and environmental protection, green and low-carbon operations, thus reducing agricultural carbon emissions.

Table 8: The regulation effect of urbanization development level is tested

Variable	(13)	(14) Western region	(15) East region
lnDFI	-0.063	0.063	-0.023
	(0.026)	(0.046)	(0.018)
lnCITY	-5.631***	-6.352***	-4.631***
	(0.635)	(1.365)	(0.596)
lnDFI×lnCITY	-0.633***	0.056	-0.731***
	(0.135)	(0.163)	(0.133)
Cons	13.662***	2.658	13.642***
	(1.635)	(2.635)	(1.635)
Control variable	YES	YES	YES
Provincial fixation effect	YES	YES	YES
Clustering to provinces	YES	YES	YES
R2	0.836	0.863	0.841
Observed value	450	100	450

V. Conclusion

Based on the ternary cycle theory, this study empirically analyzes the influence mechanism of agricultural carbon financial innovation on agricultural carbon emission reduction and draws the following conclusions:

First, agricultural carbon financial innovation has a significant inhibitory effect on agricultural carbon emissions, with a regression coefficient of -0.236 and significant at the 1% confidence level.

Second, in terms of the mediating effect, agricultural carbon financial innovation promotes agricultural carbon emission reduction through the ternary cycle: the regression coefficient of the small cycle of farmers is 0.003, which is significant at the 5% statistical level; the regression coefficients of the medium cycle of the industry and the large cycle of the society are 0.068 and 0.042, respectively, which are both significant at the 10% statistical level.

Third, the level of urbanization development plays a significant positive moderating role in the agricultural carbon emission reduction effect of agricultural carbon financial innovation, and the interaction term coefficient is -0.633 and significant at the 1% level, indicating that the higher the level of urbanization, the stronger the emission reduction effect of agricultural carbon financial innovation.

Fourth, the regional heterogeneity analysis shows that the coefficient of the impact of agricultural carbon financial innovation on carbon emissions is -1.0836 in the western region, 0.1732 (not significant) in the eastern region, and -0.0653 (not significant) in the central region, and the inhibition effect is most significant in the western region.

The study recommends: accelerating the improvement of the agricultural carbon financial system and enhancing the service capacity of rural carbon financial innovation; strengthening the synergistic effect of the small cycle of farmers, the medium cycle of industry and the large cycle of society; promoting the integration and development of urbanization and agricultural carbon financial innovation; and implementing differentiated agricultural carbon financial policies in response to regional differences, in particular, strengthening the support to the western region and giving full play to its potential in promoting agricultural carbon emission reduction.

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