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Influence of Climate Change on Carbon Emissions during Grain Production and Its Mechanism

Muziyun Liu * and Hui Liu *

School of Economics, Hunan Agricultural University, Changsha 410128, China
* Correspondence: lmuziyun@163.com (M.L.); liuh1220@163.com (H.L.)

Abstract: Abnormal climatic changes and related disasters are increasing in prevalence, with many negative impacts on ecosystems and agricultural production. The area of land in China is vast, including diverse terrain and climate types, and a substantial area is used to grow food crops. Therefore, climate change is having a huge impact on China's grain production. Currently, the relationship between climate change and carbon emissions during grain production and the underlying mechanism have not been fully clarified. Therefore, this study used an ordinary least squares regression (OLS) model and the system generalized method of moments (SYS-GMM) to examine the influence of climatic change and carbon emissions during grain production, and we constructed mediation effect models to explore the mechanism of influence between them by utilizing panel data in China from 2000 to 2020. In addition, we also examined the adjustment effect of green technology progress and farmland scale. The study found that China's carbon emissions during grain production increased from 2000 to 2015 and then presented a decreasing trend after 2015. We found that the annual average temperature has a prominent positive effect on carbon emissions during grain production, while the annual average rainfall has a negative effect. Among them, temperature changes mainly lead to the increase in carbon emissions during grain production through the increase in "fertilizer use" and "multiple cropping index", but the mechanism of rainfall changes' impact on carbon emissions during grain production is still unclear. In addition, green technology progress and farmland scale play adjustment roles in the impact of climate change on carbon emissions during grain production, and they could significantly suppress carbon emissions. On the basis of the conclusions in this paper, we propose that strengthening climate change adaptation is an important prerequisite for reducing carbon emissions during grain production. Furthermore, China should continue to reduce fertilizer use, facilitate the application of agriculture green technology, and expand the scale of farmland to achieve agricultural carbon emission reduction.

Keywords: climate change; carbon emissions during grain production; green technology progress; farmland scale; fertilizer use; multiple cropping index

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1. Introduction

China's basic national conditions of more people and less land mean that food security has always been China's primary strategic issue. The No. 1 document of China in 2023 makes it clear that we need to pay close attention to stabilizing the production and supply of grain, strengthening agricultural meteorological disaster prediction, and ensuring China's food security. Since the establishment of the People's Republic of China, its grain production has jumped from 113.18 million tons in 1949 to 686.53 million tons in 2022, which means it has doubled several times. However, the rapid growth of China's grain production has relied on the excessive use of chemical fertilizers, pesticides, and agricultural plastic film. This has also led to the deterioration of the quality of China's cultivated land and water pollution and seriously restricts China's grain production capacity [1,2].

At the same time, climate change has generated negative impacts such as continuous increases in temperature and the frequent occurrence of extreme weather events, seriously

affecting global food security. In its sixth assessment report in 2022, the Intergovernmental Panel on Climate Change (IPCC) pointed out that the Earth may face hazards such as ecosystem collapses, heat waves, and floods, which will directly lead to a reduction in grain production. Ortiz et al. [3] found that climate change has decreased the total factor productivity of global agriculture. The increase in CO2 emissions is the root cause of global warming and the frequent occurrence of extreme weather [4]. Moreover, CO2 emissions will negatively affect the Earth's climate and ecological environment, thereby threatening the sustainability of the food system [5–7]. In September 2020, China made a guarantee to realize a carbon emission peak by 2030 and achieve carbon neutrality by 2060. The 20th National Congress of China mentioned that we should make concerted efforts to promote carbon emission reduction, speed up pollution control, actively respond to climate change, and fulfill China's emission reduction commitments. China's nitrogen fertilizer production and consumption levels are among the highest in the world, and carbon dioxide emissions from agricultural activities make up 17% of the total carbon emissions [8,9]. According to data from the National Bureau of Statistics, the sown area of grain in China accounted for 69.7% of the total sown area of crops in 2020. Therefore, we must consider the inspection of the influence and mechanism of climate change on carbon emissions during grain production.

Agricultural carbon emissions are a crucial issue concerning the sustainable development of agriculture, even for human beings. Current research has mainly focused on the following aspects: First is the calculation of agricultural carbon emissions. At present, mainstream calculation starts from crop production and livestock breeding, and the sources of carbon emissions include rice cultivation, fossil fuel combustion, livestock manure emissions, and fertilizer use [10–12]. Among them, carbon emissions from crop planting mainly come from straw burning, rice planting, farmland emissions, machinery use, nitrogen fertilizer, and pesticide use [13]. Second is the indicators affecting agricultural carbon emissions, comprising urbanization, agricultural operation scale, rural economic condition, agricultural technology progress, planting structure, agricultural population size, energy consumption, and so on [14–18]. Zhong et al. [19] found that the digital economy has dampened carbon emission intensity in agriculture, and this dampening effect has been achieved through technological advancements in agriculture. In addition, the adoption of drip irrigation technology and improved farming practices in agricultural planting activities has helped reduce carbon emissions [20,21].

In addition, some researchers found that higher temperature and less frequent rainfall would lead to lower grain production and threaten food security. Climate disasters and extreme temperatures would also cause losses in grain production [22–26]. On the one hand, temperature and precipitation largely determine the process of crop growth and development [27]. On the other hand, temperature, precipitation, or extreme weather can affect food production by changing farmers' production behavior [28,29]. This is mainly reflected that farmers will avoid the adverse effects of climate change by improving crop varieties, adjusting crop sowing and harvesting times, adjusting the use of fertilizers and pesticides, and repairing agricultural irrigation and water conservancy facilities [30–35]. These climate adaptation measures will also increase the input of chemical fertilizers, machinery, and so on, giving rise to the release of carbon dioxide. In addition, Saude et al. [36] found that climate change has caused the planting boundaries of single-cropping rice and double-cropping rice to shift significantly northward. Liang et al. [37] believe that climate change will increase the multi-cropping index of China's agriculture and improve its grain production capacity. Feizienė and Kadžienė [38] found that when the use of chemical fertilizers in agricultural production increases, it will bring about an increase in agricultural carbon emissions.

Generally speaking, there are relatively few studies investigating the influence of climate change and carbon emissions on grain production. The relevant literature has neither directly explored the mechanism of climate change on carbon emissions from grain production nor paid attention to the farmland scale and agriculture green technology progress.

There is a vast area of land in China, with diverse climates. The abnormal temperatures and irregular precipitation brought about by climate change have had a major impact on Chinese farmers' planting plans, crop yield and quality, farmland management, pests and diseases, and other aspects. So, will climate change affect the carbon emissions in China's grain production? Additionally, by what mechanism does climate change affect carbon emissions in the process of food production? Under the background of China's current efforts to achieve rural revitalization and green agricultural development, answering these questions is highly significant for the promotion of sustainable food production.

Therefore, we applied an ordinary least squares regression (OLS) model and the system generalized method of moments (SYS-GMM) to assess the influence and mechanism of climate change on carbon emissions during grain production by using Chinese inter-provincial panel data. On the one hand, we verified the influence of temperature and rainfall on carbon emissions during grain production and examined the adjustment role of the farmland scale and green technology progress between climate change and carbon emissions during grain production, thus providing new empirical evidence on the factors influencing carbon emissions during grain production; on the other hand, we examined the mechanism between climate change and carbon emissions during grain production, providing farmers with new ways to cope with climate change. The research provides useful policy implications for coping with climate change, promoting low-carbon agricultural development, and ensuring food and ecological security. The research is innovative in the following areas:

(1) Continuous high temperatures and the uneven distribution of precipitation seriously affect the production of grain crops. Therefore, farmers have spontaneously changed the input structure of production factors of agricultural labor, machinery, and chemical fertilizers according to climate conditions [39,40]. This has accelerated the continuous transform of China's grain production from the traditional production method of "depending on the sky" to the modern production method of chemicalization, mechanization, and water conservancy. This has contributed to a sharp increase in China's grain output, but the carbon emissions generated by grain production activities have also risen rapidly. Therefore, this paper elects annual average rainfall and temperature to represent climate change. In addition, this paper emphasizes carbon emissions during grain production, which is different from the study object of most scholars.

(2) We examined the impact of green technology progress and the farmland scale on carbon emissions during grain production and their adjustment effects. Agricultural green technology can promote agricultural productivity and improve the agricultural ecological environment, reduce agricultural carbon emissions, and achieve sustainable food production [41,42]. Therefore, unlike other scholars, we used the variable of green technology progress. Firstly, the super-efficiency Slacks-Based Measure (SBM), a model for evaluating input–output efficiency considering slack factors, was selected to measure the green total factor productivity of grain. The Global Malmquist Luenberger (GML) index is a method that uses the global production frontier to calculate indicators that include unexpected output. Therefore, we used it to construct the green total factor productivity index of grain, and the green technology progress was obtained by decomposing the index [43].

(3) We introduced intermediary variables—fertilizer use and the multiple cropping index—to explore the mechanism of climate change and carbon emissions during grain production, broadening the scope of research.

2. Materials and Methods

2.1. Research Area

China is located in the east of Asia. It has a large agricultural population, a vast land area, and complex and diverse geographical and climatic conditions and experiences frequent meteorological disasters. Therefore, China's grain industry is one of the most climate-sensitive sectors. From 1961 to 2020, China's rainfall increased by an average of

5.1 mm every 10 years, and the temperature rose by an average of 0.3 °C every 10 years. A higher temperature will prolong the planting cycle and advance the development period of food crops and shorten the growth cycle, which is conducive to the increase in food production, but it will also expand the area affected by diseases and insect pests and increase the prevalence of extreme meteorological disasters. For example, in 2008, a cryogenic disaster occurred in China, causing damage to about 14 million hectares of crops; in 2014, North China and Northeast China were hit by drought, resulting in severe water shortages in summer grain production; in 2021, continuous rainfall in northern China decreased corn production. It can be seen that grain production activities are highly affected by climate change, thereby changing the agriculture inputs and planting decisions of farmers and affecting carbon emissions.

2.2. Model Setting

Considering the rigidity of carbon sources such as fertilizers, agricultural plastic films, pesticides, and irrigation in grain planting, carbon emissions during grain production have strong temporal continuity. To reduce the influence of omitted variables and endogeneity, we established dynamic panel models to examine the influence and mechanism of climate change on carbon emissions during grain production. The formula is as follows:

$$Carbon_{i,t} = \propto_0 + \propto_1 Carbon_{i,t-1} + \propto_2 Tem_{i,t} + \propto_3 Rain_{i,t} + \propto_4 x_{i,t} + \mu_i + \varepsilon_{i,t} \quad (1)$$

$Carbon_{i,t}$ is the carbon emissions during grain production; μ_i is an individual effect that cannot be observed; $\varepsilon_{i,t}$ is a random disturbance item; $Tem_{i,t}$ is the annual average temperature; $Rain_{i,t}$ is the annual average rainfall, $\propto$ is the parameter to be estimated; and $x_{i,t}$ is all the control variables, including provincial gross domestic product, fiscal expenditure on agriculture, agricultural planting structure, agricultural irrigation, degree of natural disasters, and agricultural mechanization.

2.2.1. Adjustment Model

In addition, green technology progress (gtc) and the farmland scale (scale) were introduced into the panel regression model; you can see it in Formula (2). Their interaction terms with climate change indicators were also constructed to assess the adjustment effect.

$$\begin{aligned} Carbon_{i,t} = \delta_0 \quad & + \delta_1 Carbon_{i,t-1} + \delta_2 Tem_{i,t} + \delta_3 Rain_{i,t} \\ & + \delta_4 gtc_{i,t} \; or \; \delta_4 scale_{i,t} + \delta_5 x_{i,t} + \mu_i + \varepsilon_{i,t} \end{aligned} \quad (2)$$

$$\begin{aligned} Carbon_{i,t} = \delta_0 \quad & + \delta_1 Carbon_{i,t-1} + \delta_2 Tem_{i,t} + \delta_3 Rain_{i,t} \\ & + \delta_4 gtc_{i,t} + \delta_5 gtc_{i,t} * Tem_{i,t} + \delta_6 gtc_{i,t} * Rain_{i,t} + \delta_7 x_{i,t} + \mu_i + \varepsilon_{i,t} \end{aligned} \quad (3)$$

$$\begin{aligned} Carbon_{i,t} = \delta_0 \quad & + \delta_1 Carbon_{i,t-1} + \delta_2 Tem_{i,t} + \delta_3 Rain_{i,t} \\ & + \delta_4 scale_{i,t} + \delta_5 scale_{i,t} * Tem_{i,t} + \delta_6 scale_{i,t} * Rain_{i.t} + \delta_7 x_{i,t} + \mu_i \\ & + \varepsilon_{i,t} \end{aligned} \quad (4)$$

2.2.2. Mediation Model

To verify whether climate change affects carbon emissions during grain production through fertilizer use(fer) and the multiple cropping index(mul), we established mediation models to assess the accuracy of the impact path. The first step is the same as Formula (1), and the second and third steps are as follows:

$$\begin{aligned} fer_{i,t} &= \beta_0 + \beta_1 Tem_{i,t} \; or \; \beta_1 Rain_{i,t} + \beta_2 x_{i,t} + \mu_i + \varepsilon_{i,t} \\ mul_{i,t} &= \beta_0 + \beta_1 Tem_{i,t} \; or \; \beta_1 Rain_{i,t} + \beta_2 x_{i,t} + \mu_i + \varepsilon_{i,t} \end{aligned} \quad (5)$$

$$Carbon_{i,t} = \delta_0 + \delta_1 Carbon_{i,t-1} + \delta_2 Tem_{i,t} + \delta_3 Rain_{i,t} + \theta fer_{i,t} + \delta_4 x_{i,t} + \mu_i + \varepsilon_{i,t}$$
$$Carbon_{i,t} = \delta_0 + \delta_1 Carbon_{i,t-1} + \delta_2 Tem_{i,t} + \delta_3 Rain_{i,t} + \theta mul_{i,t} + \delta_4 x_{i,t} + \mu_i + \varepsilon_{i,t} \quad (6)$$

2.3. Variable Description

2.3.1. Explained Variables

This paper only studied carbon emissions during grain production; therefore, it was necessary to strip the sources of carbon emissions in agricultural. First, according to the research of other scholars, we ascertained the sources of carbon emissions in agriculture, namely fertilizers, pesticides, agricultural plastic films, diesel, ploughing, and irrigation [19,44]. Then, we multiplied each source of carbon emissions by coefficient A, where coefficient A is equal to the area sown for food divided by the total area sown for crops. Thus, the emissions of each source of carbon emissions in grain production were obtained, which is T_i. δ_i is the convert coefficient. Based on the data released by Chinese and foreign laboratories, the carbon emission coefficients of fertilizers, pesticides, and agricultural plastic films were 0.8956 kg·kg^{-1}, 4.9341 kg·kg^{-1}, and 5.18 kg·kg^{-1}. The carbon emission coefficients of diesel and ploughing were 0.5927 kg·kg^{-1} and 312.6 kg·km^{-2}, and the coefficient of agricultural irrigation was 20.476 kg·hm^{-2} [44,45]. Finally, we calculated the carbon emissions during grain production, which is E_i. Considering the obvious differences in grain production and production function among provinces, for the sake of the accurate and fair portrayal of grain carbon emissions, carbon emission intensity was used in the panel model. The calculation method is shown in Table 1.

$$E = \sum E_i = \sum T_i * \delta_i \quad (7)$$

Table 1. Factors that influence carbon emissions during grain production.

Variable Type	Variable Name	Variable Description
Explained variable	Carbon	Carbon emissions during grain production/area sown for grain crops
Explanatory variable	tem	Annual temperature
	rain	Annual rainfall
Intermediary Variables	fer	Consumption of chemical fertilizers
	mul	Area sown to grain crops/farmland area
Adjustment Variables	gtc	Green technology progress
	scale	Farmland area/rural population
Control variable	gdp	Provincial Gross Domestic Product
	gov	Fiscal expenditure on agriculture, forestry and water conservancy affairs
	str	Planting area of food crops/total planting area of crops
	dis	Total area of agricultural disaster
	irr	Effective irrigation area
	mec	Total power of farming machinery

2.3.2. Explanatory Variables

Grain production is a typical process in which the natural climate and social factors act together; therefore, climate change will have a profound influence on farmers' input allocations and planting decisions in grain production. In terms of climate change, the factors with the most critical influences on planting activities are temperature and rainfall. Therefore, this study used annual average rainfall and temperature to assess their relationship.

2.3.3. Intermediary Variables

To examine the mechanism of climate change on carbon emissions during grain production, this paper selected fertilizer use (fer) and the multiple cropping index (mul) as intermediary variables. Fertilizer use is represented by the quantity of annual chemical fertilizer in each province. The multiple cropping index means the average number of crops planted in the same land area within a certain period of time, which is equal to the area sown for food crops divided by the area of planting land.

2.3.4. Adjustment Variables

In this paper, we chose green technology progress (gtc) and the farmland scale (scale) as the adjustment variables. Agricultural green technology is a set of technologies applied in agricultural production; its purpose is to reduce resource consumption and environmental pollution during agricultural production and achieve sustainable agricultural development [46–48]. To accurately calculate green technology progress during grain production, we adopted the super-efficiency Slacks-Based Measure (SBM) model and selected seven indicators of grain planting, namely labor force, land, agricultural machinery, fertilizer, pesticide, agricultural plastic films, and irrigation in grain production, as input indicators, and we used grain total output and carbon emissions during grain production as the desired and undesired outputs, respectively, and then calculated the grain green total factor productivity in each province of China. Subsequently, based on the premise of constant returns to scale, the GML index was used to construct the green total factor production efficiency of grain, and it was decomposed to obtain pure technical efficiency, scale efficiency, and green technology progress (gtc).

In addition, the basic national condition in China has always been more people and less land, which means that small-scale operations occupy an important position in China's agricultural production. However, the expansion of the farmland scale can realize the optimal combination of production factors, enhance the use efficiency of fertilizers and other inputs, and achieve carbon emission reduction [49]. In this paper, the farmland scale is the per capita cultivated area of farmers, which is equal to the area of cultivated land divided by the amount of citizens in the rural population.

2.3.5. Control Variables

Carbon emissions during grain production are influenced by many social and economic factors. Drawing on the relevant literature, the following control variables were selected: regional economic development, financial support to agriculture, planting structure, agricultural irrigation, degree of natural disasters, and farming mechanization [50–52].

2.4. Data Sources

The time dimension of grain-related data and climate data was from 2000 to 2020. Data about grain production and its input factors and carbon emission influence factors come from *China Rural Statistical Yearbook and China Environmental Statistical Yearbook* (http://www.stats.gov.cn, accessed on 2 February 2023). The carbon emission data were calculated by the author. Annual temperature and rainfall data were collected from the National Weather Data Network (http://data.cma.cn, accessed on 2 February 2023). We organized and analyzed the metrics data involved in this paper with descriptive statistics, as detailed in Table 2.

Table 2. Descriptive statistics of variables related to China's carbon emissions during grain production.

Variable Name	Mean	Standard Deviation	Minimum Value	Maximum Value
Carbon	0.532	0.24	0.149	1.384
tem	13.65	5.454	2.55	25.43
rain	940.6	448.6	200.8	2232
fer	169.6	138.5	2.500	716.1

Table 2. *Cont.*

Variable Name	Mean	Standard Deviation	Minimum Value	Maximum Value
plan	0.793	0.238	0.218	1.346
gtc	1.010	0.160	0.460	2.070
scale	3.340	2.760	0.620	21.71
gdp	15,606	17,545	117.5	110,000
gov	290	310	0.9806	1300
str	0.650	0.140	0.260	0.970
dis	1135	1077	1.100	7394
irr	1959	1536	109.2	6178
mec	2763	2687	93.97	13,353

3. Results

3.1. Trend of Carbon Emissions during Grain Production of China

According to Figure 1, it is clear that carbon emissions during grain production in China increased from 40.6712 million tons in 2000 to 52.6322 million tons in 2020, with an annual growth rate of 1.01%. Carbon emissions during grain production fluctuated upwardly since 2000, peaking at 60.0172 million tons in 2015, and then decreased. In addition, according to Figure 2, carbon emissions of fertilizer made up the highest share in grain planting, followed by agricultural plastic films, diesel, and pesticides, while ploughing and irrigation accounted for a small share, which is in agreement with the findings of Liu et al. [44]. From 2000 to 2015, carbon emissions during grain production stably increased but declined slightly in 2003. This may have been because of the sequential perfection of subsidy policies for grain planting in China. Since 2004, China has gradually reduced agricultural taxes and increased grain production subsidies to reduce farmers' costs of growing grain. Farmers' enthusiasm for growing grain has increased, causing carbon emissions to rise. However, the abuse of fertilizers and pesticides has generated the destruction of farmland ecosystems and soil and water pollution, reducing the future food production capacity. In February 2015, China's Ministry of Agriculture formulated and promulgated the "Action Plan for Zero Growth in Fertilizer and Pesticide Use by 2020". In recent years, the No. 1 Central Document of China has emphasized the need to ensure food and ecosystem security, achieving the harmonious evolution of farming production and the ecological environment. As a result, China's carbon emissions during grain production have been gradually declining since 2015.



Figure 1. Time evolution trend of total carbon emissions during grain production. (unit: 10 kt).

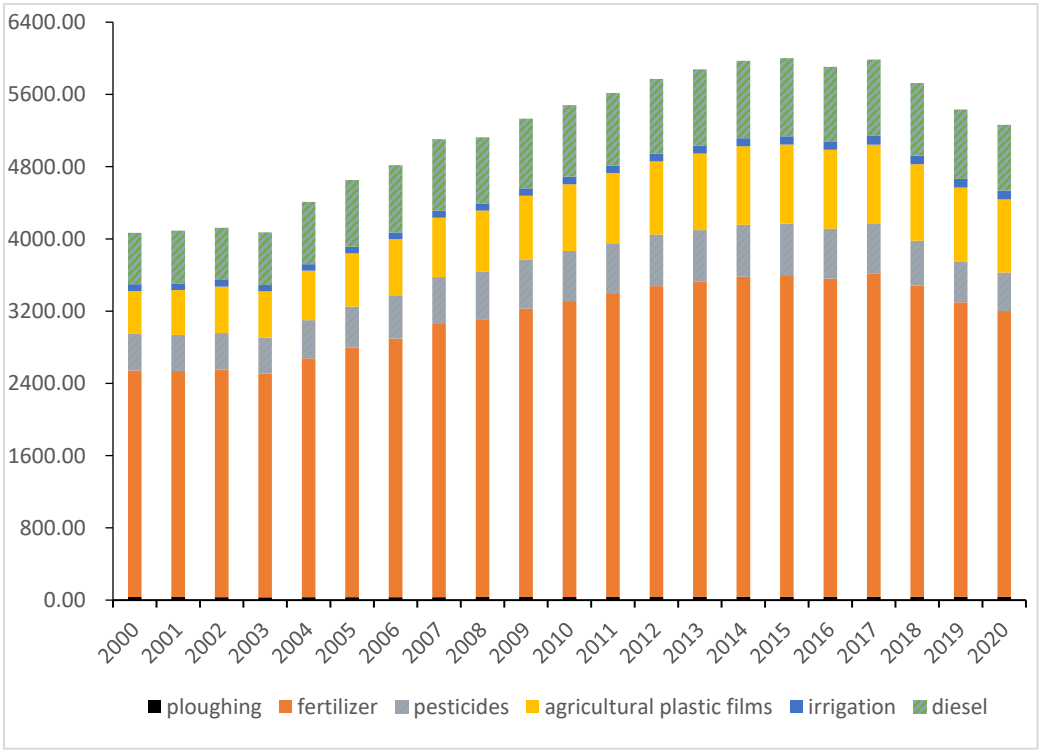

Figure 2. Sources and proportions of carbon emissions during grain production (unit: 10 kt).

According to Figure 3, we can clearly see that 10 provinces, Henan, Shandong, Hebei, Heilongjiang, Jiangsu, Anhui, Hebei, Sichuan, Jilin, and Liaoning, ranked the highest in carbon emissions during grain production, while in 7 provinces, Beijing, Tianjin, Shanghai, Henan, Tibet, Qinghai, and Ningxia, the carbon emissions were lower. It can be easily observed that provinces with high rankings of total carbon emissions during grain production are located in the main grain production areas in China, while provinces with low rankings are situated in the main grain sales areas in China. At present, China is committed to promoting green agriculture and low-carbon production, actively controlling agricultural ecological and environmental pollution, and realizing sustainable agricultural development. Therefore, the major grain producing provinces in China not only undertake the main task of protecting national food security but also need to adopt various policies and technical means to accelerate the pace of low carbon productions.

3.2. Analysis of the Influence of Climate Change on Carbon Emissions during Grain Production

The dynamic panel models were subjected to autocorrelation and over-identification tests before we validated the study results. As we used the lagged term of the dependent variable as instrumental variables, we needed to use an autocorrelation test to examine the second-order serial correlation of the random error term of the difference equation. Among them, AR1 was used to measure whether there was autocorrelation in the first-order lag item of the dependent variable; AR2 was used to measure whether there was autocorrelation in the second-order lag item of the dependent variable. According to Table 3, it shows that the AR1 *p*-value was 0.000 and the AR2 *p*-value was 0.516, showing that there was no high-order autocorrelation in the difference in the disturbance term, and the precondition of the GMM model was satisfied. In addition, we also needed to assess the validity of the instrumental variables to determine whether the instrumental variables used were related to the error term. In the over-identification test results, the *p*-value of the Hansen test was 0.835, showing that there was no over-identification. In addition, Bond et al. [53] believed that when the coefficient of the first-order lag item of the explained variable is greater than 0.8, the estimation effect of the SYS-GMM model is better. Based

on this, SYS-GMM estimation was selected for estimation in this paper, and logarithmic processing was performed on all data. To assess the robustness of the results, we replaced carbon emission intensity with the total carbon emission, and after shrinking all data, the results remained unchanged.

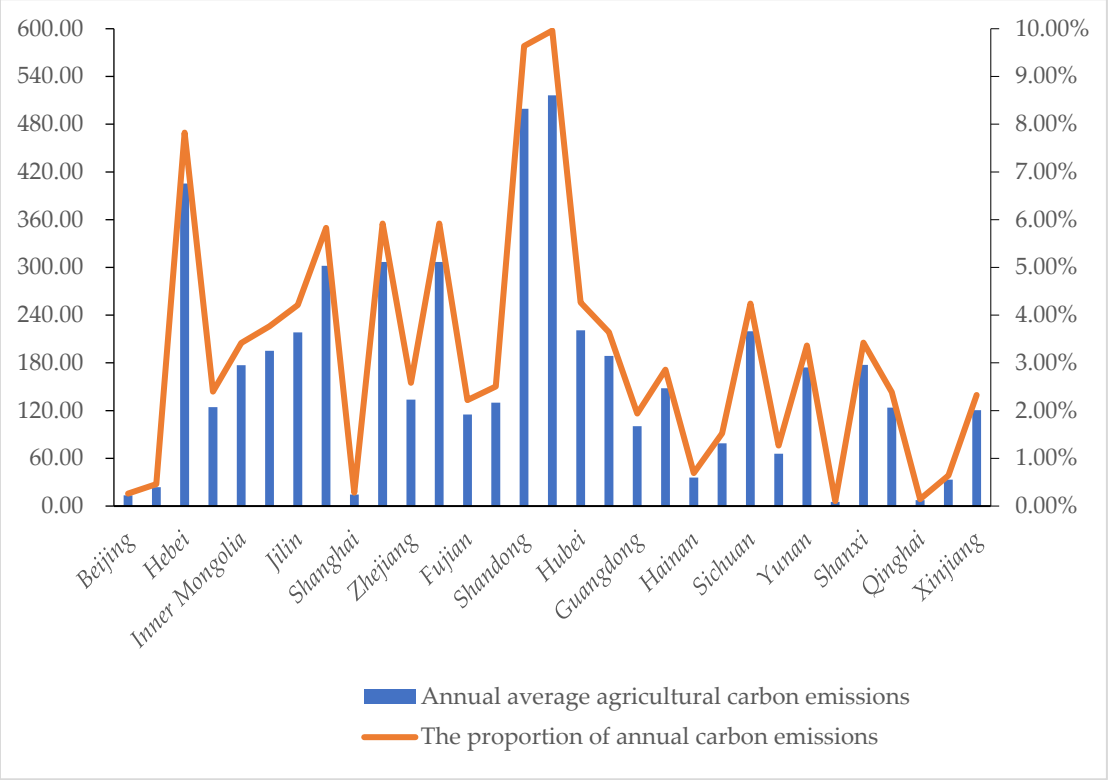

Figure 3. Total annual carbon emissions and its proportion (unit: 10 kt).

From Table 3, we can see that the first-order lagged item of carbon emissions during grain production was distinctly positive, suggesting that sources of carbon emissions during grain production are significantly rigid, and it also has obvious path dependence and time continuity. In addition, climate change has an important influence on carbon emissions during grain production, where temperature is positively related to carbon emissions during grain production, while rainfall is negatively related. This indicates that for every 1% increase in temperature, the carbon intensity of food production increases by 10.19%, while when rainfall decreases by 1%, it grows by 8.97%. The continuous rise in temperature is conducive to the prevention of freezing disasters, prolongs the planting period, and shortens the growth cycle of food crops. The improvement in climatic conditions makes Chinese farmers more willing to plant grain to obtain income. In the case of limited arable land, farmers will adopt methods such as crop rotation and intercropping to plant crops, which also give rise to an increase in the multi-cropping index of grain and chemical inputs such as fertilizers and pesticides, thus causing an increase in carbon emissions. A decrease in rainfall causes water shortages and limited grain growth. Coupled with rising temperatures, this leads to increased surface evaporation, making agricultural water resource systems more vulnerable. Moreover, extreme rainfall can also lead to nitrogen loss from the soil and insufficient nitrogen uptake by crops [54]. Therefore, farmers will increase the frequency and quantity of chemical fertilizers and use agricultural machinery to open ditches to divert water for irrigation so as to reduce the impact of reduced precipitation on agricultural planting, thereby affecting carbon emissions.

Table 3. Regression results of climate change and carbon emissions during grain production.

Variables	(1)	(2)	(3)	(4)	(5)
L.lncarbon	1.0246 ***	1.0241 ***	0.9949 ***	1.0126 ***	0.9544 ***
	−26.4271	−40.7213	−35.2711	−32.6156	−26.7356
lntem	0.1019 **	0.0562 *	0.0434	0.0772 *	0.0505
	−2.2016	−1.6655	−1.38	−1.765	−1.0087
lnrain	−0.0897 ***	−0.0886 ***	−0.0632 *	−0.1495 ***	−0.1351 ***
	(−3.2868)	(−2.9823)	(−1.8696)	(−3.8994)	(−3.4822)
lngdp	0.0015	−0.0027	0.0003	−0.0048	−0.0047
	−0.7602	(−0.6534)	−0.1259	(−1.1771)	(−1.1542)
lngov	−0.0081 ***	−0.0083 ***	−0.0078 ***	−0.0021	0.0005
	(−3.0811)	(−2.9842)	(−2.9148)	(−0.6993)	−0.1284
lnstr	0.0383	−0.0088	−0.016	0.0051	0.0336
	−0.9243	(−0.3015)	(−0.9688)	−0.112	−0.4514
lnirr	−0.021	−0.0272	−0.0136	−0.0299	−0.0777 **
	(−1.2476)	(−1.4875)	(−1.3403)	(−1.1990)	(−2.3287)
lndis	0.0146 **	0.0117 **	0.0066	0.0169 ***	0.0129 **
	−2.2689	−2.1781	−1.1697	−2.9517	−2.2785
lnmec	−0.0005	0.0132	0.0051	0.0111	0.0542 **
	(−0.0409)	−0.9455	−0.6629	−0.5742	−2.2527
_cons	0.5602 ***	0.6482 ***	0.4453 ***	0.9723 ***	0.9538 ***
		−4.5411	−2.632	−5.2651	−4.8901
c_lngtc		−0.0621 **	−0.0906 **		
		(−2.0885)	(−2.2835)		
c_Lngtc*lntem			−0.1799		
			(−1.3588)		
c_Lngtc*lnrain			0.4748 ***		
	−3.4827		−2.8262		
c_lnscale				−0.0364 **	−0.0686 ***
				(−2.2684)	(−3.6442)
c_Lnscale*lntem					−0.3497 ***
					(−3.8239)
c_Lnscale*lnrain					0.3205 **
					−2.3292
N	620	620	620	620	620
AR(1) *p* value	0.000	0.000	0.000	0.000	0.000
AR(2) *p* value	0.516	0.394	0.831	0.280	0.408
Hansen *p* value	0.835	0.741	0.798	0.827	0.814

Note: *, ** and *** indicate significant at the 10%, 5% and 1% levels, respectively; t values are in brackets.

Furthermore, areas affected by natural disasters positively affect the carbon emission intensity during grain production, while financial support to agriculture has an opposite negative impact. By looking deeper into the reasons for this, we saw that when agricultural production is faced with natural disasters such as drought or flood threats, farmers will adjust their labor allocation, fertilizer and pesticide use, agricultural machinery, and other adaptive behaviors to mitigate the negative effects, thus increasing carbon emissions [39]. When the government's financial support for agricultural production is higher, farmers can receive more subsidies for grain planting, and they are more willing to use advanced green agricultural technology for grain production, thereby reducing carbon emissions.

In addition, we introduced green technology progress, the farmland scale, and their interaction terms in the adjustment models. To reduce multicollinearity, all data were decentralized. As can be seen from Table 3, both green technology progress and farmland scale can lessen carbon emissions during grain production. The adoption of agricultural green technologies such as chemical fertilizer reduction technology, biological pesticide technology, and straw returning technology can improve the utilization efficiency of chemical fertilizers and pesticides, maintain soil fertility, and reduce carbon emissions in grain production [46,55]. In addition, the current outflow of surplus rural labor in China has pro-

moted the transfer of rural land, which is beneficial to the expansion of the farmland scale. The expansion of the farmland scale cannot only promote the agglomeration of resources and elements, but it can also facilitate the adoption of advanced agricultural machinery and agricultural green technologies, which can further lessen the input of chemical fertilizers and pesticides and help to reduce carbon emissions [56,57]. Furthermore, the coefficients of lngtc*lnrain and Lnscale*lnrain are both significantly positive, while the coefficient of Lnscale*lntem is negative. This indicates that green technology progress and farmland scale can adjust the influence of climate change on carbon emissions during grain production.

3.3. Mechanism of Climate Change on Carbon Emissions during Grain Production

On the basis of the steps and principles in the mediation effect test, we tested the mediative role of fertilizer use and the multiple cropping index. From Table 4, we found that temperature was positively and significantly correlated with both fertilizer use and the multiple cropping index. The coefficient of temperature became insignificant, and the value decreased from 0.1019 to 0.0683 after adding the fertilizer use. The coefficient of temperature became insignificant too, and the value decreased from 0.1019 to 0.081 after adding the multiple cropping index. This means that both fertilizer use and the multiple cropping index have fully mediated effects. In addition, the regression coefficients of rainfall and fertilizer use and the multiple cropping index were not significant, indicating that chemical fertilizer use and the multiple cropping index do not have mediating effects on rainfall to carbon emissions during grain production. This may be because the time and space distribution of rainfall in China has a disequilibrium. The rainfall is concentrated in summer, and the rainy season is long in the south and short in the north. Moreover, the rainfall in the southeastern coastal areas is relatively high, and the climate is humid, while the inland areas in the northwest have little precipitation and the climate is dry. Therefore, to alleviate the negative influence of the imbalanced distribution of rainfall, China has constructed water conservancy facilities for farmland. During the rainy season, water is stored to avoid the backwatering of farmland, and in the dry season, water is diverted for irrigation to prevent farmland from drying up.

Based on the actual analysis, it is clear that climate warming will lead to an increase in average temperature and accumulated temperature and contribute to a longer planting period for food crops and a shorter growth cycle. Farmers can grow food crops in multiple seasons; therefore, the multiple cropping index of food crops will grow, as well as the fertilizer demand, thereby increasing carbon emissions. Sun et al. [58] also found that climate warming has generated shorter crop cycles and longer planting times in northern China. According to the China Meteorological Administration, China's agricultural climate resources have changed significantly, with an increase in active cumulative temperatures and a longer crop growing season. The acreage of corn and rice that can be planted in Northeast China has increased, and the double-season rice planting area in the south and winter wheat planting area in the north have expanded together. This agrees with the research findings of Saud et al. [36] and Liang et al. [37]. Moreover, the increase in the multiple cropping index will lead to more production activities such as fertilization, pesticide spraying, irrigation, mechanical sowing, and so on, which will result in an increase in carbon emissions [50,56]. In addition, the paper conducted a Sobel test, and the Z values were 3.472 and 9.219, respectively, which both passed the 1% significance test. Based on this, we can conclude that temperature changes mainly affect carbon emissions from food production through "fertilizer use" and the "multi-cropping index".

Table 4. Mechanism of climate change on carbon emissions during grain production.

Variables	(1) Lncarbon	(2) lnfer		(3) Lncarbon	(4) Lnmul		(5) Lncarbon
lntem	0.1019 **	0.2652 ***	0.0093	0.0683	0.2730 ***	0.0568	
	−2.2016	−2.6214	−0.1613	−1.4268	−5.6182	−1.5047	
Lnrain	−0.0897 ***			−0.1073 ***			−0.0919 ***
	(−3.2868)			(−4.0302)			(−2.9811)
lnfer				0.1109 *			
				−1.9406			
lnmul							0.1384 ***
							−2.8723
lngdp	0.0015	0.0089 **	0.0089 **	−0.0004	0.0018	0.0011	0.0004
	−0.7602	−2.2614	−2.3388	(−0.2172)	−0.5628	−0.3268	−0.1822
lngov	−0.0081 ***	0.0462	0.0411	−0.0073 **	−0.0147	−0.0102	−0.0093 ***
	(−3.0811)	−0.9489	−0.8366	(−2.0437)	(−0.4266)	(−0.2768)	(−2.9332)
lnstr	0.0383	0.0228	0.0032	0.0291	1.0663 ***	1.1460 ***	−0.0091
	−0.9243	−0.138	−0.0189	−0.5265	−6.0053	−6.1185	(−0.1718)
Lnirr	−0.021	0.5252 ***	0.4853 ***	−0.0915 **	0.0252	0.0468	−0.0301
	(−1.2476)	−4.3043	−3.686	(−2.5255)	−0.3343	−0.4179	(−1.6099)
lndis	0.0146 **	0.0270 *	0.0282 *	−0.0032	0.0073	0.0109	0.0141 *
	−2.2689	−1.8225	−1.8715	(−0.2944)	−0.8079	−1.2832	−1.7383
lnmec	−0.0005	0.2741 ***	0.2777 ***	−0.0292	0.1244 **	0.1376 **	−0.0102
	(−0.0409)	−3.2179	−3.2246	(−1.3443)	−2.0312	−2.2286	(−0.5672)
L.lncarbon	1.0246 ***			0.9653 ***			1.0344 ***
	−26.4271			−24.4681			−22.0242
_cons	0.5602 ***	−2.6187 ***	−1.7285 *	1.0524 ***	−1.4318 **	−1.4237	0.8189 ***
	−3.4827	(−2.9858)	(−1.8614)	−5.175	(−2.3652)	(−1.4984)	−3.7828
N	620	651	651	620	651	651	620
adj. R2		0.6291	0.6372		0.596	0.589	
AR(1) *p*-value	0.000			0.000			0.000
AR(2) *p*-value	0.516			0.464			0.494
Hansen *p*-value	0.835			0.854			0.846

Note: *, ** and *** indicate significant at the 10%, 5% and 1% levels, respectively; t values are in brackets.

4. Conclusions

In this research, we explored the influence and mechanism of climate change on carbon emissions during grain production and examined the adjustment effect of green technology progress and the farmland scale. Dynamic panel models were also constructed to empirically test the research scenario by using data from 31 provinces in China. The main findings are as follows:

(1) The results show that climate change has an important influence on carbon emissions during grain production, in which temperature is positively related to carbon emissions during grain production, while rainfall is negatively related to carbon emissions during grain production. Furthermore, temperature changes mainly affect the carbon emissions during grain production through "fertilizer use" and the "multiple cropping index", which is also in line with the actual situation regarding China's grain production.

(2) Green technology progress and the farmland scale can significantly reduce carbon emissions during grain production. At the same time, they also play important adjustment roles. Among them, the farmland scale can lessen the negative impact of temperature and rainfall changes on carbon emissions of grain production. The positive adjustment effect of green technology progress mainly reflects the influence of rainfall on carbon emissions during grain production.

The research results have significant value in policies for coping with climate change, reducing carbon emissions during grain production, and promoting sustainable grain

production. (1) Climate change is an increasing threat to ecosystems and food systems. The agricultural sector should jointly evaluate the influence of extreme weather, strengthen the capacity of agricultural meteorological disaster monitoring and forecasting, provide accurate meteorological services, and provide a basis for farmers to adapt to climate change and arrange agricultural production in advance. (2) The government should use financial means to facilitate the adoption of green technologies such as soil testing for formulated fertilization technology and green pest control technology. In addition, the government should also combine financial subsidies with environmentally friendly behaviors such as fertilizer and pesticide reduction, straw utilization, and plastic film recycling, so as to provide economic incentives to reduce carbon emissions during grain production. (3) Government departments should continue to promote rural land transfer, expand the scale of farmland, and make full use of the advantages of factor agglomeration and technological advantages of large-scale operations to reduce carbon emissions.

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