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Impacts and Internal Mechanisms of High-Standard Farmland Construction on the Reduction of Agricultural Carbon Emission in China

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Abstract: In response to climate change, the reduction of carbon emissions during agricultural production has garnered increasing global focus. This study takes high-standard farmland construction (HSFC) implemented in 2011 as the standard natural experiment and adopts the continuous differences-in-differences (DID) model to explore the impact and internal mechanism of HSFC on agricultural carbon emissions based on a panel data of 31 provinces, municipalities, and autonomous regions in China from 2003 to 2021. The results show that HSFC can effectively reduce the carbon emissions in agricultural production, and the average annual reduction can reach 53.8%. The effects of HSFC on agriculture carbon emissions could be associated with reducing agricultural fossil energy consumption and reducing agricultural chemical use. Further, the heterogeneity study shows that the carbon reduction effect of HSFC was mainly reflected in non-major grain-producing areas, while there was no significant impact in major grain-producing areas. Policymakers should unswervingly continue to promote HSFC, considering their own economic and geographical conditions. This study can provide valuable information and references for developing countries similar to China to formulate policies on agricultural carbon reduction.

Keywords: high-standard farmland construction; agricultural carbon emissions reduction; agricultural chemical application; heterogeneous effects; continuous differences-in-differences (DID) model

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1. Introduction

The long-term, extensive application of fertilizers and pesticides has become an important guarantee for increasing agricultural production and farmers' incomes. However, behind the development of "high-input-high-yield" agriculture are resource consumption, environmental deterioration and excessive carbon emissions [1,2]. This has serious implications for global climate change and the stability and security of food production systems. With the continuous intensification of climate change, carbon emissions have become a common challenge. Agricultural carbon emissions from production have become a significant source of greenhouse gas (GHG) emissions on a global scale [3]. They are mainly derived from the usage of chemical fertilizers, pesticides, agricultural film, feed production in livestock, and poultry breeding processes along with daily water and electricity consumption in livestock farms [4,5]. It is considered that agricultural production activities account for more than 30% of global man-made GHG emissions, ranking second in the world [6]. Therefore, promoting carbon reduction in agricultural production is an important starting point for the global response to climate change.

High-standard farmland construction (HSFC) involves scientific planning, land reclamation, and infrastructure development to enhance the productivity and sustainability of agricultural land. Its core objectives are optimizing land resource allocation, improving agricultural productivity, ensuring food security, and promoting the harmonious development of agriculture and the environment.

HSFC principles focus on resource conservation and environmental protection, aiming to reduce agriculture's negative ecological impact through land consolidation, soil and water conservation, and ecological restoration. It also emphasizes improving farmland infrastructure, such as irrigation systems, drainage, and roads, to ensure sustainable agricultural production. Additionally, HSFC increases land productivity by applying advanced agricultural technologies and management methods, particularly in grain production. HSFC is widely applied in major grain-producing areas, utilizing precision management, smart irrigation, and fertilization systems to improve resource efficiency, reduce carbon emissions, and enhance farmland ecological quality. HSFC is considered an effective way method in the reduction of agricultural GHG emissions [7]. HSFC can enhance the scale of land management, improve the soil ecosystem service capacity and irrigation/drainage conditions, promote the intensive use of resource factors, and increase the carbon sequestration capacity of the farmland system. These improvements in irrigation and drainage conditions can, in turn, contribute to the reduction in agricultural carbon emissions. They uphold the concept of "ecological priority" and build large-scale contiguous fields by means of "combining small fields with large fields" and "land exchange" [8], aiming to build a farmland with a stable and high yield of crops and convenient field management. China had built 1 billion Chinese mu of high-standard farmland by the end of 2022 and ensured a grain production capacity of over 50 million metric tons. This plays a pivotal role in improving the quality of regional arable land and realizing the scientific matching of carbon emission factors such as fertilizers [9] in order to promote high-quality agricultural development and consolidate the foundation of food security. So, has the quality of China's agricultural ecological environment been effectively improved during the past HSFC process? In the context of high-quality agricultural development, can HSFC effectively promote a reduction in carbon emissions in agricultural production, and what is its internal mechanism? In the new round of China's HSFC, how should we take into account the ecological and economic benefits of agricultural production? These are the questions that need to be answered.

In the academic literature, relevant research on HSFC has primarily focused on two key aspects. First, many scholars have explored the connotation, characteristics, and construction pathways of HSFC [10–12]. It is understood as a system involving large-scale design, green ecological environments, efficient resource utilization, and sustainable comprehensive production capacity [13]. Furthermore, scholars emphasize the importance of improving long-term management, protection, and evaluation mechanisms in the promotion of HSFC. Additionally, lessons can be drawn from the experiences of Japan and South Korea in farmland construction systems to develop a systematic legal and regulatory framework for HSFC [14,15]. Second, some studies have focused on the implementation effects of HSFC policies, particularly regarding their impact on grain yield [16]. HSFC is often viewed as an important approach to enhancing grain production [17,18]. Moreover, certain research has examined the ecological effects of HSFC, highlighting its role in improving total green factor productivity, controlling non-point source pollution, and reducing carbon emissions [19]. However, findings across different studies are not always consistent. These discrepancies may be attributed to variations in sample selection, as some studies have examined the impact of HSFC on farmland transfer. For example, they have found that HSFC increases the likelihood of paid farmland transfers [20].

Second, scholars have measured the scale, intensity, and reduction efficiency of agricultural carbon emissions, and have analyzed their temporal and spatial characteristics from the perspective role of HSFC [21,22]. It was indicated that the total scale of China's agricultural carbon emissions shows a "V-shaped" change on the whole, but after the implementation of the "weight reduction and drug reduction" action, a trend of continuous decline was seen again [23]. In recent years, all provinces in China have shown a certain downward trend in terms of agricultural carbon emission intensity, among which the eastern and central regions show a relatively fast decline rate. Beijing, Tianjin, Jilin, and other regions have the highest comprehensive agricultural carbon emission efficiency, with Shanxi Province having the lowest [24]. Many previous studies also focused on the analysis of influencing factors affecting agricultural carbon emissions, mainly from the aspects of agricultural technology innovation [25], rural finance [5], rural industry integration [26], agricultural land transfer [27], agricultural mechanization [28], urban–rural integration, and labor flow [29]. In addition, the impacts of agriculture-related policies, such as financial support for agriculture [30], agricultural credit subsidies [31], and policies for major grain-producing areas [32], have also been explored.

In summary, the existing research can provide scientific support for carbon sequestration and emission reduction in agriculture and lays a solid foundation for in-depth study. However, research concerning farmland, as the fundamental carrier of agricultural carbon source and sink, is still relatively low in the academic community, especially on the effect of HSFC on the reduction in agricultural carbon emissions. Therefore, this study takes China's HSFC policy as a quasi-natural experiment and combines relevant panel data from 31 provinces, municipalities, and autonomous regions in China from 2003 to 2021 to scientifically evaluate the reduction effect of HSFC on agricultural carbon emissions, and performs an in-depth analysis deciphering the mechanisms of action and the heterogeneity of policy effects.

2. Policy Background and Research Hypotheses

HSFC primarily refers to the regulation of arable land through farmland leveling and the development of field infrastructure, complemented by the application and promotion of agricultural science and technology. Its goal is to create a well-organized agricultural system that includes field formation, forest networks, irrigation channels, road connections, drought irrigation, and flood drainage. In 2011, with the implementation of the National Land Regulation Plan (2011–2015) and the Standards for the Construction of High-Standard Basic Farmland (Trial), China's HSFC officially entered the standard implementation phase. The construction content in the table refers to the core aspects of land remediation in HSFC, as outlined in China's "Standards for the Construction of High-standard Basic Farmland (Trial)". These core elements can be summarized into three areas: field infrastructure construction, soil fertility engineering, and agricultural technology development. Based on these three core areas, targeted policy measures have been formulated. This study examines the impact of these three key areas on agricultural carbon emission reduction, as summarized in Table 1.

HSFC has an impact on the reduction in agricultural carbon emissions by affecting fossil energy consumption, which is mainly reflected in the use of agricultural machinery. On the one hand, field infrastructure construction further meets the requirements of agricultural machinery field operations on road transportation, which helps to improve the agricultural mechanization level and increase fossil energy consumption, thus resulting in an increase in agricultural carbon emissions [28,33]. On the other hand, HSFC adopts land integration measures such as "converting small fields into large fields" and "breaking the whole into pieces" through the implementation of land capacity engineering [8], reducing the degree of fragmentation of arable land and realizing its large-scale management, which is conducive to improving the agricultural machinery operation efficiency and reducing fossil energy use to a certain extent [34]. In addition, agricultural science and technology construction further improves the agricultural machinery operation efficiency and reduces the fossil energy consumption level, thus having a positive impact on the reduction in carbon emissions in agriculture [35]. Thus, HSFC has both positive and negative impacts on agricultural fossil energy consumption, and the expected effects are uncertain.

Table 1. Main content and objectives of high-standard farmland construction.

Construction Content	Main Measures	Construction Objectives
Field Infrastructure Construction	Field network construction; canal network construction; road network construction; electric grid construction, etc.	Enhancing agricultural disaster resistance and mechanized cultivation capability
Land Quality Engineering	Soil improvement; land leveling; land fertilization, etc.	Improving farmland quality and agricultural production capacity
Agricultural Technology Development	Breeding of fine varieties, promotion of advanced; technologies, establishment of agricultural Internet of Things (IoT) technology, etc.	Enhancing the agricultural capacity for application of technology

HSFC affects the use of agricultural chemicals, which in turn influences agricultural carbon emissions. Firstly, as mentioned above, HSFC promotes the centralized and continuous management of arable land, facilitating land transfer. The expansion of land operations through land transfers creates conditions for the mechanized use of agricultural chemicals, thereby improving the standardization, normalization, and quantification of agricultural chemical use [10,36]. For example, the concentration of cultivated land enables the use of drones for pesticide spraying, and land leveling facilitates mechanical fertilization, which enhances the efficiency of pesticide and fertilizer application while reducing the consumption of agricultural chemicals [18]. Secondly, the land fertility improvement projects in HSFC enhance agricultural production conditions, including soil improvement and land fertilization, which increase soil fertility [37]. This reduces reliance on agricultural chemicals, further decreasing their use. Finally, the promotion of superior crop varieties and the application of advanced, appropriate technologies will further reduce the use of agricultural chemicals [33]. In summary, through the implementation of HSFC policies, the use of agricultural chemicals will effectively be reduced, and agricultural carbon emissions are expected to decrease significantly in the agricultural production sector.

HSFC has an impact on agricultural carbon emission by affecting efficiency. In the same way that the social division of labor promotes social progress, the deepening of agricultural labor division also effectively promotes production efficiency and enhances agricultural carbon emission efficiency [38]. On the one hand, the expansion of land scale brought about by HSFC effectively promotes the transformation of planting mode [39], that is, it prompts farmers to transit from multi-plot and differentiated planting modes to single-plot and specialized planting modes [40], which further promotes the deepening of horizontal labor division during agricultural production. On the other hand, the improvement in agricultural mechanization brought about by HSFC has provided an excellent foundation for specialized agricultural services [41]. Relevant studies have also confirmed that HSFC plays a significant role in promoting the agricultural in-production level and post-production services [42,43], improving the development of agricultural socialization services and further deepening the vertical labor division during agricultural production. Therefore, HSFC will effectively improve the efficiency of agricultural carbon emissions by deepening the horizontal and vertical labor division in agriculture, which is conducive to energy saving and carbon reduction in agriculture.

Based on the above analysis, the following research hypotheses are proposed in this study:

H1: *High-standard farmland construction can effectively promote a reduction in carbon emissions during agricultural production.*

H2: *Based on the Hypothesis 1, the second hypothesis of this study proposes that high-standard farmland construction reduces carbon emissions during agricultural production by reducing fossil energy consumption and the usage of agricultural chemicals.*

H3: *High-standard farmland construction achieves energy saving and carbon reduction by improving the efficiency of agricultural carbon emissions.*

3. Materials and Methods

3.1. Sample and Data Sources

The differences in the implementation of HSFC policy across regions, times, and intensities provide a natural experimental condition for studying the causal effects of this policy on economic variables such as agricultural productivity, land quality, and carbon emissions. Specifically, different regions have adopted varying construction progress and intensity based on land resources, economic development, and policy priorities. Some regions implemented HSFC earlier than others, or had a higher proportion of land consolidation area, while other regions either did not implement the policy or only carried out limited construction. These regional differences provide an opportunity to compare the effects of the policy in areas where it was implemented and areas where it was not. Although the implementation is not fully random, the policy is typically influenced by external factors, such as national agricultural policies and local government financial support, which are unrelated to the specific characteristics of the regions. Therefore, by comparing the regions with and without the policy, it is possible to effectively control for confounding factors and make causal inferences. As such, the implementation of HSFC can be treated as a quasi-natural experiment for research. Therefore, this study takes the implementation of HSFC policy as a quasi-natural experiment. Based on the relevant panel data of 31 provinces, municipalities, and autonomous regions in China from 2003 to 2021, the impact of HSFC policy on the reduction in carbon emissions in agricultural production was studied. The selection of the data period from 2003 to 2021 was primarily based on two considerations: (1) land consolidation data are traceable back to 2003; (2) statistical data on high-standard farmland construction are unavailable after 2021. In addition, considering the purpose of this study, it focuses on explaining the policy effect of HSFC, that is, focusing on causal inference, and does not pay too much attention to its long-term dynamic effect. The data used are from the China Statistical Yearbook, China Rural Statistical Yearbook, China Financial Yearbook, China Rural Operation and Management Statistical Annual Report.

At the same time, interpolation and trend extrapolation methods are used to supplement some missing data.

3.2. Econometric Model

During the implementation of HSFC policy, the construction tasks and progress of various provinces and autonomous regions vary greatly because of the large differences in the natural endowment conditions and construction needs of various provinces [7]. Therefore, the implementation of policies causes differences in the land consolidation of the same province before and after the policy implementation, and also leads to differences in the land consolidation of different provinces [44], which lays a foundation for the usage of the DID model to estimate the policy effect in this study. Meanwhile, since the implementation scope is nationwide, a control and experimental group cannot be set by dummy variables, that is, the traditional DID model cannot be used for estimation. Therefore, in reference to the practice of relevant research [45], this study uses the continuous time variable of "the proportion of land consolidation in arable land" to divide the samples into the control group (the sample with a relatively high proportion of land consolidation) and the experimental group (the sample with a relatively low proportion of land consolidation). The continuous DID model was used to evaluate the effect of HSFC on the reduction in agricultural carbon emissions. The continuous DID model not only retains the basic properties, but also reflects the degree of data change [46]. Thus, the measurement model was constructed as follows:

$$lnCO2_{it} = \beta_0 + \beta_1 * Hrate_i \times {T_t}^{2011} + \beta_k X_{it}^k + \lambda_t + \mu_i + \varepsilon_{it} \quad (1)$$

In Equation (1), $lnCO2_{it}$ represents the natural logarithm of total agricultural carbon emissions for the i province in the t year; $Hrate_i$ denotes the proportion of land consolidation area; ${T_t}^{2011}$ is the dummy variable for the implementation of HSFC policy; X_{it}^k includes a series of control variables; λ_t and μ_i represent time fixed effects and province fixed effects, respectively; ε_{it} is the error term; the parameter of interest β_1 measures the net effect of the HSFC policy implementation on agricultural carbon emissions.

3.3. Variable Descriptions

Agricultural carbon emissions were considered as the explained variable. Based on the experience of relevant studies, this study calculated the agricultural carbon emissions of the 31 provinces, municipalities, and autonomous regions in China by using the IPCC carbon emission coefficient method based on six types of carbon sources, namely agricultural diesel, fertilizer, pesticide, agricultural film, plowing, and irrigation [45,46]. The carbon emission coefficients for the aforementioned six categories were as follows: 0.59 kg/kg for agricultural diesel, 0.89 kg/kg for fertilizers, 4.93 kg/kg for pesticides, 5.18 kg/kg for plastic mulch, 266.48 kg/hm^2 for plowing, and 312.60 kg/hm^2 for irrigation.

The HSFC policy is considered the core explanatory variable ($Hrate * T^{2011}$), which is measured by the virtual variable interaction term of the proportion of land regulation area in arable land and the implementation time of HSFC policy. Among them, land regulation area refers to the sum of the low-yield farmland reconstruction and HSFC area. The implementation of HSFC policy started in 2011; hence, the variable was set as 1 for years 2011 and onwards, and 0 for years before 2011.

Three factors were included in the mechanism variables in this study: (1) Agricultural Fossil Fuel Consumption ($lnOil\_use$): measured by the natural logarithm of agricultural diesel usage. (2) Use of Agricultural Chemicals ($lnFer\_use$): measured by the natural logarithm of fertilizer usage. (3) Agricultural Carbon Emission Efficiency ($lnCO2\_eff$). To calculate carbon emission efficiency, this study first utilizes an Undesirable–Dynamic-SBM model to compute the slack variables for agricultural inputs in each province based on a previous study [25]. Subsequently, the carbon emission efficiency is determined as (actual carbon emissions—slack variables)/actual carbon emissions, which allows for the calculation of carbon emission efficiency. The indicators for agricultural production input include employment in the primary sector, total power of agricultural machinery, fertilizer usage, total sown area of crops, pesticide usage, plastic film usage, etc. The expected output indicator is the gross domestic product from the primary sector in each province, while the undesired output indicator is the agricultural carbon emissions.

This study includes several control variables to account for various factors that may influence agricultural carbon emissions. These include: (1) Urbanization Rate ($Urban\_rate$): determined by the proportion of urban residents. (2) Food Marketization Rate ($Food\_market\_rate$): measured by the ratio of cash food consumption expenditure of rural residents to the total food consumption expenditure of rural residents. (3) Level of Agricultural Mechanization ($Mechan\_rate$): determined by the degree of mechanization per labor unit in agriculture. (4) Farmers' Income Structure ($Income\_str$): measured by the ratio of per capita household operating income of rural households to per capita income of rural residents. (5) Agricultural Planting Structure ($Plant\_str$): determined by the ratio of area planted with grain crops to the total area sown with crops. (6) Disaster Rate ($Disaster\_rate$): determined by the ratio of disaster-affected crop area to the total. (7) Financial Support for Agriculture Rate (Fe_rate): determined by the proportion of local financial expenditure on agriculture, forestry, and water affairs to the general budgetary expenditure of the region. (8) Urban–Rural Income gap ($Income\_gap$): determined by the ratio of per capita disposable income of urban residents to that of rural residents. The descriptive statistics of relevant variables are shown in Table 2.

Table 2. Descriptive statistics of variables.

	Var	Code	Obs	Mean	Std
Dependent Variable	Natural Log of Agricultural Carbon Emissions	$\ln CO_2$	589	5.314	1.112
Core Explanatory Variables:	Percentage of Land Consolidation Area	Hrate	589	0.185	0.201
	Time Dummy Variables	T^{2011}	589	0.579	0.494
	High-standard Farmland Construction Policy	$Hrate \times \times T^{2011}$	589	0.151	0.215
Mechanism Variables:	Agricultural Fossil Fuel Consumption	lnOil_use	589	3.116	1.150
	Use of Agricultural Chemicals	lnFer_use	589	4.634	1.228
	Agricultural Carbon Emission Efficiency	CO_2_eff	589	0.698	0.210
Control Variables:	Urbanization Rate	Urban_rate	589	0.512	0.172
	Food Marketization Rate	Food_market_rate	589	0.769	0.155
	Level of Agricultural Mechanization	Mechan_rate	589	3.781	2.216
	Farmers' Income Structure	Income_str	589	0.462	0.160
	Agricultural Planting Structure	Plant_str	589	0.651	0.132
	Disaster Rate	Disaster_rate	589	0.194	0.147
	Financial Support for Agriculture Rate	Fe_rate	589	0.102	0.039
	Urban–Rural Income gap	Income_gap	589	2.832	0.583

4. Results

4.1. Baseline Regression

The baseline regression results of the model are shown in Table 3. No matter whether control variables are added or not, and no matter what standard error is adopted, the effect of HSFC policy on the agricultural carbon emission is negative, and all pass the test at the significance level of 1%, which indicates that the implementation of HSFC policy can significantly reduce carbon emissions during agricultural production and has a good ecological effect. Hypothesis 1 has been preliminarily verified. This is also supported by Wang et al., (2020) [26] and Du et al., (2023) [45], that is, HSFC improves agricultural production efficiency and promotes a reduction in pesticides and fertilizers along with the green and low-carbon development of agriculture by improving the farmland quality and making up for the shortcomings of agricultural infrastructure. Specifically, if other conditions remain unchanged, HSFC can reduce the agricultural carbon emissions by 53.8% per year on average. Compared with the emission reduction effect of about 10% in existing research results, the reduction in carbon emissions is relatively high because we considered the lag and long-term effect of HSFC policy and used the proportion of accumulated land improvement area in the cultivated land area of each province as the core explanatory variable. Meanwhile, previous studies only used the proportion of newly added land improvement area in the current year as a policy indicator to measure HSFC, neglecting the long-term effects. In addition, the estimated coefficients of urbanization rate, farmers' income structure, and agricultural planting structure are also significantly negative, indicating that the increase in urbanization rate, farmers' operating income, and food crop sown area are also conducive to the reduction of carbon emissions during agricultural production [47,48].

Table 3. Baseline regression results.

Var	**(1) lnC02**	**(2) lnC02**	**(3) lnC02**	**(4) lnC02**
$Hrate \times T^{2011}$	−0.604 *** (0.036)	−0.604 *** (0.101)	−0.538 *** (0.033)	−0.538 *** (0.078)
Urban_rate			−0.642 *** (0.080)	−0.642 *** (0.213)
Food_market_rate			0.086 (0.061)	0.086 (0.112)
Mechan_rate			0.039 *** (0.004)	0.039 *** (0.008)
Income_str			−0.556 *** (0.087)	−0.556 ** (0.254)
Plant_str			−0.880 *** (0.091)	−0.880 *** (0.207)
Disaster_rate			−0.049 (0.033)	−0.049 (0.030)
Fe_rate			0.301 (0.212)	0.301 (0.416)
Income_gap			−0.054 *** (0.016)	−0.054 (0.043)
Time Fixed	Yes	Yes	Yes	Yes
Province Fixed	Yes	Yes	Yes	Yes
Constants	5.102 *** (0.018)	5.102 *** (0.029)	6.220 *** (0.130)	6.220 *** (0.251)
Obs	589	589	589	589
R-sq	0.595	0.595	0.765	0.765

Note: *** $p < 0.01$, ** $p < 0.05$. The results in Column (1) and Column (3) correspond to estimates using ordinary standard errors, while the results in Column (2) and Column (4) correspond to estimates using robust standard errors.

4.2. Parallel Trend Test

The parallel trend test is an prerequisite for the DID model [36], that is, it helps to ensure that the carbon emissions in both the control group and the experimental group remain relatively parallel without significant difference before the implementation of the HSFC policy. Thus, this study uses the event study method to test the parallel trend as shown in Figure 1, which shows that the estimated coefficient values are not statistically significant before the HSFC policy implementation (pre7-current), and the estimated coefficients all contain 0 values within the 95% confidence interval. This indicates that there is no significant difference in agricultural carbon emissions between the regions with relatively high land regulation area (with HSFC) and regions with relatively low land regulation area (without HSFC), which passes the parallel trend test.

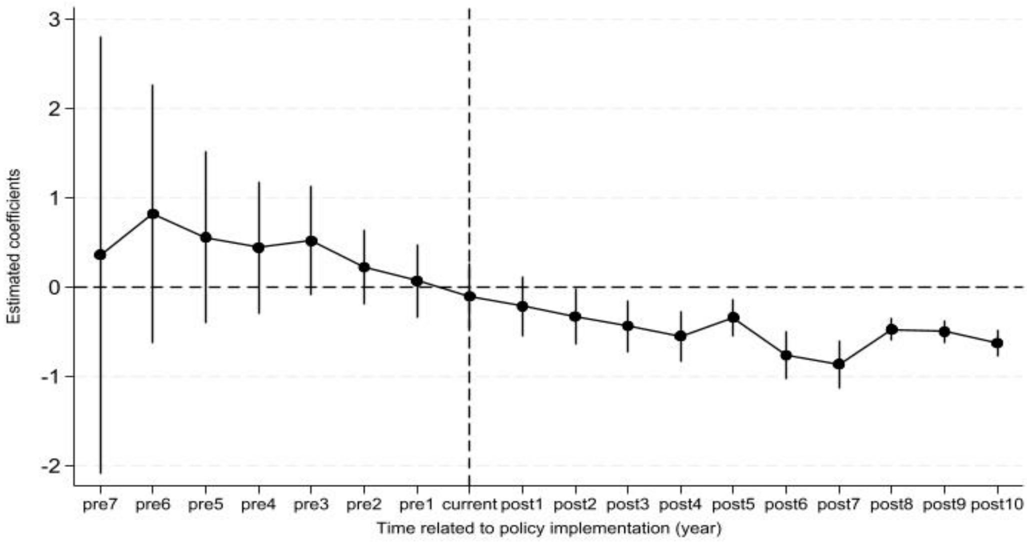

Figure 1. Parallel trend test. The dashed line represents the boundary of the HSFC policy implication. Pre and Post indicate the before and after of the HSFC policy.

4.3. Robustness Test

This study further uses the replacement of explained variables, counter-fact test, repeated random sampling by self-help method, and exclusion of zero-growth fertilizer policy to test the robustness of the baseline regression results.

First, the explained variable was replaced. As mentioned above, agricultural carbon emissions are mainly derived from six types of carbon sources. Therefore, carbon emissions generated by agricultural diesel use ($lnCO_2$_Oil) and chemical fertilizer use ($lnCO_2$_Fer) were also used as alternative variables to estimate agricultural carbon emissions. The results are shown in Columns (1) and (2) of Table 4. The core explanatory variables' regression coefficients were still negative and pass the test at the significance level of 5% and 1%, respectively, indicating that the baseline regression results have a certain robustness.

Second, counter-fact testing was conducted. By artificially assuming a policy implementation time, this study tests the HSFC policy effect. If the estimated coefficient cannot pass the significance level test, it means that the reduction in agricultural carbon emissions is caused by the HSFC policy; otherwise, it means that the above regression results are not robust enough. Therefore, this study set the policy time points as 2009 and 2010, both of which have nothing to do with HSFC. The results are shown in Columns (3) and (4) of Table 4. The HSFC policy estimated coefficients ($Hrate \times T^{2010}$ and $Hrate \times T^{2009}$) both pass the significance level test of 10%. Thus, the robustness is verified.

Table 4. Robustness Test Results Part I.

Var	(1) lnC02_Oil	(2) lnC02_Fer	(3) lnC02	(4) lnC02
Hrate×T^{2011}	−0.625 ** (0.110)	−0.812 *** (0.203)		
Hrate×T^{2010}			−0.099 (0.102)	
Hrate×T^{2009}				−0.165 (0.995)
Control variable	Yes	Yes	Yes	Yes
Fixed time	Yes	Yes	Yes	Yes
Regional fixation	Yes	Yes	Yes	Yes
Constants	5.635 *** (0.286)	3.891 *** (0.563)	6.363 *** (0.260)	6.321 *** (0.251)
Obs	589	589	589	589
R-sq	0.707	0.554	0.765	0.764

Note: *** $p < 0.01$, ** $p < 0.05$; standard errors in parentheses.

Third, random sampling was repeated through the self-help method. To further alleviate the inconsistency in the standard errors of the estimated coefficients caused by the correlation of model sequences, this study also adopts the self-help method to repeat random sampling 1000 times to calculate the robust standard errors of the estimated coefficients, as shown in Columns (1) and (2) of Table 5. After 1000 times of random repeated sampling, the standard error of the HSFC policy estimation coefficient converged to 0.149 and 0.131, respectively, which changed slightly compared with the robust standard error of the benchmark regression, but the significance level of the estimation coefficient did not change, indicating that the conclusion of baseline regression was still valid after considering the problem that the sequence correlation may cause bias in the model estimation.

Table 5. Robustness test results part II.

Var	(1) lnC02	(2) lnC02	(3) lnC02	(4) lnC02
Hrate×T^{2011}	−0.604 *** (0.077)	−0.538 *** (0.075)	−0.635 *** (0.064)	−0.470 *** (0.062)
Control variable	No	Yes	No	Yes
Fixed time	Yes	Yes	Yes	Yes
Regional fixation	Yes	Yes	Yes	Yes
Constants	5.102 *** (0.054)	6.220 *** (0.186)	5.102 *** (0.014)	6.019 *** (0.140)
Obs	589	589	372	372
R-sq	——	——	0.691	0.816

Note: (1) *** $p < 0.01$. Standard errors in parentheses.——means no data.

Fourth, the interference of the fertilizer zero-growth policy was eliminated. Not only will the HSFC policy impact agricultural carbon emissions, but the 2015 "zero-growth action Plan for fertilizer use by 2020" issued by the Ministry of Agriculture (now the Ministry of Agriculture and Rural Affairs) will also directly affect agricultural carbon emissions. Thus, this study also re-estimated the data in 2015 and after to eliminate the impact of the zero-growth policy on the model estimation, as shown in Columns (3) and (4) of Table 5. The results are still robust even after removing the effect of the zero-growth fertilizer policy.

4.4. Internal Mechanisms Analysis

The above empirical analysis fully demonstrates that HSFC policy can significantly reduce agricultural carbon emissions. Meanwhile, HSFC policy will impact the total amount of agricultural carbon emissions by influencing fossil energy consumption, agricultural chemical use, and the efficiency of agricultural carbon emission. Therefore, this study mainly adopted the two-stage method to verify the influencing mechanisms of HSFC on agricultural carbon emissions from the perspective of these three influencing mechanisms. In the first stage, the impact of HSFC implementation on agricultural fossil energy consumption, agricultural chemical input, and the efficiency of agricultural carbon emission was verified. In the second stage, the impact of the following three factors on agricultural carbon emissions was verified: agricultural fossil energy consumption, agricultural chemical input, and the efficiency of agricultural carbon emission. The measurement model was constructed as follows:

$$M_{it} = \beta_0 + \beta_1 * Hrate_i \times T_t^{2011} + \beta_k X_{it}^k + \lambda_t + \mu_i + \varepsilon_{it} \quad (2)$$

$$lnCO2_{it} = \beta_0 + \beta_1 * Hrate_i \times T_t^{2011} + \varphi M_{it} + \beta_k X_{it}^k + \lambda_t + \mu_i + \varepsilon_{it} \quad (3)$$

In the above equation, M_{it} represents the mechanism variables, φ is the parameter to be estimated, and the meanings of other variables are the same as in Equation (1). The model estimation results are shown in Table 6.

Table 6. Mechanism analysis.

Var	(1) **lnOil_use**	(2) **lnFer_use**	(3) **C02_eff**	(4) **lnC02**
Hrate×T^{2011}	−0.812 *** (0.083)	−0.757 * (0.435)	−0.073 (0.063)	−0.367 *** (0.030)
lnOil_use				0.217 *** (0.014)
lnFer_use				0.236 *** (0.028)
C02_eff				−0.078 *** (0.029)
Control variable	Yes	Yes	Yes	Yes
Fixed time	Yes	Yes	Yes	Yes
Regional fixation	Yes	Yes	Yes	Yes
Constants	3.891 *** (0.257)	4.867 *** (1.334)	0.660 *** (0.129)	5.422 *** (0.106)
Obs	589	589	589	589
R-sq	0.554	0.365	0.370	0.841

Note: *** $p < 0.01$, * $p < 0.1$. Standard errors in parentheses.

The regression coefficients of HSFC policy are negative, as shown in Column (1) and Column (2) of Table 6, and are −0.812 and −0.757, respectively, passing the test at the significance levels of 1% and 10%, respectively. This indicates that the HSFC implementation effectively reduced agricultural energy consumption and agricultural chemical usage [15], and that the increase in energy consumption and chemical use will lead to an increase in agricultural carbon emissions according to the estimated results in Column (4). Based on the results of Column (1), (2), and (4), the HSFC has a good policy effect on agricultural carbon reduction by reducing agricultural energy consumption and the use of agricultural chemicals, and the second research hypothesis is verified. In addition, the improved efficiency of carbon emissions can significantly impact the agricultural carbon reduction (Column (4)), but unfortunately the HSFC did not significantly improve agricultural carbon emission efficiency (Column (3)). Therefore, the above-mentioned third research hypothesis fails the test.

4.5. Heterogeneity Analysis

In view of the large differences in natural geographical conditions and resource endowments among the regions in China, the impact of HSFC on agricultural carbon emissions may vary significantly. Thus, this study further discusses the heterogeneity effect of HSFC from the two dimensions of geographical location and agricultural functional area positioning. The estimated results are shown in Table 7.

Table 7. Heterogeneity analysis.

Var	**Geographical Location**			**Agricultural Functional Zoning**	
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
	Eastern Region	**Central Region**	**Western Region**	**Major Grain-Producing Areas**	**Non-Major Grain-Producing Areas**
	lnC02	**lnC02**	**lnC02**	**lnC02**	**lnC02**
$Hrate \times T^{2011}$	−0.488 ** (0.089)	0.022 (0.030)	−0.513 ** (0.1630	−0.002 (0.099)	−0.596 *** (0.103)
Control variables	Yes	Yes	Yes	Yes	Yes
Fixed time	Yes	Yes	Yes	Yes	Yes
Fixed region	Yes	Yes	Yes	Yes	Yes
Constants	5.951 *** (0.265)	6.075 *** (0.358)	4.897 *** (0.397)	7.086 *** (0.317)	5.455 *** (0.251)
Obs	209	152	228	247	342
R-sq	0.721	0.933	0.914	0.793	0.824

Note: *** $p < 0.01$, ** $p < 0.05$. Standard errors in parentheses.

According to the National Development and Reform Commission of China, the classification of East, Central, and West China is based on policy considerations rather than administrative or geographical divisions. The Eastern region, which includes Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan, is the most economically developed. The Central region, comprising Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, and Hunan, is moderately developed. The Western region, which includes Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, Guangxi, and Inner Mongolia, is the least economically developed. The Qinling–Huaihe Line is widely accepted as the geographical dividing line between northern and southern China. The northern provinces, including Heilongjiang, Jilin, Liaoning, Beijing, Tianjin, Hebei, Shandong, Henan, Shanxi, Shaanxi, Inner Mongolia, Ningxia, Gansu, Xinjiang, Qinghai, and Tibet, are mostly located north of this line. The southern provinces, which include Jiangsu, southern Anhui, Zhejiang, Shanghai, Hubei, Hunan, Jiangxi, Fujian, Guangdong, Guangxi, Hainan, Sichuan, Chongqing, Guizhou, Yunnan, and southern Tibet, are predominantly located south of the Qinling–Huaihe Line.

Firstly, HSFC has a significant negative impact on agricultural carbon emissions in both the eastern and western regions from the perspective of geographical location

(Column (1), (2), and (3) of Table 7), while no significant impact on agricultural carbon emission efficiency is observed in the central region. Secondly, HSFC has no significant impact on agricultural carbon emissions in China's 13 major grain-producing areas from the perspective of the positioning of agricultural functional areas (Columns (4) and (5) of Table 7) but can significantly impact agricultural carbon reduction in non-major grain-producing areas.

There may be two reasons for this. On the one hand, the main grain-producing regions bear the pressure of China's grain supply security [49]. In order to achieve high grain yield, more fertilizers and pesticides are invested per acre, while the agricultural ecological environment is not paid enough attention [50], which results in limited emission reduction through HSFC. On the other hand, the cultivated land in major grain-producing regions is relatively flat and the land fertility is relatively strong compared with non-major grain-producing areas [51], and the marginal improvement effect brought by HSFC is relatively small. The limited impact on agricultural emission reduction in the central region can be explained by the other seven provinces that are major grain-producing areas in China, except Shanxi.

5. Discussion

Promoting carbon reduction in agricultural production is an effective way for all of mankind to combat climate change. This study takes China's HSFC policy as a quasi-natural experiment, combines it with panel data from 31 provinces, municipalities, and autonomous regions in China, and adopts a continuous DID model to assess the impact of HSFC on the reduction of agricultural carbon emissions. The marginal contribution of this study can be drawn from the two aspects: First, this study takes HSFC as a quasi-natural experiment, combined with provincial panel data from 2003 to 2021, scientifically evaluates the carbon emission reduction effect of HSFC policy, and explores the policy heterogeneity from the two dimensions of geographical location and agricultural functional area positioning, so as to provide a policy reference for different regions relying on HSFC to promote agricultural carbon emission reduction in the future. Second, combined with the content of HSFC, the internal mechanisms affecting agricultural carbon emissions by HSFC are theoretically explained, and the relevant mechanism is empirically tested, which provides a record of the experience for other developing countries with similar agricultural development problems to China to help formulate targeted policies for green and low-carbon agricultural development.

China's HSFC policy can significantly reduce agricultural carbon emissions, which was confirmed through a series of robustness tests including the replacement of explained variables, counter-fact testing, repeated random sampling by using the self-help method, and the exclusion of interference from zero-growth fertilizer policy. This research conclusion is consistent with some other current empirical studies, while the average carbon reduction effect in this study is 53.8%, which is 3–4 times the value from previous studies [26,52]. The main reason for the difference is that HSFC in previous years will have also had an impact on the carbon emission in the next year, and the effect of the HSFC policy lags and is long-term; as such, this study innovatively selects the cumulative land renovation area of the year as the core explanatory variable, which can more truly reflect the HSFC policy effect, making the research results in this study more scientific and convincing.

In terms of influencing mechanisms, this study combined with the objectives and contents of HSFC in China fully considered the top two carbon sources in agricultural production and investigated the three influencing mechanisms of agricultural fossil energy consumption, agricultural chemical use, and agricultural carbon emission efficiency. Compared with previous studies on the mechanisms of HSFC affecting agricultural carbon emissions from the perspectives of agricultural labor division and social service [13,53], the three mechanisms selected in this study are more abundant and comprehensive. The results found that HSFC contributes to a reduction in agricultural carbon emissions mainly through reducing agricultural fossil energy consumption and agricultural chemical usage. Although improvements in carbon emission efficiency play an important role in reducing agricultural carbon emissions, unfortunately, the impact of HSFC in this regard has been relatively limited. The main reason lies in the need for sufficient technological support and training to enhance carbon emission efficiency. While HSFC has increased agricultural productivity, its direct impact on the widespread adoption of green technologies, such as precision agriculture and smart irrigation systems, remains relatively limited. As a result, it has not significantly contributed to the improvement in agricultural carbon emission efficiency.

In terms of heterogeneity analysis, this study examines the heterogeneous effects of HSFC from two dimensions: agricultural functional area positioning and geographical location, drawing on previous research [54]. The results indicate that the carbon reduction effects of HSFC are primarily observed in non-major grain-producing areas, while no significant impact is detected in major grain-producing areas. This is also supported by a previous study [55]. This can be attributed to two main factors. First, major grain-producing areas bear the pressure of ensuring China's grain supply security, leading to higher applications of chemical fertilizers and pesticides per unit area to achieve high grain yields. This results in insufficient attention to improving the agricultural ecological environment, thereby reducing the effectiveness of carbon reduction [56]. Second, compared to non-major grain-producing areas, the arable land in major grain-producing areas is generally more leveled and has relatively higher soil fertility, which limits the marginal improvement effects of HSFC. These findings are supported by previous studies [57]. From a geographical perspective, HSFC significantly reduces agricultural carbon emissions in eastern and western China but has a limited impact in central China. This is primarily because eight provinces in central China, except Shanxi Province, are major grain-producing areas.

6. Conclusions, Limitations, and Future Research

This study focuses on the topic of carbon emission reduction in agricultural production in China from the perspective of HSFC policy and discusses its impact mechanism and heterogeneity. The results show that HSFC can effectively reduce the carbon emissions in agricultural production, with an average annual reduction of 53.8% when other conditions remain unchanged. The carbon emission reduction can be attributed to reducing agricultural fossil energy consumption and agricultural chemicals usage caused by HSFC. In addition, the carbon reduction effect of HSFC mainly happens in non-major grain-producing areas, and no significant impact is observed in major grain-producing areas. Therefore, policymakers should unswervingly continue to promote HSFC and combine their own economic and geographical conditions. The findings of this study provide an important reference for other developing countries with similar situations to China to formulate policies on agricultural carbon reduction.

The main policy implications are as follows: First, it is essential to continue promoting the development of HSFC. While maintaining its role in increasing food production, further efforts should be made to enhance the ecological benefits of HSFC. Second, regions should adapt their HSFC implementation strategies to local economic and geographical conditions. In major grain-producing areas, the marginal effect of HSFC on carbon reduction is relatively low. The impact of infrastructure projects, such as field infrastructure and soil improvement, may not effectively reduce agricultural carbon emissions. Therefore, these regions should prioritize the acceleration of engineering projects, such as agricultural technology development, with national policy support to improve carbon emission efficiency. In contrast, non-major grain-producing areas should focus more on engineering, speeding up the construction of field infrastructure and soil fertility projects to strengthen the carbon reduction effects of HSFC.

This study is an expansion and deepening of the green development of agriculture, and it provides new ideas along the path of reducing carbon emissions in agricultural production. However, there are still certain limitations. First, China's land renovation data are only published at the provincial level, and there is a lack of smaller scale data such as city and county. As a result, the number of samples in this study is limited, and the heterogeneity effect of HSFC policy cannot be discussed from more dimensions. Second, this study is a macro-level study, and it lacks more microscopic individual survey data analysis, so it cannot accurately describe the mechanism role of human behaviors in the effect of HSFC policies, especially the farmers.

In future research, in-depth investigation and research should be conducted in China's major grain-producing areas, especially in the central region, to continue exploring the more detailed and accurate reasons for the failure of HSFC policies to effectively reduce carbon emissions in agricultural production. In addition, it is important to emphasize the role of farmers in the county areas with regard to HSFC policy. The impact of their behaviors on carbon emissions in agricultural production should be analyzed at the micro level, and the influence of these behaviors on the effectiveness of HSFC policies should be clarified. This would contribute to a deeper understanding and expansion of research on sustainable agricultural development and green agriculture.

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References

1. Liu, M.; Yang, L. Spatial pattern of China's agricultural carbon emission performance. *Ecol. Indic.* **2021**, *133*, 108345. [CrossRef]
2. Shan, T.; Xia, Y.; Hu, C.; Zhang, S.; Zhang, J.; Xiao, Y.; Dan, F. Analysis of regional agricultural carbon emission efficiency and influencing factors: Case study of Hubei Province in China. *PLoS ONE* **2022**, *17*, e0266172. [CrossRef] [PubMed]
3. Batoukhteh, F.; Darzi-Naftchali, A. A global study on decoupling greenhouse gas emissions from agricultural development. *Environ. Dev. Sustain.* **2024**, *26*, 13159–13183. [CrossRef]
4. Phiri, R.; Rangappa, S.M.; Siengchin, S. Agro-waste for renewable and sustainable green production: A review. *J. Clean. Prod.* **2023**, 139989. [CrossRef]

5. Guo, L.; Zhao, S.; Song, Y.; Tang, M.; Li, H. Green finance, chemical fertilizer use and carbon emissions from agricultural production. *Agriculture* **2022**, *12*, 313. [CrossRef]
6. Zongyun, S.; Le, S.; Shengwei, C. Study on the effect and mechanism of agricultural insurance on agricultural carbon sequestration efficiency. *Chinese J. Agric. Resour. Reg. Plan.* **2022**, *43*, 263–272. (In Chinese)
7. Zhu, J.; Wang, M.; Zhang, C. Impact of high-standard basic farmland construction policies on agricultural eco-efficiency: Case of China. *Natl. Account. Rev.* **2022**, *4*, 147–166. [CrossRef]
8. Wang, Y.; Li, G.; Wang, S.; Zhang, Y.; Li, D.; Zhou, H.; Yu, W.; Xu, S. A Comprehensive Evaluation of Benefit of High-Standard Farmland Development in China. *Sustainability* **2022**, *14*, 10361. [CrossRef]
9. Ye, F.; Wang, L.; Razzaq, A.; Tong, T.; Zhang, Q.; Abbas, A. Policy impacts of high-standard farmland construction on agricultural sustainability: Total factor productivity-based analysis. *Land* **2023**, *12*, 283. [CrossRef]
10. Tang, W.; Huang, K.; Zhou, F. Can high-standard farmland construction policy promote agricultural green development? evidence from quasi natural experiments in hunan, china. *Polish J. Environ. Stud.* **2023**, *32*, 5333–5346. [CrossRef] [PubMed]
11. Yang, G.; Sun, X. China's land consolidation policies from the perspective of supply-demand and resilience: Changes, evolutive logic and policy orientation. *Rural Econ.* **2024**, *3*, 44–53.
12. Peng, J.; Zhao, Z.; Chen, L. The impact of high-standard farmland construction policy on rural poverty in China. *Land* **2022**, *11*, 1578. [CrossRef]
13. Li, L.; Han, J.; Zhu, Y. Does environmental regulation in the form of resource agglomeration decrease agricultural carbon emissions? Quasi-natural experimental on high-standard farmland construction policy. *J. Clean. Prod.* **2023**, *420*, 138342. [CrossRef]
14. Lee, J.; Oh, Y.G.; Yoo, S.H.; Suh, K. Vulnerability assessment of rural aging community for abandoned farmlands in South Korea. *Land Use Policy* **2021**, *108*, 105544. [CrossRef]
15. Iba, H.; Lilavanichakul, A. Farm Business Model on Smart Farming Technology for Sustainable Farmland in Hilly and Mountainous Areas of Japan. *Land* **2023**, *12*, 592. [CrossRef]
16. Chen, Y.; Sun, Z.; Wang, Y.; Han, Y. Impact of high-standard farmland construction on farmers' income growth—Quasi-natural experiments from China. *Front. Sustain. Food Syst.* **2023**, *7*, 1303642. [CrossRef]
17. Liu, H.; Zhang, W. Spatial and temporal variation and convergence in the efficiency of high-standard farmland construction: Evidence in China. *J. Clean. Prod.* **2024**, *452*, 142200. [CrossRef]
18. Gong, Y.; Zhang, Y.; Chen, Y. The Impact of High-Standard Farmland Construction Policy on Grain Quality from the Perspectives of Technology Adoption and Cultivated Land Quality. *Agriculture* **2023**, *13*, 1702. [CrossRef]
19. Tian'en, Z.; Li, Z.; Kun, F.; Xuejie, Z.; Huning, G.; Zhang, M.; Ma, Y. Effects of high-standard farmland construction on farmland quality and contribution of irrigation and drainage index. *J. Agric. Resour. Environ.* **2022**, *39*, 978. [CrossRef]
20. Wang, W.; Gong, J.; Wang, Y.; Shen, Y. Exploring the effects of rural site conditions and household livelihood capitals on agricultural land transfers in China. *Land Use Policy* **2021**, *108*, 105523. [CrossRef]
21. Yang, L.; Guan, Z.; Chen, S.; He, Z. Re-measurement and influencing factors of agricultural eco-efficiency under the 'dual carbon'target in China. *Heliyon* **2024**, *10*, e24944. [CrossRef]
22. Liao, J.; Yu, C.; Feng, Z.; Zhao, H.; Wu, K.; Ma, X. Spatial differentiation characteristics and driving factors of agricultural eco-efficiency in Chinese provinces from the perspective of ecosystem services. *J. Clean. Prod.* **2021**, *288*, 125466. [CrossRef]
23. Liu, S.; Jia, J.; Huang, H.; Chen, D.; Zhong, Y.; Zhou, Y. China's CO_2 Emissions: A Thorough Analysis of Spatiotemporal Characteristics and Sustainable Policy from the Agricultural Land-Use Perspective during 1995–2020. *Land* **2023**, *12*, 1220. [CrossRef]
24. Chen, H.; Qi, S.; Tan, X. Decomposition and prediction of China's carbon emission intensity towards carbon neutrality: From perspectives of national, regional and sectoral level. *Sci. Total Environ.* **2022**, *825*, 153839. [CrossRef]
25. Anser, M.K.; Ahmad, M.; Khan, M.A.; Zaman, K.; Nassani, A.A.; Askar, S.E.; Abro, M.M.Q.; Kabbani, A. The role of information and communication technologies in mitigating carbon emissions: Evidence from panel quantile regression. *Environ. Sci. Pollut. Res.* **2021**, *28*, 21065–21084. [CrossRef]
26. Wang, G.; Liao, M.; Jiang, Z. Research on agricultural carbon emissions and regional carbon emissions reduction strategies in China. *Sustainability* **2020**, *12*, 2627. [CrossRef]
27. Fei, R.; Lin, Z.; Chunga, J. How land transfer affects agricultural land use efficiency: Evidence from China's agricultural sector. *Land Use Policy* **2021**, *103*, 105300. [CrossRef]
28. Guan, N.; Liu, L.; Dong, K.; Xie, M.; Du, Y. Agricultural mechanization, large-scale operation and agricultural carbon emissions. *Cogent Food Agric.* **2023**, *9*, 2238430. [CrossRef]
29. Peng, L.; Sun, N.; Jiang, Z.; Yan, Z.; Xu, J. The impact of urban–rural integration on carbon emissions of rural household energy consumption: Evidence from China. *Environ. Dev. Sustain.* **2023**, 1–29. [CrossRef]

30. Tang, L.; Sun, S. Fiscal incentives, financial support for agriculture, and urban-rural inequality. *Int. Rev. Financ. Anal.* **2022**, *80*, 102057. [CrossRef]
31. Zhang, Z.; Tian, Y.; Chen, Y.H. Can agricultural credit subsidies affect county-level carbon intensity in China? *Sustain. Prod. Consum.* **2023**, *38*, 80–89. [CrossRef]
32. Li, Z.; Li, J. The influence mechanism and spatial effect of carbon emission intensity in the agricultural sustainable supply: Evidence from China's grain production. *Environ. Sci. Pollut. Res.* **2022**, *29*, 44442–44460. [CrossRef] [PubMed]
33. Xiaokaiti, X.; Zhang, H.; Jia, N. The Impacts and Spatial Characteristics of High-Standard Farmland Construction on Agricultural Carbon Productivity. *Sustainability* **2024**, *16*, 1481. [CrossRef]
34. Gorjian, S.; Ebadi, H.; Trommsdorff, M.; Sharon, H.; Demant, M.; Schindele, S. The advent of modern solar-powered electric agricultural machinery: A solution for sustainable farm operations. *J. Clean. Prod.* **2021**, *292*, 126030. [CrossRef]
35. Guo, Z.; Zhang, X. Carbon reduction effect of agricultural green production technology: A new evidence from China. *Sci. Total Environ.* **2023**, *874*, 162483. [CrossRef]
36. Liu, Y.; Liao, W.; Zhang, X.; Qiu, H. Impact of high standard farmland construction policy on chemical fertilizer reduction: A case study of China. *Front. Environ. Sci.* **2023**, *11*, 1256028. [CrossRef]
37. Chen, Y.; Lu, H.; Luo, J. How does agricultural production outsourcing services affect chemical fertilizer use under topographic constraints: A farm-level analysis of China. *Environ. Sci. Pollut. Res.* **2023**, *30*, 100861–100872. [CrossRef]
38. Zhou, S.; Qing, C.; He, J.; Xu, D. Impact of agricultural division of labor on fertilizer reduction application: Evidence from Western China. *Int. J. Environ. Res. Public Health* **2023**, *20*, 3787. [CrossRef] [PubMed]
39. Zhou, Y.; Li, X.; Liu, Y. Cultivated land protection and rational use in China. *Land Use Policy* **2021**, *106*, 105454. [CrossRef]
40. Wang, Y.; Lu, H.; Chen, Y.; Yang, P.; Cheng, X.; Xie, F. The Impact of Farmland Management Rights Mortgage Loan on the Agri-Food Industrial Agglomeration: Case of Hubei Province. *Land* **2023**, *12*, 1389. [CrossRef]
41. Yang, S.; Li, W. The Impact of Socialized Agricultural Machinery Services on the Labor Transfer of Maize Growers. *Agriculture* **2023**, *13*, 1249. [CrossRef]
42. Sun, X.; Zhang, L.; Wang, Z. The impact of well-facilitated farmland construction on agricultural production: From the perspectives of agricultural factor elasticity and agricultural total factor productivity. *China Rural Surv.* **2023**, *4*, 89–108.
43. Zang, L.; Wang, Y.; Ke, J.; Su, Y. What drives smallholders to utilize socialized agricultural services for farmland scale management? Insights from the perspective of collective action. *Land* **2022**, *11*, 930. [CrossRef]
44. Zhu, Y.; Huo, C. The impact of agricultural production efficiency on agricultural carbon emissions in China. *Energies* **2022**, *15*, 4464. [CrossRef]
45. Du, Y.; Liu, H.; Huang, H.; Li, X. The carbon emission reduction effect of agricultural policy—Evidence from China. *J. Clean. Prod.* **2023**, *406*, 137005. [CrossRef]
46. Wu, Y.; Shen, J.; Zhang, X.; Skitmore, M.; Lu, W. The impact of urbanization on carbon emissions in developing countries: A Chinese study based on the U-Kaya method. *J. Clean. Prod.* **2016**, *135*, 589–603. [CrossRef]
47. Zhang, Z.; Meng, X.; Elahi, E. Protection of cultivated land resources and grain supply security in main grain-producing areas of China. *Sustainability* **2022**, *14*, 2808. [CrossRef]
48. Li, Y.; Han, X.; Zhou, B.; Lv, L.; Fan, Y. Farmland Dynamics and Its Grain Production Efficiency and Ecological Security in China's Major Grain-Producing Regions between 2000 and 2020. *Land* **2023**, *12*, 1404. [CrossRef]
49. Cao, Y.; Bai, Y.; Zhang, L. The impact of farmland property rights security on the farmland investment in rural China. *Land Use Policy* **2020**, *97*, 104736. [CrossRef]
50. Tang, Y.; Lu, X.; Yi, J.; Wang, H.; Zhang, X.; Zheng, W. Evaluating the spatial spillover effect of farmland use transition on grain production–An empirical study in Hubei Province, China. *Ecol. Indic.* **2021**, *125*, 107478. [CrossRef]
51. Hu, N.; Hu, Y.; Luo, Y.; Wu, L. The Effect of High-Standard Farmland Construction Policy on Grain Harvest Losses in China. *Land* **2024**, *13*, 1058. [CrossRef]
52. Wang, S.; Bai, X.; Zhang, X.; Reis, S.; Chen, D.; Xu, J.; Gu, B. Urbanization can benefit agricultural production with large-scale farm-ing in China. *Nat. Food* **2021**, *2*, 183–191. [CrossRef] [PubMed]
53. Ke, S.; Wu, Y.; Cui, H.; Lu, X. The mechanisms and spatial-temporal effects of farmland spatial transition on agricultural carbon emission: Based on 2018 counties in China. Environmental Science and Pollution Research. *Environ. Sci. Pollut. Res.* **2023**, *30*, 107716–107732. [CrossRef] [PubMed]
54. Cheng, Y.; Hu, Y.; Zeng, W.; Liu, Z. Farmer heterogeneity and land transfer decisions based on the dual perspectives of economic endowment and land endowment. *Land* **2022**, *11*, 353. [CrossRef]
55. Li, M.; Wang, J.; Zhao, P.; Chen, K.; Wu, L. Factors affecting the willingness of agricultural green production from the perspective of farmers' perceptions. *Sci. Total Environ.* **2020**, *738*, 140289. [CrossRef] [PubMed]

56. Gu, Z.; Liang, X.; Liu, J.; Han, B.; Zhou, Y. Diversification of food production in rapidly urbanizing areas of China, evidence from southern Jiangsu. *Sustain. Cities Soc.* **2024**, *101*, 105121. [CrossRef]
57. Zhu, W.; Chen, J.; Liang, X.; Li, D.; Chen, K. Government regulations, benefit perceptions, and safe production behaviors of family farms—A survey based on Jiangxi Province, China. *J. Clean. Prod.* **2024**, *450*, 141824. [CrossRef]