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Can Land Transfer Promote the Green and Low-carbon Development of Agriculture?

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Abstract: Based on the panel data of 30 provinces in China from 2005 to 2022, this paper uses the two-way fixed effect model, the mediating effect model and the instrumental variable method, this paper systematically examines the impact of land transfer on agricultural carbon productivity and its mechanism. The empirical results indicate that: (1) land transfer contributes substantially to the improvement of farm carbon productivity, a result that verifies the two-pronged advantage of carbon reduction and efficiency elevation; (2) moderate scale management is the key intermediary path for land transfer to promote agricultural carbon productivity; (3) regional heterogeneity analysis shows that land transfer has a significant role in promoting agricultural carbon productivity in the eastern and western regions, followed by the Northeast region, while the central region is restricted by resource endowment and utilization mode, the impact is not significant. Based on this, this paper provides a theoretical basis and empirical support for optimizing the design of land transfer policy and promoting the low-carbon transformation of agriculture.

Keywords: Land Transfer; Agricultural Carbon Productivity; Green and Low-carbon.

1. Introduction

The "State of the Global Climate 2023" report, issued by the World Meteorological Organization (WMO) in March 2024, points out that greenhouse gas concentrations, land surface temperatures, ocean heat content, ocean acidification, and sea level rise have all hit record highs. This fully demonstrates that humanity is facing an unprecedented climate crisis. There is an urgent need for countries around the world to make a greater contribution to reducing carbon emissions if the world is to peak global carbon emissions in 2025 and achieve the 1.5 ℃ temperature target. As a major source of global greenhouse gases, the agricultural sector accounts for roughly one-fifth to one-quarter of total emissions, ranking as the second-largest emitter globally [1]. As the largest carbon emitter, China is also a developing agricultural country. Green development and low-carbonization of agricultural production in China is significant to alleviate the global climate crisis. To advance both food security and climate action in a coordinated manner, Chinese government issued a specialized implementation plan for agricultural emission reduction in May 2022, which maps out a path for green and low-carbon transformation. The carbon productivity concept aligns well with the prevailing notion of green development and low-carbonization in agriculture and rural areas. In contrast to indicators like economic growth rate and carbon emissions, carbon productivity enables a comprehensive evaluation of how effectively economic development and carbon emission reduction are achieved [2]. Scholarly research into agricultural carbon productivity has also been steadily expanded. Factors such as agricultural digital transformation [3], green technology innovation [4], agricultural industry agglomeration [5], and urbanization development [6] can promote the improvement of agricultural carbon productivity. It is clear that agricultural carbon productivity levels are closely correlated with the high-quality green development of agriculture. Therefore, exploring ways to improve agricultural carbon productivity is an inevitable requirement for the low-carbon transformation of agriculture and rural areas [7], and also a key task for China to achieve the "Double Carbon" goal.

The farmland circulation policy has effectively advanced the optimal allocation of rural land resources and the upgrading of agricultural production modes [8]. On one hand, this policy allows farmers to retain their land contract rights while transferring land management rights to large-scale and specialized farmers, facilitating the transformation of fragmented household contracted land into large-scale and specialized agricultural parks. On another note, subsequent to land assignment, concentrated contiguous large-scale farmland has established the basic requirements for mechanized farming and intensive operation. The main actors in farming have also shifted from part-time farmers to professional farmers, leading to a significant improvement in production efficiency. While land transfer optimizes resource allocation and improves production efficiency, it is bound to have an impact on agricultural carbon emissions. Some scholars argue that the expansion of farmland circulation can curb agricultural carbon emissions through technological innovation and reduced chemical input intensity[9][10]. In contrast, other scholars argue that farmland circulation enlarges agricultural operation scales, speeds up the modernization and mechanization of agriculture, and thus raises agricultural carbon emissions. Influenced by the demonstration effect mechanism and regional competition mechanism[11][12], it also has a negative spillover effect on agricultural carbon emissions in adjacent areas[13]. Can the extra economic benefits generated by scale operations via farmland circulation offset the adverse impacts of higher agricultural carbon emissions? In other words, can scale operations driven by land transfer balance the dual needs of "maintaining growth" and "promoting emission reduction" in China?

In summary, some scholars have explored how farmland circulation affects agricultural carbon emissions from both macro and micro perspectives, but few studies have incorporated farmland circulation and agricultural carbon productivity into a unified analytical framework. Improving agricultural carbon productivity acts as the core pathway to advance China's agricultural green and low-carbon transition. Therefore, this paper employs macro panel data from 30 Chinese provinces (excluding Tibet, Hong Kong, Macao, and Taiwan) spanning 2005–2022 to explore how farmland circulation functions in and affects agricultural carbon productivity. This study makes the following marginal contributions: (1)it integrates farmland circulation and agricultural carbon productivity into a unified analytical framework; (2)it systematically analyzes how land transfer acts on agricultural carbon productivity and the relevant mechanism pathways using a two-way fixed effects model, a mediating effect model, and an instrumental variable method, confirming that land transfer has a positive effect on agricultural carbon productivity; (3)it explores how the impact of farmland circulation on agricultural carbon productivity varies across regions.

2. Theoretical Analysis and Research Hypothesis

Farmland circulation exerts a direct effect by optimizing land resource allocation. As an important driving force of agricultural modernization, the direct effect of farmland circulation is to optimize the allocation of land resources. From the natural resource endowment perspective, farmland circulation can effectively mitigate land fragmentation and abandonment, integrate scattered farmland resources into contiguous large-scale farmland, improve land use efficiency, and thereby contribute to the growth of agricultural output value. From the human resource endowment perspective, land transfer can concentrate the management rights of agricultural land in the hands of agricultural management entities with planting willingness and planting technology, and large-scale planting and professional farmers have replaced traditional individual smallholder farmers, boasting richer farm management knowledge and stronger financing capacity [14], which significantly improves the level of agricultural specialization and mechanization [15], thereby promoting the increase in agricultural output value. Based on the rational broker theory, from the perspective of maximizing farmers' interests, farmers tend to adopt advanced agricultural technologies and equipment to improve agricultural production efficiency in order to obtain higher land transfer income. At the same time, the excessive use of chemicals such as fertilizers and pesticides is reduced[16], which not only saves costs but also ensures the ecological sustainability of land and reduces the carbon emission intensity of agricultural production. In conclusion, on the one hand, farmland circulation can improve agricultural production efficiency and increase agricultural output value; on the other hand, it can reduce carbon emissions caused by excessive chemical inputs. It is an important way to promote agricultural carbon productivity and a necessary means to realize the green and low-carbon development of agriculture.

Based on this, hypothesis 1 is proposed: Land transfer can promote the improvement of agricultural carbon productivity.

The indirect effect of farmland circulation on agricultural carbon productivity. Based on a comprehensive review of existing literature, this study argues that farmland circulation exerts both direct and indirect impacts on agricultural carbon productivity. Moderate-scale operation acts as a core mediating variable that links farmland circulation to agricultural carbon productivity. According to economies of scale theory, expanding the scale of operation will help increase crop yields initially; only when exceeding a critical threshold will large-scale extensive operation lead to a decrease in average yield per mu. Relevant studies [17] have also confirmed this conclusion. Given the actual land use conditions in China, even if land transfer effectively expands the operation scale, the land scale is usually still within the scope of moderate scale. The realization of moderate scale management can not only effectively alleviate the disadvantages of land fragmentation, but also realize the scale economy and enhance comprehensive agricultural production capacity, and improve the operational efficiency per unit area[18]. At the same time, the process of achieving moderate scale management is also the process of optimizing the allocation of resources. Through rational land allocation, agricultural operators can promote the efficient allocation of production factors such as labor, machinery and so on, improve resource use efficiency, and reduce carbon emissions per unit of output. Additionally, empirical evidence shows that when farmland circulation expands farmers' operation scale, land circulation contracts will significantly strengthen the incentive effect on farmers' adoption of green agricultural production technologies[19] . Therefore, appropriate scale management is also conducive to the promotion of green production technologies, such as precision fertilization, ecological planting, and further reducing carbon emissions in agricultural production.

Accordingly, hypothesis 2 is proposed: Land transfer promotes the improvement of agricultural carbon productivity by facilitating moderate scale operation.

3. Variable Selection and Model Setting

Sources of data. Based on panel data from 30 Chinese provinces (autonomous regions and municipalities) spanning 2005 to 2022 (excluding Tibet, Hong Kong, Macao, and Taiwan), this study investigates how farmland circulation affects agricultural carbon productivity. The data are mainly obtained from national and provincial statistical yearbooks, agricultural yearbooks, and government work reports of the corresponding years. To ensure the completeness and reliability of the sample, linear interpolation is used to supplement a small number of missing values.

Explained variables. Agricultural carbon productivity (ACP) measures the ratio between agricultural economic output and carbon emissions, specifically referring to the agricultural output generated per unit of carbon dioxide emitted. Referring to the existing research, the calculation formula is presented below:

$$\mathrm{Acp} = \frac{\sum \mathrm{P_i Q_i}}{\sum \mathrm{C_i}} \tag{1}$$

Among them, $\mathrm{P_i}$ is the market price of agricultural product i, $\mathrm{Q_i}$ is the total output of agricultural product i, $\sum \mathrm{P_i Q_i}$ represents the total agricultural output value (expressed by the total output value of the planting industry), and $\sum \mathrm{C_i}$ represents the total agricultural carbon emissions.

This study adopts the IPCC carbon emission coefficient method. In formula (1) , the specific calculation formula is as follows:

$$\sum C = \sum E_i \times \varepsilon_i \quad (2)$$

In Equation (2), $\sum E_i$ refers to the total carbon emissions from agricultural activities, E_i represents the input quantity of the i-th carbon source in agricultural activities, and ε_i represents the carbon emission coefficient of the i-th carbon source. This study employs the emission coefficient method to estimate carbon emissions from crop cultivation. The specific coefficients used are detailed in Table 1, referring to the framework of Li Bo and Zhang Junbiao et al.

Table 1. Inventory of Key Agricultural Carbon Sources and Their Emission Coefficients[19][20][21][22][23]

Carbon sources	Carbon emission factor	Sources of reference
Diesel	0.59 kg/kg	IPCC2013[20]
Fertilizer	0.89 kg/kg	Oak Ridge National Laboratory [21]
Agriculture	4.93 kg/kg	Oak Ridge National Laboratory [19]
Agricultural film	5.18 kg/kg	Institute of Agricultural Resources and ecological environment, Nanjing Agricultural University [22]
Irrigation	266.48 kg/hm^2	Duan Huaping et al. [23]
Plowing	312.60 kg/km^2	Li Bo et al. [20]

Core explanatory variables. Drawing on the research of Wang Jiayue et al.[24], land transfer (LR) is expressed as the ratio of the total area of transferred cultivated land to the area of cultivated land under household contract management. At the same time, referring to Qian Li et al. [25], the total area of household contracted land transfer (LS) is used as an alternative variable for robustness testing.

Control variables. In line with existing research, this study incorporates the following six control variables into the model to account for the potential influence of economic, social, and natural factors on agricultural carbon productivity: (1) Level of economic development (GDP). Generally, economically more developed regions tend to have higher carbon emissions. This variable is measured by the logarithm of per capita GDP.(2) Population size (Pop) , the larger the regional population, the greater the carbon emissions from living and production activities, expressed by the logarithm of the regional resident population.(3) Measured by the proportion of local fiscal expenditure on agriculture, forestry, and water affairs in the total local fiscal expenditure.(4) Environmental regulation (Enr) , environmental regulation refers to the government's regulation of enterprises' production behaviors through administrative orders. This paper draws on the practice of Chen Shiyi[26] and uses the statistical results of relevant word frequencies in provincial government work reports.(5) The level of farmers' income (Fre) , expressed by the logarithm of rural residents' per capita disposable income.(6) Represented by the proportion of the primary industry's added value in the regional GDP.

Intermediate variables. The intermediary variable in this paper is moderate scale operation (Sca) . Drawing on the research of Xiong Feixue et al.[27], it is expressed as the ratio of the total sown area of crops to the number of employees in the primary industry.

In summary, the explanation and descriptive statistics of each variable are shown in Table 2.

Table 2. Description of variables and descriptive statistics

Types of variables	The name of the variable	Variable notation	Mean	Std.	Min	Max
Explained variable	Agricultural carbon productivity	Acp	33.08	22.35	6.58	203.12
Explanatory variables	Land transfer	LR	25.22	18.48	1.36	91.11
Control variables	Level of economic development	GDP	21401.94	21083.01	499.40	129119.00
	Population size	Pop	4528.30	2784.28	543.00	12684.00
	The level of financial support for agriculture	Afin	10.21	3.90	1.49	20.38
	Environmental Regulation	Enr	49.32	23.84	0.00	124.00
	Level of income of farmers	Fre	10960.07	6805.96	1971.00	39729.00
	Industrial structure	Ind	10.60	5.73	0.22	32.76
Mediating variables	Moderate scale operation	Sca	0.72	0.40	0.21	2.94

Note: Acp refers to the GDP output level per unit of carbon dioxide emitted during agricultural activities, with the unit of 10,000 yuan/ton;LR represents the proportion of total transferred cultivated land area relative to household-contracted cultivated land area; GDP denotes the regional gross domestic product, with the unit of 100 million yuan; Pop is the permanent resident population at the end of the year, with the unit of 10,000 people; Afin stands for the share of local fiscal expenditure on agriculture, forestry and water affairs in total local fiscal expenditure; Enr is the statistical result of the frequency of relevant words in provincial government work reports; Fre refers to the per capita disposable income of rural residents, with the unit of yuan; Ind represents the share of primary industry added value in regional gross domestic product; Sca is the total sown area of crops divided by the number of employees in the primary industry, with the unit of hectares/person.

Model settings. Two-way fixed-effects models. To ensure that the estimation results are robust against unobservable individual heterogeneity and time-varying factors, this study follows standard econometric practices and constructs a panel model incorporating both provincial and year two-way fixed effects. The model utilizes provincial panel data from 2005 to 2022 (excluding Tibet, Hong Kong, Macao, and Taiwan) in China, with the core goal being to analyze the impact of land transfer on agricultural carbon productivity. The specified econometric model is as follows:

$$Acp_{it} = \alpha_0 + \alpha_1 LR_{it} + \alpha_2 control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

In equation (3), Acp_{it} denotes the agricultural carbon productivity of a certain region in a specific year, LR_{it} represents the land transfer of a certain region in a specific year, and $control_{it}$ stands for control variables, including economic development level, population size, environmental regulation, financial support for agriculture level, industrial structure, and farmers' income level. μ_i refers to the provincial fixed effect, λ_t denotes the time fixed effect, and ε_{it} is the error term. α_1 indicates the estimated coefficient, which is used to measure the impact degree of land transfer on agricultural carbon productivity, and its sign reflects the direction of the effect of land transfer on agricultural carbon productivity.

Mediating effect model. In order to further study the path and mechanism of land transfer on agricultural carbon productivity, this paper adopts the mediating effect test method. Referring to the research of Jiangting [28], this paper uses the two-step mediating effect method to directly examine the impact of land transfer on moderate scale operation. On the basis of equation (3), the following mediation effect model is constructed:

$$Sca_{it} = \beta_0 + \beta_1 LR_{it} + \beta_2 control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

In equation (4) , Sca_{it} denotes the mediating variable of appropriate-scale operation, and the other variables have the same meanings as in equation (3) .

4. Empirical Results and Analysis

Benchmark regression analysis. Through the Hausman test, the random effect model is rejected, which effectively alleviates the endogeneity problem caused by individual heterogeneity and time trend. The benchmark regression adopted a strategy of gradually adding control variables to test the robustness of the estimated results of the core explanatory variables, and the R^2 value of the model steadily increased from 0.711 to 0.735 in terms of the model goodness of fit, indicating that the core explanatory variables can be used to estimate the core explanatory variables. It shows that the added control variables effectively enhance the explanatory power of the model, and the overall fitting degree is good. Table 3 shows the regression results of adding each control variable in turn.

Table 3. The benchmark regression results of land transfer on agricultural carbon productivity

Variables	(1)	(2)	(3)	(4)
LR	0.720 * * *	0.782 * * *	0.657 * * *	0.652 * * *
	(0.0680)	(0.0681)	(0.0758)	(0.0766)
GDP		0.000223 * * *	0.000129 *	0.000116
		(4.96e-05)	(7.53 e-05)	(7.72e-05)
Pop			0.00450 *	0.00494 *
			(0.00252)	(0.00259)
Afin			-1.071 * * *	-1.030 * * *
			(0.326)	(0.338)
Fre			-0.00113 * * *	-0.00114 * * *
			(0.000300)	(0.000309)
Ind				-17.11
				(27.58)
Enr				-0.0169
				(0.0309)
Constant term	19.52 * * *	18.48 * * *	6.989	7.561
	(1.764)	(1.745)	(10.83)	(11.08)
Fixed effects by region	Yes	Yes	Yes	Yes
Time-fixed effects	Yes	Yes	Yes	Yes
N	540	540	540	540
R^2	0.711	0.722	0.734	0.735

Note: * * *, * *, * means passing the significance test of 1% , 5% , 10% respectively; T value is in brackets. The same below

From Model (1) to model (4) , it can be seen that after gradually incorporating a series of control variables, the estimated coefficient of land transfer is always significantly positive at the statistical level of 1% , which fully indicates that land transfer has a significant and stable positive effect on agricultural carbon productivity, and the hypothesis H1 is verified. The above results prove that land transfer is an effective way to promote the green and low-carbon transformation of agriculture. from the dimension of “Maintaining growth”, land transfer optimizes the allocation of land resources by promoting large-scale and specialized management, reducing the fragmentation and abandonment of cultivated land, directly improving agricultural production efficiency and economic output; from the perspective of “Promoting emission reduction”, large-scale operators have the ability and motivation to invest in green technologies such as precision fertilization, water-saving irrigation, and organic agriculture, significantly improving the utilization efficiency of key elements such as chemical fertilizers and pesticides, thus reducing agricultural non-point source pollution and carbon emissions.

Robustness test. To enhance the credibility of the baseline regression results, this study conducts robustness tests through three approaches, namely replacing the core explanatory variable, adjusting the control variables, and addressing endogeneity by introducing the instrumental variable method. The results are presented in Table 4.

First, the method of replacing the core explanatory variables is adopted for re-estimation, and the core explanatory variables are replaced by the core explanatory variables, the ratio of the total area of cultivated land transfer to the area of cultivated land under household contract management was replaced by the natural logarithm form of the total area of cultivated land transfer under household contract, and the results were re-incorporated into the model as shown in Model (1) . After replacing the variables, the estimated coefficient of land transfer is still significantly positive at the level of 1% , indicating that the positive effect of land transfer on agricultural carbon productivity does not change with the change of the measurement method of core variables, the benchmark conclusion has good robustness.

Secondly, the robustness of the model is further tested by adjusting the set of control variables. This paper deletes the population structure and environmental regulation and then re-regresses. The empirical results indicate that after adjusting the control variables, the coefficient of land transfer still remains positive and significant at least at the level of 1%, the coefficient is close to the benchmark regression result, which further indicates that the core promoting effect of land transfer on agricultural carbon productivity is still robust.

Finally, this paper considers the possible endogeneity problems of the model. Because there may be a two-way causal relationship between agricultural carbon productivity and land transfer, that is, areas with higher agricultural carbon productivity may have better natural resource endowments, and then it is easier to implement land transfer. In order to alleviate this endogenous interference, this paper selects the lag phase of land transfer as an instrumental variable for regression, and the results are shown in Model (3) . After using the instrumental variable method to control endogeneity, the estimated coefficient of land transfer is still significantly positive at the level of 1% , and the coefficient value is significantly higher than that of the baseline regression, which further proves the reliability of the research conclusions.

Across multiple robustness tests, the promoting effect of land transfer on agricultural carbon productivity consistently proves significant. This confirms the robustness of the benchmark regression results and lends additional support to Hypothesis H1.

Table 4. robustness tests

Variables	Alternative explanatory variables	Adjustment for control variables	Core explanatory variables were lagged by one period
	(1)	(2)	(3)
LR	6.13 e-07 * * *	0.692 * * *	0.704 * * *
	(8.59e-08)	(0.0734)	(0.0852)
Constant term	16.08	25.84 * * *	10.73 * *
	(11.75)	(2.417)	(4.558)
Control variables	Control	Control	Control
Fixed effects by region	Yes	Yes	Yes
Time-fixed effects	Yes	Yes	Yes
N	540	540	540
R^2	0.724	0.733	0.517

Heterogeneity analysis. China has a vast territory, and the eastern, Central, western and northeastern regions have significant differences in resource endowments, economic development stages and agricultural management models. These differences may lead to different mechanisms and effects of land transfer on agricultural carbon productivity. The analysis based on the national total sample may conceal its inherent regional heterogeneity. In order to further explore this difference, this paper refers to the division standard of the National Bureau of Statistics of the People’s Republic of China, and divides the total sample into four regions for regression test, the results are shown in Table 5.

The empirical results show that the impact of land transfer on agricultural carbon productivity does have distinct regional heterogeneity, and its promotion shows a gradient characteristic of "strong in the east and west, obvious in the northeast, and not obvious in the middle".

Specifically, in the eastern region, the promotion effect of land transfer on agricultural carbon productivity is the strongest at the 1% significance level, with a coefficient of 0.716. This is mainly due to the superior economic development foundation and the leading level of agricultural modernization in the eastern region. The high degree of urbanization in the Eastern Region and the full transfer of rural labor force have created a huge supply and demand market for land transfer. The region has a strong economy, new agricultural operators and government capital, and it is more inclined and able to apply green and low-carbon technologies such as water-saving irrigation, precision fertilization and intelligent agricultural machinery to the land that has flowed in, large-scale and intensive green production. Therefore, land transfer is more effective in promoting agricultural carbon productivity in the eastern region.

In the Western Region, land transfer also has a significant positive impact on agricultural carbon productivity at the level of 1% , with a coefficient of 0.577. This is related to the late-development advantage and policy preference of the Western Region. The agricultural economy in the Western Region is relatively backward, with low resource utilization efficiency, and the base of agricultural carbon productivity is small, so there is a huge room for improvement. The state's sustained policies of large-scale development of the Western Region, ecological compensation, and key assistance for rural revitalization have provided strong external support for the construction of agricultural infrastructure and the promotion of green technology in the Western Region, and promote the improvement of agricultural carbon productivity.

In the Northeast Region, land transfer has a significant role in promoting agricultural carbon productivity at the level of 5% , with a coefficient of 0.268. As China's "Big Granary", the Northeast Region is rich in black soil resources, perfect infrastructure such as irrigation and Water Conservancy, large-scale agriculture, high degree of mechanization. Therefore, the marginal utility of land transfer in this area is relatively limited, and its role is more reflected in further optimizing the allocation of resources and promoting the adoption and application of green agricultural technologies by large-scale management entities, so as to steadily promote the improvement of agricultural carbon productivity.

In contrast, the estimated coefficient of the central region did not pass the significance test. This phenomenon may be due to its internal differences and resource and environmental constraints. The central region includes not only major grain producing areas such as Henan and Anhui, but also mineral resources provinces such as Shanxi and hilly and mountainous areas. The agricultural development model, resource distribution and challenges faced within the region are quite different. Some major grain-producing areas are facing the pressure of overdraft of arable land fertility and shortage of water resources, while non-major grain-producing areas may be limited by natural conditions such as drought and salinization, and their land use patterns are relatively single, the environment is more fragile [29]. This internal heterogeneity may lead to the land transfer effect being not significant. In addition, under the trend of "Non-food", the use of transferred land for the cultivation of cash crops with high carbon and water consumption may also weaken the positive impact of land transfer on the green and low-carbon development of agriculture to a certain extent, as a result, the promotion effect has not been fully demonstrated.

Additionally, control variables indicate GDP significantly boosts agricultural carbon productivity across regions (via green agricultural technology capital support). Regional differences in Pop and Afin confirm heterogeneity, emphasizing region-specific land transfer and low-carbon agricultural policies.

Table 5. Regression results of regional heterogeneity test

Variables	Model 1 The east	Model 2 The middle	Model (3) The west	Model 4 The northeast
LR	0.716 * * *	0.0728	0.577 * * *	0.268 * *
	(0.115)	(0.0711)	(0.198)	(0.104)
GDP	0.000213 *	0.000272 * * *	0.000990 * * *	-0.000175
	(0.000115)	(6.94e-05)	(0.000273)	(0.000784)
Pop	-0.000232	0.00265	0.00602	0.0321 * *
	(0.00387)	(0.00373)	(0.0117)	(0.0120)
Afin	-0.805	-0.0671	-2.166 * * *	0.104
	(0.672)	(0.309)	(0.626)	(0.391)
Fre	-0.00169 * * *	0.00345 * * *	-0.000896	0.00754 * *
	(0.000537)	(0.00111)	(0.00147)	(0.00282)
Ind	114.4	87.17 * * *	-145.2 * *	76.99 * * *
	(124.4)	(26.49)	(70.43)	(20.68)
Enr	-0.0806	0.00782	0.0426	0.0132
	(0.0553)	(0.0164)	(0.0583)	(0.0396)
Constant term	26.52	-27.80	32.59	-138.3 * * *
	(17.34)	(23.83)	(32.49)	(47.88)
Fixed effects by region	Yes	Yes	Yes	Yes
Time-fixed effects	Yes	Yes	Yes	Yes
N	198	90	198	54
R^2	0.743	0.977	0.805	0.983

Mechanism analysis. To explore the impact mechanism of land transfer on agricultural carbon productivity, this paper tests the mediating effect of moderate scale operation. From Table 6, we can see that the regression coefficient of land transfer to moderate scale management is positive at the level of 1%, indicating that land transfer can be achieved by concentrating land management rights, optimizing land resource allocation, and merging small plots. Land transfer effectively improved the scale of agricultural land management, and promoted large-scale and centralized agricultural production. The moderate scale management of agriculture is an important way of agricultural modernization. On the one hand, it can raise land utilization efficiency and promote the growth of agricultural output value; on the other hand, it can promote the specialized agglomeration of agricultural production, in order to promote the application of agricultural machinery and agricultural green technology, so as to play the carbon productivity improvement effect of land transfer. Thus, hypothesis 2 is established.

In order to further explore the internal path of land transfer affecting agricultural carbon productivity, this paper tests the mediating effect of moderate scale management. From Table 6, we can see that the regression coefficient of land transfer to moderate scale management is significantly positive at the level of 1%, indicating that land transfer can be achieved by concentrating land management rights, optimizing land resource allocation, and merging small plots. Land transfer effectively improved the scale of agricultural land management, and promoted large-scale and centralized agricultural production. As an important way of agricultural modernization transformation, moderate scale management plays a key intermediary role in the process of land transfer to improve agricultural carbon productivity. Its transmission mechanism is mainly reflected in the following two aspects: first, in the aspect of "Reducing costs and increasing efficiency", scale operation has significantly enhanced agricultural production efficiency and reduced the average cost of unit output, it has promoted the growth of agricultural output value and laid the foundation for the promotion of carbon productivity. The scale management entities have more ability and willingness to invest in advanced agricultural machinery, adopt soil testing and formula fertilization, implement water-saving irrigation technology and promote green prevention and control means, so as to significantly enhance resource utilization efficiency. Second, in terms of "Emission reduction and efficiency improvement", production specialization and spatial agglomeration are conducive to the large-scale application of standardized and standardized green production technologies, overcoming the bottleneck of technology adoption under the smallholder business model, it has effectively reduced the excessive input of chemical fertilizers and pesticides and the redundant operation of agricultural machinery, reduced the intensity of carbon emissions from the source, and achieved the goal of "Promoting emission reduction". In summary, land transfer acts as a dual driver, directly enhancing agricultural carbon productivity while also fostering a shift toward green, low-carbon agriculture through the development of moderate-scale management. Therefore, the research hypothesis H 2 can be established.

Table 6. The regression results of the test of intermediary mechanism of moderate scale operation

Variables	(1) moderate scale of operation
LR	0.589 * * * (0.0773)
Constant term	25.20 * (12.94)
Control variables	Control
Fixed effects by region	Yes
Time-fixed effects	Yes
N	540
R^2	0.576

5. Conclusion and Policy Recommendations

Research conclusion. This study empirically examines the impact and mechanism of land transfer on agricultural carbon productivity using a two-way fixed effects model and a mediation effect model, based on panel data from 30 Chinese provinces from 2005 to 2022. The findings are as follows: (1) Land transfer significantly improves agricultural carbon productivity. (2) It indirectly enhances agricultural carbon productivity by promoting moderate-scale operation. (3) The impact of land transfer exhibits significant regional heterogeneity: its promoting effect is more pronounced in the eastern and western regions, relatively weaker in the northeast region, and insignificant in the central region.

Policy recommendations.

Continue to standardize and promote land transfer policies. First of all, we should improve the land transfer market mechanism, establish a transparent and standardized land transfer trading platform, ensure the legitimacy and execution efficiency of the transfer contract through digital means, and reduce the risk of disputes. Secondly, it is necessary to strengthen policy support, such as providing financial subsidies, tax incentives or credit support for farmers who participate in land transfer, so as to reduce their transfer costs and operational risks. In addition, it is necessary to strengthen publicity and guidance, and enhance farmers' cognition and willingness to participate in land transfer through typical case demonstration and farmer cooperative training, so as to gradually break the thinking mode of "Small-scale peasant economy".

We will vigorously support large-scale agricultural operations. We should focus on supporting new business entities such as family farms and agricultural cooperative. Through land integration, promote agricultural production mechanization, intelligence, reduce the waste of resources caused by decentralized management. For example, large-scale farming can reduce carbon intensity per unit of output by harmonising fertilisation and irrigation, optimising the allocation of production factors and reducing the overuse of fertilisers and pesticides. At the same time, encourage the transfer of land to the green certification farm tilt, carbon emission reduction targets into the land transfer performance appraisal system, the formation of "Green Transfer" incentive mechanism. Through the above measures, land transfer can not only increase agricultural output value, but also achieve "Carbon reduction and efficiency increase" through intensive management.

We should formulate differentiated land transfer policies to adapt to regional resource endowment and development needs. The regional development of China is not balanced, needs to adjust measures to local conditions, design differentiated land transfer policy framework. For example, the eastern region has developed an agricultural economy and strong technological innovation ability, and the policy should focus on the deep integration of land transfer and green technology. At the same time, through the carbon trading market mechanism, agricultural carbon emission reduction can be transformed into economic benefits and attract social capital to participate. As a major grain producing area, northeast China should focus on "Stabilizing production and increasing efficiency", and take grain production increase as the top priority of land transfer performance investigation. In addition, it is necessary to establish inter-regional coordination mechanisms, such as technology transfer from the east to the west and cross-regional carbon compensation mechanisms, so as to promote the balanced improvement of national agricultural carbon productivity. Through differentiated policy design, land transfer can adapt to local actual needs, finally, a multi-level and sustainable agricultural green and low-carbon development system will be constructed.

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