DOI: 10.53469/jgebf.2026.08(03).08

High-standard Farmland Construction and Agricultural Green Low-carbon Transition: Impact Relationship and Mechanism Path Analysis

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Abstract: ***In order to clarify the mechanism of the role of high-standard farmland construction on the green and low-carbon transformation of agriculture, this study explores the impact of high-standard farmland construction on the green and low-carbon transformation of agriculture and its possible transmission paths based on panel data from 31 provinces using a two-way fixed-effects panel model as well as the super-efficient SBM-GML model that includes undesired outputs. The results show that: 1) the construction of high-standard farmland can significantly promote the green and low-carbon transformation of agriculture, and the conclusion still holds after a series of robustness tests; 2) the results of the mechanism test show that the construction of high-standard farmland mainly helps the green and low-carbon transformation of agriculture by improving the quality of land resources and promoting the use of agricultural socialized services; the scale operation of agriculture plays a positive moderating role in the process of the construction of high-standard farmland to help the green and low-carbon transformation of agriculture; and the scale operation of agriculture plays a positive moderating role in the process of the construction of high-standard farmland to help the green and low-carbon transformation of agriculture. 3) [] Heterogeneity analysis found that the construction of high-standard farmland has a significant positive impact on the eastern part of China, the main grain-producing areas and the main non-grain-producing areas, while the impact on the central and western parts of the country is not obvious. Accordingly, we put forward policy recommendations such as strengthening inputs and policy support for high-standard farmland construction, continuously promoting the use of socialized services and large-scale operation, implementing regional differentiation strategies for different regions, and focusing on improving the construction process in the central and western regions.***

Keywords: High-standard farmland, Green and low-carbon, Improvement of cultivated land quality, Agricultural socialization services.

1. Introduction

Green and low-carbon development is an important topic of global concern. The report of the 20th National Congress of the Communist Party of China proposed to adhere to the green and low-carbon development of agriculture and practice the development concept that green mountains and clear waters are invaluable assets. In 2021, the Ministry of Agriculture and Rural Affairs jointly issued the "14th Five-Year Plan for Green Development of Agriculture in China", which clarified the overall requirements for green development of agriculture during the "14th Five-Year Plan" period. Since the reform and opening up, China's agriculture has developed rapidly. The extensive agricultural production mode that previously pursued "quantity" has brought about a serious ecological and environmental crisis [1], forcing the transformation of agriculture towards green and intensive development [2]. The green transformation of agriculture that China is currently promoting has shown a synergistic effect on carbon emission reduction [3]. Agriculture is not only an important source of greenhouse gas emissions, but also a huge carbon sink system [4]. In order to achieve the dual carbon goals, emission reduction and carbon sequestration are particularly important [5]. Scholars' research on the green and low-carbon development of agriculture is not limited to the agricultural perspective, but also extends the research boundaries to the fields of financial instruments and policy implementation. Some scholars have found from an empirical perspective that the synergistic effect of scale operation and technological progress jointly promotes the low-carbon and green development of agriculture [6]. In the long run, the green total factor productivity of agriculture has a significant promoting effect on the green and low-carbon transformation of agriculture [7]. Digitalization [8], agricultural production trusteeship [9], and digital inclusive finance [10] also play a significant role in the green and low-carbon transformation of agriculture. At the same time, the lack of sound incentive and constraint mechanisms for factor input, scientific and technological research and development, and green development is an obstacle to the green development of agriculture under the "dual carbon" strategy [11].

The report of the 20th CPC National Congress pointed out that the foundation of national food security should be consolidated in all aspects, and higher requirements should be put forward for how to ensure food security in the new era. The construction of high-standard farmland is a key measure to stabilize and improve grain production capacity and safeguard national food security, and an effective means to promote sustainable agricultural development [12]. By the end of 2022, a total of 66.6667 million hm2 of high-standard farmland had been built nationwide, ensuring a grain production capacity of more than 500 billion kg [13]. Regarding the relationship between the high-standard farmland policy and the green and low-carbon development of agriculture, it was found that the construction of high-standard basic farmland has promoted the reduction of fertilizer use by expanding the scale of cultivated land and improving the horizontal and vertical division of labor in agriculture [14], and has a continuous inhibitory effect on agricultural carbon emissions [15] and agricultural non-point source pollution [16], which can reduce the average amount of pesticide input per mu of rice farmers by 22.12% [17]. In the calculation system of green total factor productivity in agriculture, carbon emissions from pesticides and fertilizers and agricultural non-point source pollution are important sources of undesirable outputs. By reducing these undesirable outputs, the green total factor productivity of agriculture can be effectively improved, and the green development of agriculture can be promoted. The construction of high-standard farmland has improved the total factor productivity of agriculture by improving the agricultural production environment [18], promoting labor transfer and adjusting the planting structure [19], and has promoted the green development of agriculture by driving agricultural production services [20].

While scholars have conducted substantial and beneficial research, there are still areas for further exploration. First, many scholars have focused on the impact of high-standard farmland construction on food security, neglecting the environmental benefits of such projects. Therefore, is it possible for the implementation of high-standard farmland projects to promote green and low-carbon agricultural development? Second, the mechanisms and transmission pathways by which high-standard farmland contributes to green and low-carbon agricultural development need further investigation. Most scholars have explored single impact pathways on green and low-carbon agricultural development, with few discussing the roles of arable land quality and agricultural services in the green and low-carbon transformation of agriculture, or whether large-scale agricultural operations play a moderating role in the process of high-standard farmland construction and green and low-carbon transformation. Therefore, this paper’s marginal contributions are: first, linking the nationally prioritized high-standard farmland construction with the green and low-carbon transformation of agriculture, exploring whether high-standard farmland construction, while ensuring national food security, also drives green and low-carbon agricultural development; and second, exploring the effects of multiple mechanisms, including arable land quality, agricultural socialized services, and large-scale operations, on the relationship between high-standard farmland construction and the green and low-carbon transformation of agriculture.

2. Theoretical Analysis and Research Framework

2.1 The Green and Low-Carbon Development Logic of High-Standard Farmland Construction

Ecological economics theory emphasizes the unity of ecological benefits and economic benefits to ensure the sustainability of agricultural development. High-standard farmland construction is a series of policy measures taken by the government to improve farmland quality and agricultural production efficiency, ensure food security and promote agricultural modernization. Through the continuous advancement of high-standard farmland construction, not only can food security be guaranteed, but it can also play an important role in ensuring the overall stability of the ecosystem and promoting green agricultural development [21]. The role of high- standard farmland construction in green and low-carbon development is reflected in the improvement of the efficiency of production factor allocation through a series of project constructions. First, the construction projects cover land leveling, construction of field roads, optimization of irrigation and drainage, farmland protection, ecological environment maintenance, etc. The implementation of this series of projects has created conditions for improving the green total factor productivity of agriculture [22]. Secondly, green agricultural development represents a trend in agricultural development, and its efficiency growth can better reflect the trend change [23]. The construction of high-standard farmland can optimize the allocation of production factors [24]. The improvement of resource factor allocation efficiency is an important source of the improvement of total factor productivity [25]. The improvement of green total factor productivity in agriculture reflects the leap in the level of green and low-carbon development in agriculture.

Based on this, hypothesis H1 is proposed: The construction of high-standard farmland helps to achieve the green and low-carbon transformation of agriculture.

2.2 Green and Low-Carbon Development Mechanism of High-Standard Farmland Construction

China’s arable land resources have poor natural endowment and have long been fragmented. The high-standard farmland construction policy has effectively achieved land leveling and concentrated management through projects such as consolidating small fields into large fields, turning fragmented fields into large fields, and land consolidation, which has greatly reduced the degree of fragmentation of arable land and formed a beneficial pattern of land expansion [12]. On the other hand, the implementation of land consolidation projects has enhanced the soil and fertilizer retention capacity of farmland, provided the necessary nutrients and water for crop growth, solved the problem of soil fertility decline, improved the soil’s water retention and buffering capacity, and ultimately improved the quality of arable land.

The construction of high-standard farmland has laid the foundation for the development of agricultural service industry by promoting the concentrated and contiguous management of land. Farmers who build high-standard farmland will increase their adoption rate of agricultural socialized services [26]. As a practical way and policy guide for small farmers to integrate into modern agriculture, agricultural socialized services play an important role in improving the green total factor productivity of agriculture and promoting the green transformation of agriculture and rural areas [27]. Collective action theory believes that certain problems can be solved more effectively through collective action. In the green development of agriculture, socialized service organizations can take unified environmental protection measures, such as unified fertilization and unified pest and disease control, to reduce the input of agricultural chemicals and improve agricultural production efficiency [28].

Based on this, hypothesis H2 is proposed: the construction of high-standard farmland can help the green and low-carbon transformation of agriculture by improving the quality of land elements and increasing the use of agricultural socialized services.

According to the theory of economies of scale, economies of scale can bring economies of scale, optimize the allocation of factors, and reduce production costs. The construction of high-standard farmland has effectively solved the problems of farmland fragmentation and decentralization through a series of supporting measures such as improving land quality and increasing the use of socialized services [29], thereby expanding the scale of farmland operation to an appropriate level [30]. The construction of high-standard farmland can promote the flow of factors, and large-scale farmers with advantages in farming may expand their agricultural operation scale by transferring farmland [31]. The transfer of farmland can promote the concentration of production, thereby promoting agricultural carbon emission reduction and affecting the green development of agriculture [32].

Based on this, Hypothesis H3 is proposed: Large-scale operations play a positive regulatory role in the construction of high-standard farmland and the green and low-carbon transformation of agriculture. The theoretical framework is shown in Figure 1.

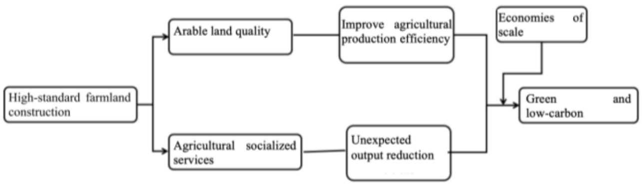

Figure 1: Theoretical analysis framework

3. Variable Definition and Model Building

3.1 Variable Definition

1) Explained variable: Green and low-carbon transformation of agriculture. The agricultural production process is an agricultural production activity in which two kinds of outputs, expected output and unexpected output, are produced by inputting production factors [33]. As an important part of the green economy, the green and low-carbon transformation of agriculture refers to the transformation of the traditional extensive agricultural production mode to an intensive agricultural production mode under the guidance of the concept of green and low-carbon development, which reduces the input and consumption of agricultural production factors, reduces agricultural carbon emissions and agricultural non-point source pollution, and increases agricultural economic output, that is, increases agricultural green total factor productivity [34]. Therefore, this paper uses agricultural green total factor productivity, which includes unexpected output, to measure the level of green and low-carbon development of agriculture. Based on the availability of data, agricultural carbon emissions focus on the planting industry. Referring to the research of Tian Yun et al., carbon emission coefficients are used to calculate the total carbon emissions generated in the six processes of pesticide, fertilizer, agricultural film, agricultural diesel input, agricultural tillage and irrigation [35].

Table 1: Indicators for Measuring Green Total Factor Productivity in Agriculture

Indicator Categories	Indicator Name	Variable indicators	Indicator Explanation
Input indicators	Labor input	Agricultural workers (10,000 people)	This refers to rural residents aged 16 and above who actually participate in production and business activities and receive income in kind or in monetary form.
	Land Investment	Crop planting area (thousand hm^2)	The area of sown or transplanted crops on all land.
	Mechanical input	Total power of agricultural machinery (10,000 kW)	The sum of the rated power of all agricultural machinery
	Water input	Effective irrigated area (thousand hm^2)	The area of arable land that can be irrigated normally.
	fertilizer input	Pure fertilizer content (10,000 tons)	This refers to the quantities of nitrogen fertilizer, phosphorus fertilizer, and potassium fertilizer after conversion based on their respective 100% nitrogen, phosphorus pentoxide, and potassium oxide content.
	pesticide input	Pesticide usage (in ten thousand tons)	The amount of pesticides used in agriculture within a year
	Agricultural film input	Agricultural film usage (10,000 tons)	The amount of plastic film used in agriculture within one year
	Energy input	Agricultural diesel consumption (10,000 tons)	The amount of diesel fuel used in agriculture within one year
Output indicators	Expected output	Total agricultural output value (100 million yuan)	The total amount of all agricultural products expressed in monetary terms within a year
	Unexpected output	Agricultural carbon emissions (10,000 tons)	The result is calculated by summing the products of the six types of emission sources and their corresponding carbon emission coefficients.

2) Core Explanatory Variable: Construction Status of High-Standard Farmland. The construction of high-standard farmland is being implemented and promoted in all provinces. This paper uses the proportion of land consolidation area, i.e., the ratio of (area of low- and medium-yield farmland renovated + area of high-standard farmland constructed) / total cultivated land area, to represent this. For data from 2018 to 2020, the data on the annual high-standard farmland construction task arrangements published by the Ministry of Agriculture and Rural Affairs for each province is used as a reference. This task arrangement data is formulated by the provincial agricultural and rural affairs departments based on the resource endowment and previous construction status of each province, and is adjusted annually according to the previous year's completion status. Furthermore, the report shows that the completed construction area and the area of the assigned task are almost identical.

3) Mechanism variables: Based on the theoretical analysis above, the mechanism variables in this paper include the improvement of arable land resources, agricultural social services, and large-scale operation.

4) Control variables: Referring to scholarly research, agricultural industrial structure, rural economic development level, per capita GDP, disaster rate, number of agricultural workers, and level of fiscal support for agriculture are the control variables in this paper. Table 2 below shows the descriptive statistics of the variables.

Table 2: Descriptive statistics of all the variables

Variable categories	Variable name	Variable definition	mean	Standard deviation	Minimum value	Maximum value
Explanatory variable	Green and low-carbon agriculture	Super-efficient SBM-GML model	2.12	1.38	0.60	7.88
Explanatory variables	Land consolidation area ratio	(Area of transformed low- and medium-yield farmland + area of high-standard farmland) / Area of cultivated land	0.43	0.27	0.09	1.57
Mechanism variables	Improved quality of arable land	Natural logarithm of the area treated for soil erosion	7.70	1.38	2.72	9.49
	Labor allocation optimization	Take the logarithm of the number of grain-growing laborers	5.18	1.23	2.17	6.88
	Intensive farmland irrigation (%)	Effective irrigated area / Crop sown area	0.44	0.19	0.18	1.03
	level of mechanization	Total power of agricultural machinery / sown area of crops	0.65	0.33	0.25	2.08
	Agricultural socialized services	Agricultural, forestry, animal husbandry and fishery service industry output value / crop sown area	0.26	0.20	0.003	0.10
	Large-scale operation (%)	Grain sown area / Crop sown area	0.65	0.13	0.37	0.96
control variables	Agricultural fiscal support level (in 100 million yuan)	Expenditure on agriculture, forestry and water affairs	407.38	289.33	17.74	1127.88
	Disaster impact rate (%)	Affected area / Crop planting area	0.15	0.30	0.008	2.20
	Per capita GDP (yuan / person)	per capita GDP	45547.43	27166.55	8970.00	140211.2
	Number of people employed in agriculture (in ten thousand)	Number of people employed in agriculture	835.80	614.66	36.3 5	2527.00
	Rural economic development level	Total agricultural output / rural population	0.45	0.21	0.13	1.11
	Industrial structure (%)	Gross output of primary industry / Gross regional output	0.1	0.05	0.003	1.26

3.2 Model Setting

3.2.1 Calculation of green total factor productivity in agriculture

The GML index under the super-efficiency SBM function containing undesirable outputs was selected to measure the green total factor productivity of agriculture in China from 2006 to 2020. Compared with the traditional DEA method, the advantages of the super-efficiency SBM are: first, it makes the input and output indicators dimensionless and eliminates the influence on the efficiency value; second, it can effectively solve the problem of variable slackness; and third, it fully considers the problem of undesirable outputs. Referring to the research of Guo Haihong et al. [36], the input and output indicators are selected as shown in Table 1.

According to the super-efficiency model proposed by TONE [37], it is assumed that there are k production decision-making units, n input factors x, and m expected outputs y_g and i unexpected outputs y_b, where λ_j represents the weight of each decision-making unit in constructing the production reference set, sn^-, sm^g and si^b are the slack variables of input, expected output and unexpected output respectively; ρ represents the efficiency value. The super-efficiency SBM model that includes unexpected output can be expressed as equation (1):

$$min\,\rho = \frac{1+\frac{1}{N}\sum_{n=1}^{N}\frac{s_i^-}{x_{nk}}}{1-\frac{1}{M+I}\left(\sum_{m=1}^{M}\frac{s_m^g}{y_{mk}^g}+\sum_{i=1}^{I}\frac{s_i^b}{y_{ik}^b}\right)}$$

$$\text{s.t.}\begin{cases}\sum_{j=1,j\neq k}^{K} x_{nj}\,\lambda_j - s_n^- \le x_{nk}, n=1,2,\dots,N \\ \sum_{j=1,j\neq k}^{K} y_{mj}\,\lambda_j + s_m^g \ge y_{mk}^g, m=1,2,\dots,M \\ \sum_{j=1,j\neq k}^{K} y_{ij}\,\lambda_j - s_i^b \le y_{ij}^b i=1,2,\dots,I \\ \lambda\ge 0, s^g\ge 0, s^b\ge 0, s^-\ge 0, k=1,2,\dots,K\end{cases} \quad (1)$$

A global Malmquist-Luenberger (GML) index is constructed based on a global directional SBM distance function that includes undesirable outputs. The GML index is both comparable and can effectively avoid situations where there may be no solution. Referring to OH's research [38], this paper expresses the GML index as Equation (2):

$$GML^{t,t+1}(x^t,y^t,b^t;x^{t+1},y^{t+1},b^{t+1}) = \frac{1+D^G(x^t,y^t,b^t)}{1+D^G(x^{t+1},y^{t+1},b^{t+1})} \quad (2)$$

Where $GML^{t,t+1}$ represents the green total factor productivity of agriculture from period t to period t+1, and x, y, and b represent input, expected output, and unexpected output, respectively.

3.2.2 Benchmark Regression Model

In order to examine the direct effect of high-standard farmland construction on the green and low-carbon transformation of agriculture, a baseline regression model was set up. Since the high-standard farmland construction policy is continuously promoted and each province has high-standard farmland construction projects, a two-way fixed effects panel model was adopted based on Jiang Ting's research [39]. The model is expressed as equation (3):

$$G_{it} = \alpha + \beta H_{it} + \lambda X_{it} + \eta_i + \gamma_t + \varepsilon_{it} \quad (3)$$

Where i represents the province, t represents the year, G_{it} represents the green total factor productivity of province i in year t, H represents the proportion of land consolidation area, X represents a series of control variables, η_i represents the regional fixed effect, γ_t represents the time fixed effect, ε_{it} is the random error term, and α, β, and λ are the parameters to be estimated.

3.2.3 Mechanism testing model

3.3.1 Mediation effect model. In order to explore whether the allocation of production factors and agricultural socialized services play a mechanistic role in promoting the green and low-carbon transformation of agriculture through the construction of high-standard farmland, a mechanism test model was established. This paper adopts the two-step mediation effect method [40] to directly examine the influence of high-standard farmland on the mechanism variable. Based on equation (3), equation (4) is added. The mediation test model is expressed as equation (4):

$$M_{it} = \alpha + \beta H_{it} + \lambda X_{it} + \eta_i + \gamma_t + \varepsilon_{it} \quad (4)$$

Where M represents the variables of arable land quality and agricultural socialized service mechanism, the rest are the same as in the above formula.

3.3.2 Moderating Effect Model. To verify whether the process of promoting green and low-carbon agricultural development through the construction of high-standard farmland is affected by large-scale operations, the following moderating effect model is established, expressed as equation (5):

$$G_{it} = \alpha + \beta H_{it} + \rho A_{it} + \sigma H_{it} * A_{it} + \lambda X_{it} + \eta_i + \gamma_t + \varepsilon_{it} \quad (5)$$

Where A_{it} represents large-scale agricultural operations, $H_{it} * A_{it}$ is the interaction term between high-standard farmland and large-scale operations, ρ and σ the sum is the coefficient to be estimated. The rest is the same as in equation (3).

3.3 Data Sources

This paper selects panel data from 31 provinces in China from 2006 to 2020. Data on high-standard farmland are obtained from the annual *China Fiscal Yearbook*. Data on agricultural green total factor productivity, agricultural carbon emissions, and related mechanism variables are obtained from the annual *China Rural Statistical Yearbook*, *China Agricultural Yearbook*, and the National Bureau of Statistics, etc. Missing data were supplemented using linear interpolation. To avoid the influence of extreme values, all data were shortened at the 1% and 99th percentiles to enhance reliability and robustness.

4. Empirical Results and Analysis

4.1 The Impact of High-standard Farmland Construction on the Green and Low-carbon Transformation of Agriculture

To examine the direct effect of high-standard farmland on the green and low-carbon transformation of agriculture, a baseline regression was performed on the data. The Hausman test results showed that the two-way fixed-effects panel model was more reasonable in this study. Table 3 reports the baseline regression results of high-standard farmland on the green and low-carbon development of agriculture. Columns (1) to (4) report the regression results with the gradual addition of different control variables. R^2 *shows* that the model fits well, and with the addition of control variables, the impact of high-standard farmland construction on the green and low-carbon development of agriculture is always positively significant at the 1% significance level. This indicates that high-standard farmland construction has a significant positive impact on the green and low-carbon development of agriculture, and the results are relatively robust.

The above results indicate that the high-standard farmland construction model not only focuses on farmland yield and stability but also emphasizes ecological benefits and sustainability. From an input-output perspective, the green and low-carbon development logic of high-standard farmland construction lies in the following aspects: First, reduced input. High-standard farmland construction rationally lays out and optimizes the planting structure, reducing the use of chemical fertilizers and pesticides, improving utilization efficiency, and reducing undesirable outputs such as agricultural carbon emissions and non-point source pollution; at the same time, the implementation of precision irrigation effectively avoids the waste of water resources. Second, high-efficiency output. Through land leveling, irrigation and drainage, field roads, and other infrastructure construction, high-standard farmland construction improves farmland production conditions, increasing the proportion of large-scale operations by 30% to 40% compared to ordinary farmland, facilitating the entry of mechanized equipment and socialized service organizations, and improving the output efficiency and stability of farmland.

Table 3: Benchmark regression results of high standard farmland for green and low carbon development of agriculture

Variable name	(1)	(2)	(3)	(4)
High-standard farmland construction	1.272 *** (0.432)	1.593 *** (0.492)	1.485 *** (0.472)	2.258 *** (0.455)
Agricultural fiscal support level	0.397 *** (0.0366)	0.385 *** (0.0361)	0.253 *** (0.0417)	0.257 *** (0.0392)
Disaster rate		-0.924 *** (0.198)	-0.047(0.238)	-0.333(0.226)
per capita GDP		0.156 *** (0.0480)	0.149 *** (0.0458)	0.157 *** (0.0429)
Number of agricultural workers			-0.143 *** (0.0275)	-0.171 *** (0.0261)
Rural economic development level			2.654 *** (0.541)	2.548 *** (0.508)
Industrial structure				14.80 *** (1.957)
constant term	0.381 ** (0.187)	0.0532 (0.193)	0.794 ** (0.383)	-1.033 ** (0.433)
control variables	YES	YES	YES	YES
Regional fixed effects	YES	YES	YES	YES
Time fixed effect	YES	YES	YES	YES
N	465	465	465	465
R^2	0.729	0.745	0.770	0.798

*Note: * * *, * *, * represent significance levels of 1%, 5%, and 10%, respectively; the numbers in parentheses are standard errors.*

4.2 Robustness Test of the Impact of High-standard Farmland Construction on the Green and Low-carbon Transformation of Agriculture

To verify the robustness of the regression results, the following methods were used for robustness testing. The first method was to change the explained variable. Since the results of high-standard farmland construction may have a time lag, the regression was performed using the one-period lag of the explained variable. The results are shown in column (1) of Table 4. Column (1) of Table 4 shows that the results are still significant at the 1% significance level, indicating that high-standard farmland construction still has a significant positive impact on the green development of agriculture. The second method was to change the sample interval. Since high-standard farmland construction entered the standardized implementation stage in 2011, the regression was performed only on the data from 2011 to 2020. Column (2) of Table 4 shows that the results are also significant at the 1% significance level. Furthermore, the regression coefficients show that the impact on the green transformation of agriculture was more significant after the standardized implementation began in 2011. The third method was to change the regression model and use the least squares method for regression. Column (3) of Table 4 shows that the results have a significant positive impact. The fourth type is endogeneity treatment. The implementation of high-standard farmland construction projects led by the government has strong exogenous characteristics, so there is almost no need to consider endogeneity issues [15]. In order to enhance the robustness of the results, the two-period lag of the explained variable is used as the instrumental variable, and the GMM model, which can effectively control endogeneity issues, is used for regression. The results are shown in column (4) of Table 4. The regression results show that they are significant at the 1% significance level. In summary, the results of the baseline regression have strong robustness. Based on this, hypothesis H1 is verified.

Table 4: Robustness test results

Variable name	(1) The explained variable is lagged by one period	(2) Change the sample interval	(3) OLS regression	(4) GMM estimation
High-standard farmland is one phase behind	2.019 *** (0.521)			
High-standard farmland construction		2.793 *** (0.661)	1.151 *** (0.308)	0.842 *** (0.296)
constant term	-1.172 ** (0.475)	-4.102 *** (0.949)	-0.001(0.191)	-0.224(0.234)
control variables	YES	YES	YES	YES
Regional fixed effects	YES	YES	NO	NO
Time fixed effect	YES	YES	NO	NO
N	434.000	310.000	465.000	403.000
R^2	0.756	0.655	0.668	0.643

*Note: * * *, * *, * represent significance levels of 1%, 5%, and 10%, respectively; the numbers in parentheses are standard errors.*

4.3 Regional Heterogeneity Analysis of the Impact of High-Standard Farmland Construction on the Green and Low-Carbon Transformation of Agriculture

To explore the differentiated effects of policy implementation and to propose targeted policy recommendations, heterogeneity tests were conducted on different regions according to natural geographical zoning and grain functional zoning.

4.3.1 Natural geographical location dimension

Based on geographical location, China can be divided into eastern, central, and western regions. There are certain differences in economic development level and natural resource endowment among different regions, but the differences within the regions are relatively small. Columns (1) to (3) of Table 5 report the regression results for the eastern, central, and western regions, respectively. The results show that the construction of high-standard farmland has a significant positive impact on the eastern region, with the results being significant at the 5% significance level. The impact on the central and western regions is not obvious. The reasons can be analyzed from three aspects: political, economic, and natural factors. From a political perspective, the eastern coastal areas have always been the focus of China’s development and received more policy support and preferential treatment in the early years. From an economic perspective, the eastern region is relatively developed and has relatively strong financial and technical support, enabling it to invest more funds in the construction of high-standard farmland. However, many areas in the central and western regions may have weak infrastructure, making it inconvenient to carry out high-standard farmland construction projects. From a natural perspective, the eastern region has a mild and humid climate, suitable for the growth of various crops. The central and western regions are limited by land conditions and have relatively simple land use methods, and may face problems such as drought and salinization, which limits the effectiveness of high-standard farmland construction.

Table 5: Results of heterogeneity analysis

Variable name	(1) Eastern region	(2) Central region	(3) Western region	(4) Major grain-producing areas	(5) Non-grain-producing areas
High-standard farmland construction	1.413 ** (0.624)	1.228 (2.109)	-1.782(1.334)	3.328 *** (1.165)	1.990 *** (0.316)
constant term	-0.683(1.089)	0.359 (1.349)	2.799 *** (0.842)	0.439 (0.831)	-2.179 *** (0.443)
control variables	YES	YES	YES	YES	YES
Regional fixed effects	YES	YES	YES	YES	YES
Time fixed effect	YES	YES	YES	YES	YES
N	165.000	120.000	180,000	195,000	270,000
R^2	0.820	0.821	0.781	0.773	0.803

*Note: * * *, * *, * represent significance levels of 1%, 5%, and 10%, respectively; the numbers in parentheses are standard errors.*

4.3.2 Grain functional zoning dimension

As early as 2001, in order to adapt to the changes in the new grain production and circulation pattern, the state designated 13 major grain-producing areas [The main grain-producing areas include 13 provinces and autonomous regions: Heilongjiang, Jilin, Liaoning, Inner Mongolia, Hebei, Henan, Shandong, Jiangsu, Anhui, Jiangxi, Hubei, Hunan, and Sichuan.], and the grain output of these 13 major grain-producing areas accounted for more than 75% of the total national output [5]. Columns (4) to (5) of Table 5 report the regression results of major grain-producing areas and non-major grain-producing areas respectively. It can be seen from the results that the construction of high-standard farmland has a significant positive impact on both major grain-producing areas and non-major grain-producing areas. The results are all significant at the 1% significance level, and the regression coefficient of major grain-producing areas is greater than that of non-major grain-producing areas, indicating that the construction of high-standard farmland has a greater impact on major grain-producing areas than on non-major grain-producing areas. On the one hand, major grain-producing areas are themselves major grain-producing provinces, with relatively superior land resources and well-developed infrastructure, which is more conducive to the promotion of high-standard farmland construction projects. On the other hand, major grain-producing areas are themselves important pilot areas for the implementation of high-standard farmland construction, and enjoy more policy support for agricultural development because of their important position in grain production.

4.4 Examination of the Mediating Mechanism of Production Factor Allocation and Agricultural Socialized Services

The empirical analysis above has confirmed that the construction of high-standard farmland has a significant positive impact on the green and low-carbon development of agriculture. This section verifies the intermediate mechanism. Referring to the research conclusions of Jiang Ting, Qian Long and others, this paper adopts the two-step method of mediating effect to directly test the impact of the construction of high-standard farmland on the theoretical hypothesis [39, 40].

Table 6 shows the regression results of the mechanism of action. Column (1) shows that the construction of high-standard farmland has a significant positive impact on land quality optimization, indicating that the soil and water conservation in the high-standard farmland construction project has achieved significant results. Through soil improvement, irrigation and drainage system improvement, and environmental protection measures such as farmland shelterbelts, the quality of cultivated land has been significantly improved. Column (2) shows that the regression coefficient of high-standard farmland on agricultural socialized services is significantly positive, confirming that after the construction of high-standard farmland, agricultural production conditions have been significantly improved. The emergence of large-scale operations and specialized division of labor has spurred demand for agricultural socialized services from small farmers. Agricultural socialized service providers utilize their own advantages and resources to provide comprehensive services such as cultivation, harvesting, and management for high-standard farmland, improving agricultural production efficiency and land utilization, and promoting the green and low-carbon transformation of agriculture. Therefore, hypothesis H2 is validated.

Table 6: Regression results of the test of intermediation mechanism of production factor allocation and agricultural socialization services

Variable name	(1) Improvement of arable land quality	(2) Agricultural socialized services
High-standard farmland construction	1.209 *** (0.254)	0.034 *** (0.005)
constant term	7.437 *** (0.236)	0.002 (0.005)
control variables	YES	YES
Regional fixed effects	YES	YES
Time fixed effect	YES	YES
N	451.000	465.000
R^2	0.344	0.781

*Note: * * *, * *, * represent significance levels of 1%, 5%, and 10%, respectively; the numbers in parentheses are standard errors.*

4.5 Examination of the Regulatory Mechanism of Economies of Scale

The previous analysis suggested that large-scale farming might have a moderating effect on the relationship between high-standard farmland construction and green and low-carbon transformation. To verify this hypothesis, a moderating effect model was constructed for regression analysis, and the results are shown in Table 7. From the results of the interaction terms in column (2) of Table 7, it can be seen that when large-scale farming and high-standard farmland construction occur simultaneously, they have a significant positive impact on the green and low-carbon transformation of agriculture. This indicates that large-scale farming plays a significant positive moderating role in promoting the green and low-carbon transformation of agriculture through high-standard farmland. The reasons are as follows: First, large-scale farming can optimize resource allocation, meaning more resources can be invested in environmentally friendly technologies and management practices. Second, from a cost-benefit perspective, large-scale farming can achieve economies of scale, meaning that as the production scale expands, the cost per unit of product decreases. This motivates farmers to adopt green and low-carbon technologies because the cost of the technology can be shared, and the improved cost-benefit also makes farmers more willing to invest in long-term sustainable agricultural practices. At the same time, demonstration and peer effects are easily generated among farmers; successful large-scale farming cases can inspire other farmers to follow suit, thereby accelerating the diffusion of green and low-carbon technologies throughout the agricultural sector. Therefore, hypothesis H3 is verified.

Table 7: Regression results of the regulation mechanism of scale operation

Variable name	(1) Green and low-carbon transformation	(2) Green and low-carbon transformation
High-standard farmland construction	2.088 *** (0.450)	
High-standard farmland construction * economies of scale		11.576 ** (5.078)
constant term	-0.961 ** (0.427)	-0.156(0.381)
control variables	YES	YES
Regional fixed effects	YES	YES
Time fixed effect	YES	YES
N	465.000	465.000
R^2	0.774	0.775

*Note: * * *, * *, * represent significance levels of 1%, 5%, and 10%, respectively; the numbers in parentheses are standard errors.*

5. Conclusions and Policy Recommendations

5.1 Conclusion

This study, based on panel data from 31 provinces (excluding Hong Kong, Macao, and Taiwan), used a two-way fixed-effects panel model and an ultra-efficient SBM-GML model incorporating undesirable outputs to explore the impact of high-standard farmland construction on the green and low-carbon transformation of agriculture and its possible transmission pathways. The following conclusions were drawn:

1) The baseline regression results show that the construction of high-standard farmland has a significant promoting effect on the green and low-carbon transformation of agriculture. This conclusion still holds after a series of robustness tests,

including replacing the explained variable, changing the sample interval, changing the regression method, and handling endogeneity.

2) The mechanism test results show that in the process of high-standard farmland construction helping agriculture achieve green and low-carbon transformation, the quality of arable land resources and agricultural socialized services play an intermediary role; and large-scale operation plays a positive regulatory role.

3) Heterogeneity analysis revealed that, according to geographical location, the construction of high-standard farmland has a significant positive impact on eastern China, while the impact on central and western China is not obvious; according to grain function zoning, the construction of high-standard farmland has a significant positive impact on both major grain-producing areas and non-major grain-producing areas, but the effect is more obvious on major grain-producing areas.

5.2 Policy Recommendations

Ensuring national food security and promoting the green transformation of agriculture are two major issues facing agriculture today. The construction of high-standard farmland is an important measure to ensure national food security and has had a positive impact on the green transformation of agriculture during its implementation. Based on this, the following policy recommendations are proposed.

1) Continue to strengthen investment and policy support for the construction of high-standard farmland. To further promote the green and low-carbon transformation of agriculture, the government should continue to increase financial investment in the construction of high-standard farmland and introduce more supporting policies and measures. Firstly, a special fund can be established to guarantee the funding needs for the construction of high-standard farmland, and financial institutions can be encouraged to provide low-interest loans to reduce the financial pressure on farmers and cooperatives. Secondly, a sound regulatory mechanism should be established to ensure the transparency and efficiency of fund use and prevent resource waste and misappropriation.

2) Continuously promote the use of socialized services and large-scale operations. Given the importance of socialized services and large-scale agricultural operations in driving the green and low-carbon transformation of agriculture, the government needs to take measures to further promote these practices. On the one hand, the government should actively guide and support the construction of an agricultural socialized service system, including agricultural technology extension, agricultural machinery services, and agricultural input supply, to improve agricultural production efficiency and reduce energy consumption and emissions. On the other hand, farmers should be encouraged to achieve large-scale operations through land transfer, cooperative management, and other means to better leverage the benefits of high-standard farmland and promote the development of green and low-carbon agriculture.
3) Implement a differentiated regional strategy, focusing on accelerating the construction process in the central and western regions. Considering the varying impacts of high-standard farmland construction across different regions, particularly its limited impact on China's central and western regions, it is recommended that the government intensify its efforts to promote high-standard farmland construction in these areas. Firstly, appropriate farmland improvement plans and technical standards should be formulated based on the natural conditions and economic development levels of the central and western regions. Secondly, increased financial investment and policy support should be provided for high-standard farmland construction in the central and western regions to improve its quality and speed. Simultaneously, inter-regional experience exchange and cooperation should be strengthened to promote the dissemination of advanced technologies and management models, thereby achieving balanced and green agricultural development nationwide.

Acknowledgments

Funding: Jiangsu Provincial Postgraduate Scientific Research and Innovation Program Project "A Study on the Impact Mechanism of High-Standard Basic Farmland Construction Policy on the Resilience of my country's Agricultural Economy".

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