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Quantitative Assessment of Climate Change Impact and Anthropogenic Influence on Crop Production and Food Security in Shandong, Eastern China

Junqi Cheng and Shuyan Yin *

School of Geography and Tourism, Shaanxi Normal University, Xi'an 710119, China; junqicheng@snnu.edu.cn
* Correspondence: yinshy@snnu.edu.cn

Abstract: Food security plays an important role in maintaining national stability and sustainable development of human society, and its research has become a hot issue at present. Shandong is the main grain producing area in China, and its grain production plays an important role in national food security. Accordingly, this paper is based on the county climate change, grain yield, sown area, fertilizer use, total power of rural machinery, and total population data in Shandong Province from 1995 to 2020. The evolution process of the food security pattern was studied by the methods of spatial analysis and comprehensive evaluation, the influencing factors of food security were quantitatively analyzed, and the adaptive countermeasures to alleviate the food security risks in this region were discussed. The results show that: Grain production increased by 30.62% from 1995 to 2020. The total population and per capita food availability also increased. Since 2000, more than a quarter of counties have experienced a high risk of food insecurity. The spatial agglomeration of grain production was enhanced, and the local agglomeration characteristics were significantly different. The average temperature in the growing season, the sown area, and the total power of agricultural machinery had a significant positive impact on grain production, while the annual average temperature had a significant negative impact on grain production. Improving the food supply system, strengthening the protection of cultivated land, improving the efficiency of fertilizer utilization, and increasing investment in agricultural science and technology can effectively alleviate food security risks.

Keywords: food supply; food security; spatial autocorrelation; panel model; Shandong

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1. Introduction

The Food and Agriculture Organization of the United Nations (FAO) has defined 'food security' three times, namely 'anyone can get enough food for survival and health at any time' in 1974, and 'anyone can get enough food for survival and health' in 1983. The basic foodstuffs they need are both available and affordable at all times [1] is another explanataion, and the 1996 definition: 'Enable all people at all times to have material and economic access to adequate and safe food and nutritious food to meet their dietary needs and food preferences for an active and healthy life' [2,3].

The issue of food security is an overall and fundamental strategic issue involving the national economy and social stability of our country and is an important cornerstone for safeguarding national security [4]. There are many factors that affect food security, not only natural factors, but also social factors. The existing literature has studied many factors affecting food security from the perspective of single factor influence and multi-factor coupling and synergy. The influencing factors involved include climate change [5–8], urbanization [9–11], land-use change [12–14], land-use policy [15–17], water management [18,19], fertilizer use [20,21], and soil degradation [22,23]. The academic community has carried out a series of studies on China's grain production and its influencing factors. The results show that the regional differences in total grain output [24], per capita grain output [25], grain production structure [26], and grain production efficiency [27] are important reasons for the changes in the temporal and spatial pattern of grain. The research methods mainly include the nexus approach [28,29], spatial autocorrelation analysis [30], etc. However, there are still many challenges in the field of food security at present. Along with the achievements of food security, there are also many hidden crises, which inhibit the stable, sustainable, and healthy development of China's food. At the same time, the domestic and foreign environment has changed, which has had a serious impact on the national food security, causing the national food security to face new problems. The existing food security concepts and food policies have been challenged, and the existing research results are no longer sufficient to support the needs of China's food security strategic decision making in the new era. Therefore, based on the domestic and foreign environment in the new era, it is necessary to rethink the key issues and countermeasures involved in food security.

Shandong is a major agricultural province in China and one of the main grain producing areas. The grain production in this region plays an important role in national food security. Since the 1990s, due to rapid urbanization and economic development, a large amount of farmland has been encroached on, putting enormous pressure on crop production and food security in the region. In order to better reveal the food security problems facing the world, it is imperative to quantitatively analyze the influencing factors of the food security pattern.

This work aims to analyze and quantify the impact of climate change, grain yield, planting area, fertilizer use, total rural machinery power, and total population on grain production and local food security in Shandong during 1995–2020. The specific goals of this work are to (1) determine the spatial accumulation of food production and the temporal and spatial variation characteristics of local food security patterns, (2) distinguish the different impacts of each influencing factor on food production in the study area, and (3) discuss mitigation in this area and adaptive responses to food security risks.

2. Data and Methods

2.1. Study Area

Shandong Province is a coastal province in East China, located between 34°22.9′~38°24.0′ N and 114°47.5′~122°42.3′ E (Figure 1). The terrain is dominated by mountains and hills, the east is the Shandong Peninsula, the west and north belong to the North China Plain, and the central and southern parts are mountains and hills, forming a landform with mountains and hills as the skeleton, where the plains and basins are intertwined. Shandong is a key production area of grain crops and cash crops in the country, and is known as 'the storehouse of grain, cotton, and oil, the hometown of fruits and aquatic products'. The output of wheat, corn, sweet potatoes, soybeans, millet, sorghum, cotton, peanuts, flue-cured tobacco, and hemp is very large and occupies an important position in the country. The region belongs to the warm temperate monsoon climate zone, with four distinct seasons, sufficient sunlight, and the same season of rain and heat. It is suitable for the growth and development of a variety of crops and plays an important role in national food security [31].

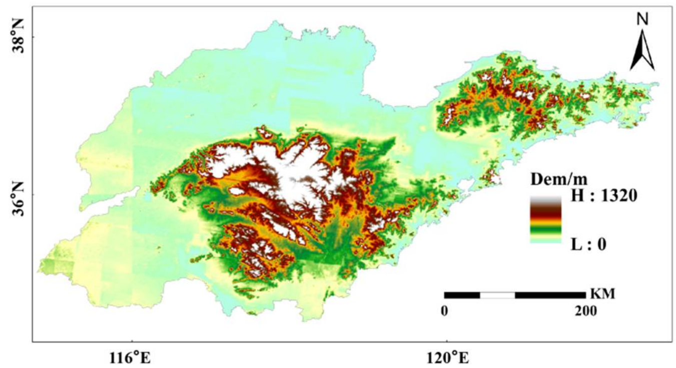

Figure 1. Location map of the study area.

2.2. Data Source

2.2.1. Food Security Indicators

In this study, the total output of county-level grain was used as the measure of grain production. The food security situation is divided into five categories: severe shortage (<150 kg per capita per year), moderate shortage (150–300 kg per capita per year), supply-demand balance (300–400 kg per capita per year), moderate surplus (400–600 kg per capita per year), and severe surplus (>600 kg per capita per year) [4,25]. The first three categories can be considered high, medium, and low risks to food security, while the last two categories are considered no risk to food security.

2.2.2. Spatial Autocorrelation

Spatial dependence refers to the consistency between the similarity of the attribute value of the research object and the similarity of its location [32]. Spatial autocorrelation is an important form of spatial dependence, which refers to the correlation between a research object and its spatial location. Spatial autocorrelation is an important indicator to test whether the attribute value of a certain element is significantly related to the attribute value of its adjacent spatial points [33,34], which can be divided into two categories: positive correlation and negative correlation. A positive correlation indicates that the attribute value change of a unit has the same trend as its adjacent spatial units, and a negative correlation is the opposite.

(1) Global space autocorrelation: Global spatial autocorrelation is a description of the spatial characteristics of attribute values in the entire region. There are many indicators and methods to express global spatial autocorrelation, mainly including connection statistics, Moran's *I*, Geary's C, and Getis' G, among which Moran's *I* is commonly used. Moran's *I* is used to measure the interrelationship of spatial elements. It is similar to the correlation coefficient in general statistics. Its value is between 1 and −1. If it is greater than zero, it indicates that there is a positive spatial correlation. Otherwise, it is a negative correlation. Its calculation formula is as follows:

$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}(x_i - \overline{x})} \quad (1)$$

In the formula: I is the Global Moran index; n is the number of provincial units; x_i and x_j are the grain production in i and j provinces, respectively; and $\overline{x}$ is the mean of food production. W_{ij} is the Queen-based spatial adjacency matrix; the value range of the Global Moran's I index is $[-1, 1]$, and the Global Moran's I index is statistically tested according to the Z value [34]. The calculation formula of the Z value is:

$$Z = \frac{I - E(I)}{\sqrt{VAR(I)}} \quad (2)$$

If $Z > 0$ and significant, it indicates that there is a significant positive spatial correlation of grain production; if $Z < 0$, it indicates that there is a negative spatial correlation of grain production; if $Z = 0$, it indicates that grain production is randomly distributed.

(2) Local space autocorrelation: Although the global spatial autocorrelation analysis reflects the overall spatial agglomeration of grain production, it cannot determine its local spatial agglomeration. Therefore, the local spatial autocorrelation is used to make up for its insufficiency, identify the local spatial heterogeneity, and further

measure the local spatial autocorrelation characteristics. The measurement method is expressed by Local Moran's I index, and the formula is as follows:

$$I_i = n(x_i - \overline{x})\sum_{j=1}^{n} W_{ij}(x_j - \overline{x}) / \sum_{i=1}^{n}(x_i - \overline{x})^2 \quad (3)$$

If I_i is positive, it means H-H (high-high) and L-L (low-low) spatial agglomeration of grain production; when I_i is negative, it means H-L (high-low) and L-H (low-high) spatial agglomeration of grain production.

2.2.3. Influencing Factors

Food production is mainly affected by climate change, population size and structure, fertilizer use intensity, sown area, agricultural technology and seed production levels, food policy, and international trade [17,35,36]. Due to limitations in data availability, this paper focuses on climate change, total population, fertilizer scalar, total power of agricultural machinery, and sown area.

(1) Model Construction

In view of the fact that the data used in the research on the influencing factors of food production include both time series and cross-sectional data, only using traditional OLS estimation that ignores spatial effects may lead to bias in the model setting process, resulting in biased regression results [37]. However, the spatial panel econometric model nests the spatial interaction effect and pays attention to the interaction between variables due to spatial dependence and spatial spillover. Therefore, the spatial panel econometric model [38,39] is used to investigate the influencing factors of food production. The formula is as follows [40]:

$$y_{it} = \delta\sum_{j=1}^{n} W_{ij}y_{ij} + \lambda\sum_{i=1}^{n} W_{ij}U_{jt} + \beta_1 X_{it} + \mu_i + \lambda_t + \beta_0 + \varepsilon \quad (4)$$

where i and j represent the province; t is the year; y_{it} represents the grain production in province i in period t; X_{it} represents a series of factors affecting grain production in province i in period t (Table 1); δ, λ represent the spatial lag values of the regression coefficient and spatial error coefficient, respectively; β_0, β_1 represent the coefficient to be estimated; W_{ij} is an element in the spatial weight matrix W; U_{jt} represents the random error vector of j province in period t, μ_i represents the spatial fixed effect; λ_t represents the time fixed effect; and ε represents Random perturbation term.

Table 1. Factors influencing food production.

Type	Index
Geographical environment	Growing season temperature and precipitation, average annual temperature and precipitation, sown area
Socioeconomic	Total population
Factor input	Fertilizer usage (in scalar volume), total power of agricultural machinery

(2) Index selection

Eight factors were selected from the three aspects of geographical environment, social economy, and factor input to analyze the influencing factors of food production [41–44] (Table 1).

2.3. Data

The meteorological data used in this study were obtained from the National Meteorological Data Center of China (http://data.cma.cn/) (accessed on 27 April 2021). The daily average temperature and precipitation data from 22 national meteorological stations in Shandong Province from 1995 to 2020 were selected. To reveal the impact of climate change on crop yields, growing season (March to October) temperature, precipitation, annual mean temperature, and precipitation were used as meteorological inputs to the panel model. The monthly precipitation and average temperature at the county level were extracted using ArcGIS zoning statistics and county-level administrative division maps. The county-level statistics on grain output, sown area, total population, fertilizer use, and total power of agricultural machinery were sourced from the Shandong Statistical Yearbook.

3. Results

3.1. Trends in Food Production and Food Security

Grain output in Shandong Province displayed an increasing trend, from 42.464 million tons in 1995 to 54.4681 million tons in 2020, an increase of 30.62%, and the average growth rate (1.18%) was lower than the national average (1.75%). The population of the region was also increasing (16.77%), and the per capita food supply also increased from 487.6 kg in 1995 to 527 kg in 2020.

From 2015 to 2020, the number of counties with severe food shortage increased by 13, moderate shortage increased by 15, moderate surplus decreased by 17, and severe surplus increased by 14 (Table 2). In particular, since 2000, more than a quarter of counties have experienced a high risk of food insecurity (i.e., severe or moderate shortages).

Table 2. Shandong county-level per capita grain supply from 1995 to 2020.

Year	Number of Shandong Counties (%) (Missing Data Are Not Included in the Calculation)				
	Severe Shortage	Moderate Shortage	Supply-Demand Balance	Moderate Surplus	Severe Surplus
1995	10 (7.5%)	11 (8.3%)	7 (5.3%)	63 (47.4%)	42 (31.6%)
2000	16 (12%)	14 (10.5%)	20 (15.1%)	55 (41.4%)	28 (21.1%)
2005	21 (15.8%)	10 (7.5%)	20 (15.1%)	43 (32.3%)	39 (29.3%)
2010	18 (13.6%)	10 (7.6%)	14 (10.6%)	35 (26.5%)	55 (41.7%)
2015	19 (14.4%)	18 (13.6%)	14 (10.6%)	30 (22.7%)	51 (38.6%)
2020	23 (17.6%)	16 (12.2%)	19 (14.5%)	17 (13%)	56 (42.7%)

3.2. Spatial Pattern of Food Production

In order to reveal the spatial correlation and agglomeration of grain production in Shandong Province, the spatial autocorrelation analysis method was used to study the spatial agglomeration pattern of grain production in Shandong from 1995 to 2020.

(1) Global spatial autocorrelation: the global Moran's I index of grain production was all positive (Table 3), Z (I) were all greater than the critical value of 1.96, and the p value passed the 1% significance test, indicating that there was an overall spatial autocorrelation phenomenon in grain production at the county level in Shandong. Counties with relatively high (low) grain yields also have relatively high (low) grain yields in their surrounding counties. From 1995 to 2020, the Moran's I index of total grain production showed an upward trend, changing from 'weak correlation' to 'strong correlation'. It can be seen that the spatial agglomeration of total grain production in Shandong Province became stronger.

Table 3. Global Moran's I statistics of food production.

Year	Moran's I	$Z(I)$	p
1995	0.162213	2.767059	0.005656
2000	0.255560	4.284913	0.000018
2005	0.251523	4.229677	0.000023
2010	0.277339	4.549589	0.000005
2015	0.343385	5.602631	0.000000
2020	0.373844	6.069967	0.000000

(2) Local spatial autocorrelation: Since the global spatial autocorrelation analysis method does not effectively evaluate the local agglomeration characteristics of grain yield, this paper introduces the local spatial autocorrelation analysis method. With the help of ArcGIS spatial statistics tools, we further explored the local spatial agglomeration of food production (Figure 2). The high-high (H-H) agglomeration effect experienced a transition from east to west, and the high-low (H-L) change was similar to that of H-H. The low-high (L-H) agglomeration emerged from scratch and was mainly distributed in the west, while the low-low (L-L) agglomeration evolved from the north to the northeast and the center. It can be seen that the local agglomeration characteristics of grain production in Shandong from 1995 to 2020 were significantly different.

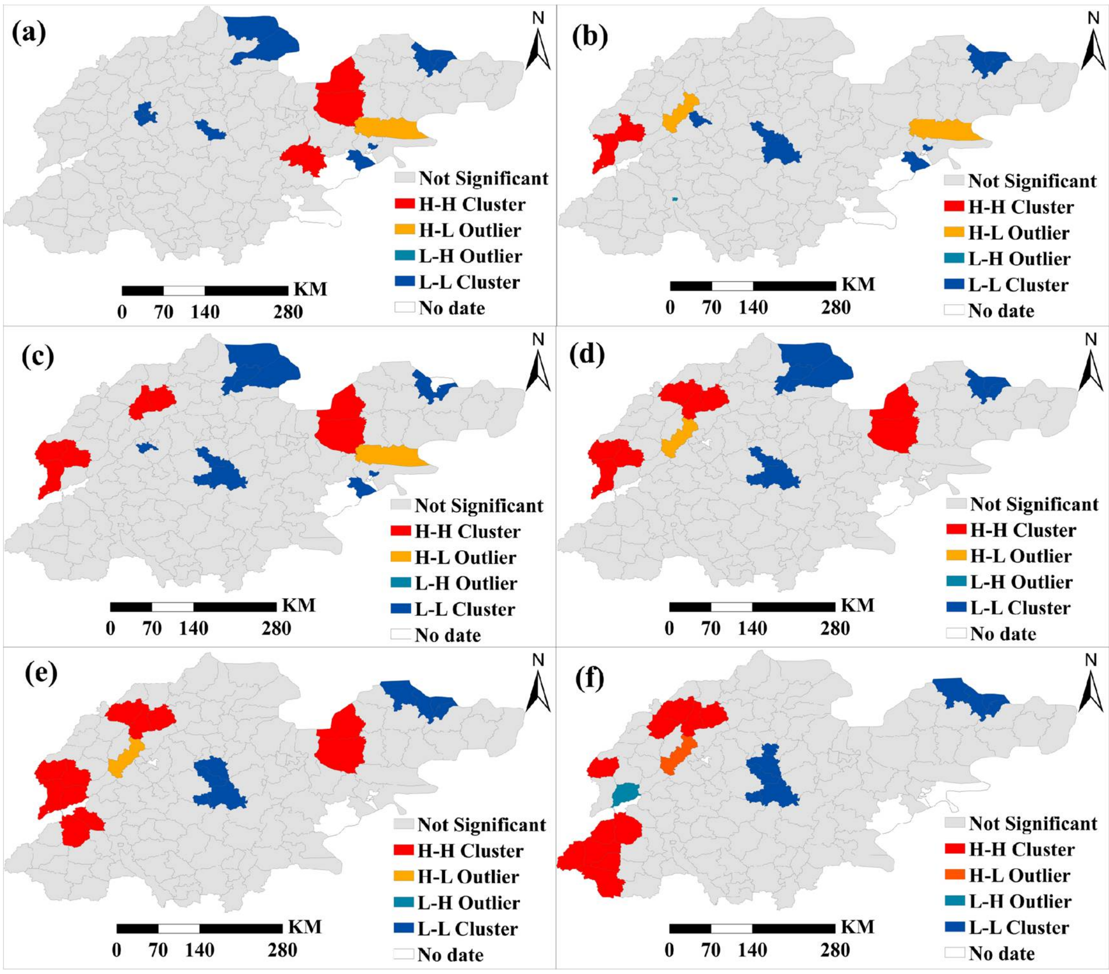

Figure 2. Lisa map of the spatial pattern of grain production in 1995 (**a**), 2000 (**b**), 2005 (**c**), 2010 (**d**), 2015 (**e**), and 2020 (**f**).

3.3. Spatial Pattern of Per Capita Food Supply

The number of counties with severe food shortages increased, and the distribution extended to the west. Counties with moderate shortages also increased, mostly in the central and eastern regions. The number of supply-demand balance counties has experienced the characteristics of less-more-less change, and the distribution was relatively scattered. The number of counties with moderate surplus decreased, and spatially concentrated to the central and eastern regions. Counties with severe surplus have always dominated, and the spatial distribution has not changed significantly (Figure 3).

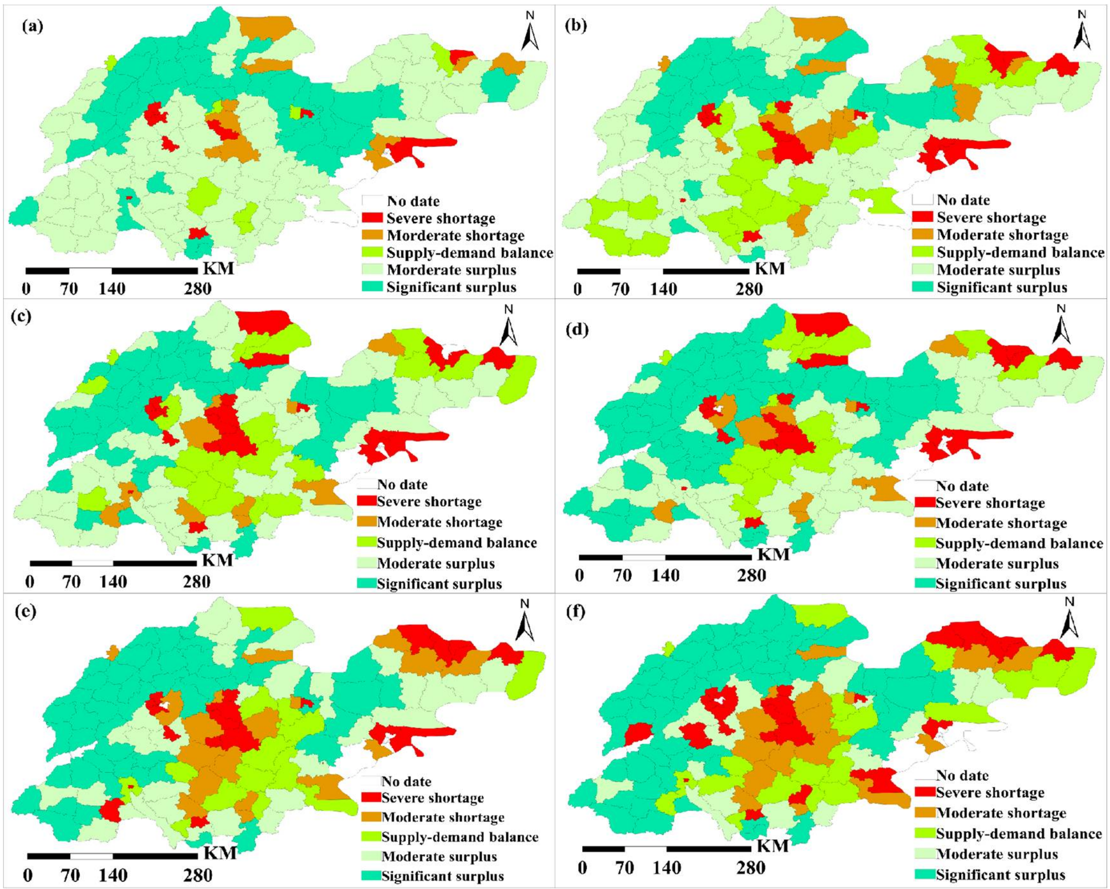

Figure 3. Spatial pattern of county level grain supply in 1995 (**a**), 2000 (**b**), 2005 (**c**), 2010 (**d**), 2015 (**e**), and 2020 (**f**).

3.4. Influencing Factors

The results of the panel model (Table 4) show that the selected factors have different degrees of influence on grain yield. Four variables in Model 1 (annual average temperature, average temperature during growth period, sown area, and total power of agricultural machinery) could well predict grain yield ($p < 0.05$ or $p < 0.01$). Therefore, we used Model 1 as the final model to analyze how some key factors influence and shape changes in crop production.

Table 4. Panel model results.

Influencing Factors	**Model 1**		**Model 2**		**Model 3**	
	Coef	**t**	**Coef**	**t**	**Coef**	**t**
Annual precipitation	409.17	1.608	107.82	0.351	464.79	1.917
Annual average temperature	−9213.79 *	−2.238			−10119.07 *	−2.208
Growing season precipitation	−242.75	−1.162	−718.22	−0.366	−306.01	−1.571
Growing season temperature	5525.51 *	2.088			5964.27	1.95
Total population	0.003	0.508	−0.302	0.000	0.001	0.090
Sown area	4.65 **	6.412	6.94 **	5.89	4.91 **	6.588
Fertilizer usage	−0.129	−0.095	3.305	1.017	−0.407	−0.032
Total power of agricultural machinery	1.46 **	4.78	8.51	2.122	1.41 **	4.918
R^2	0.982		0.915		0.981	
R^2(within)	0.917		0.947		0.924	

* $p < 0.05$, ** $p < 0.01$.

Annual precipitation, growing season temperature, total population, sown area, and total power of agricultural machinery had a positive effect on grain yield, while annual average temperature, growing season precipitation, and fertilizer usage had a negative impact on grain yield; sown area and total power of agricultural machinery had the greatest impact on grain yield, followed by growing season temperature. In the growing season, if the temperature increases by one unit, the grain output will increase by 5525.51 tons; if the annual average temperature increases by one unit, the grain output will decrease by 9213.79 tons; if the planting area and the total power of agricultural machinery increases by one unit, the grain output will increase by 4.65 tons and 1.46 tons, respectively. The sown area and the total power of rural machinery have the most significant impact on food security.

4. Discussion

4.1. Government Intervention

4.1.1. Improve the Food Supply System

This study has shown that climate change has a significant impact on food production, which is consistent with the results of related studies in other regions [7,45,46]. Although climate change has different degrees of impact on food production in different regions, with the intensification of climate change, especially the frequent occurrence of extreme weather, it will definitely have a great negative impact on food production and food security. Food export restrictions during the novel coronavirus disease may pose the risk of food insecurity in many low- and middle-income countries [47]. Shandong Province is one of the main grain producing areas in China, and its food security is directly related to the national food security. Therefore, governments at all levels should formulate relevant policies to establish a reliable food supply system to ensure food security.

4.1.2. Protect Cultivated Land

The influence of cultivated land on grain yield is unquestionable. The results of Model 1 show that the sown area has a significant impact on grain yield, which also confirms the relevant research results of other scholars [48–51]. In the past 20 years, due to the influence of cultivated land reclamation, urbanization encroachment of cultivated land, and conversion of farmland to forests and grasslands, China's cultivated land resources have undergone tremendous changes in terms of area, spatial distribution, and quality [47,52–54]. Grain production has a strong dependence on the sown area of grain. At present, with the continuous development of urbanization, the area of arable land may continue to shrink in the future. Therefore, it is necessary to accurately understand the impact of the loss of main arable land on grain production and reasonably control it. On the basis of farmland transfer, continuous development, improvement, renewal, and restoration of farmland productivity is an important way to ensure food supply and national food security [55].

4.1.3. Improve the Efficiency of Fertilizer Use

From 1995 to 2020, the use of agricultural chemical fertilizers (in pure volume) in Shandong increased by 27.94%, which was 2.4 times the growth rate of grain production. Both the fertilizer use efficiency and the marginal effect on crop yield in China are much lower than the corresponding rates in developed countries [21]. However, while promoting the increase of grain production, the application of large amounts of chemical fertilizers also causes serious pollution to the ecological environment, making it difficult to reverse in the short term [56–58]. In view of this, China began to implement a large-scale soil testing and formula fertilization subsidy project in 2005; in 2015, the Ministry of Agriculture promulgated the 'Action Plan for Zero Growth of Chemical Fertilizer Application by 2020', and proposed the goal of achieving zero growth in chemical fertilizer application by 2020. The report of the 9th National Congress of the Communist Party of China also emphasized the need to 'develop green agriculture, rationally use fertilizers, and accelerate the modernization of agriculture and rural areas' [59]. From 1995 to 2020, the use of chemical fertilizers in some areas of Shandong Province exceeded the overall average level. Therefore, it is necessary to reduce the use of chemical fertilizers in some areas. At the same time, our analysis also shows that the use of chemical fertilizers can increase grain production, so in some areas with relatively low fertility, it is necessary to increase the input of chemical fertilizers to increase grain production. Therefore, reducing the amount of chemical fertilizer use and improving the efficiency of chemical fertilizer use can effectively ensure food security.

4.1.4. Increase Investment in Agricultural Science and Technology

Existing studies [40] have shown that the positive impact of technological progress on China's food production is much greater than that of climate, and the influence will continue to expand in future grain production, which will become the 'main force' factor of China's grain production. In the future, Shandong's grain production also needs to expand the 'trend surface' of technological influence, mitigate the negative impact of climate change on grain production, and ensure food security.

4.2. Contribution to the Sustainable Development Goals

On September 25, 2015, the 193 member states of the United Nations jointly adopted the "2030 Agenda for Sustainable Development". Commitment to the international community to eradicate poverty and hunger between 2016 and 2030, restore and sustainably manage natural resources, and achieve sustainable development in three dimensions: social, economic, and environmental, including a total of 17 Sustainable Development Goals (SDGs) and 169 targets [60]. SDGs are the main reference for formulating relevant policies at the national level, countries can review the 17 SDGs according to their own priorities, needs, stages of development, capabilities, resources, strategies, partnerships, and implementation modalities, and then determine how to translate them into viable development plans and make tangible changes [61]. SDG2 is "End hunger, achieve food security, improve nutrition, and promote sustainable agriculture". Therefore, the development of food production is particularly important to improve food security and achieve SDG2 by 2030. With food security, SDG2 can be achieved. Shandong is a major agricultural province in China and one of the main grain producing areas. The grain output in this area plays an important role in national food security. Quantitatively analyze the influencing factors of grain production in Shandong, so as to clarify the improvement areas and restrictive factors of grain production in Shandong and provide suggestions for formulating grain production policies according to local conditions. This will provide strong scientific support and evidence for the realization of SDG2 in 2030.

4.3. Limitations and Prospects

Using a panel model, this study quantitatively analyzed the effects of climate change, planting area, population growth, fertilizer use, and total power of agricultural machinery on grain yield and food security in Shandong Province from 1995 to 2020. Most of the previous studies were based on single factors [62,63], and the results were uncertain. Therefore, this study has more reference value on how to mitigate food security risks in the context of climate change.

There are still limitations in this study. First, the main crops cereals, pulses, and potatoes are used to replace food production. This approximation cannot reflect changes in food consumption patterns and their impact on food security. Therefore, when more data are available, need to be improved.

Second, it is valuable to reiterate important contextual factors such as seed production levels, breeding of new genotypes, trade, and policy; however, due to data availability, these contextual factors were not included in this study, and future studies, these factors deserve further study.

Finally, this study did not consider the effects of drought and heat stress [64–66], soil health [67], air pollution [68] on food yield, in fact, with global warming and industrial development, drought, and heat stress, soil and soil pollution will increase, which will threaten food security, and further research is needed.

5. Conclusions

Grain production in Shandong Province has shown an increasing trend from 1995 to 2020, especially since 2000, more than a quarter of the counties experienced a high risk of food insecurity (i.e., severe or moderate shortage). The average temperature in the growing season, the sown area and the total power of agricultural machinery had a significant impact on grain production. It is recommended to improve the food supply system, strengthen the protection of cultivated land, improve the efficiency of fertilizer utilization, and increase investment in agricultural science and technology to enhance the adaptability of agricultural production to climate change and ensure food security. In a large agricultural province like Shandong, a better understanding of the different impacts of climate change and other constraints on food production and food security will help relevant stakeholders to make some effective adjustments to food security policies in the region.

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