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Spatio-Temporal Differentiation and Driving Factors of County-Level Food Security in the Yellow River Basin: A Case Study of Ningxia, China

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Abstract: Food security is the primary condition for the development of human society. The Great River Basin is very important to ensure the accessibility and availability of agricultural irrigation, which is vital for food security. The Yellow River Basin plays a significant role in China's food security, with counties serving as key administrative units for guaranteeing this security. This study uses the Yellow River Basin in China as a case study to construct an evaluation index system for county-level food security. It assesses the food security of 22 counties (districts) in Ningxia from 2013 to 2022, applying spatial correlation theories and driving factor analysis methods to explore the factors influencing county-level food security. The results reveal the following: (1) Overall, the food security index in Ningxia has been on the rise, but there is significant internal variation among counties. (2) Spatially, the food security index is relatively low in administrative centers, while the irrigation areas along the Yellow River play a crucial role in maintaining food security, and the overall food security index in the central arid areas is improving. (3) Food security is driven by multiple factors including economic, social, and climatic influences. To enhance food security in the Yellow River Basin, it is necessary to manage land resources systematically, improve grain production technology, and balance ecological protection with food security.

Keywords: food security; the Yellow River Basin; county-level food security; spatio-temporal differentiation; geodetector; Ningxia

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1. Introduction

Food security is a fundamental guarantee for world peace and development and a critical foundation for building a community for humanity, affecting sustainable human development and future prospects. However, in the 21st century, hunger and malnutrition still remain significant global challenges [1,2]. In 2015, the United Nations Sustainable Development Summit adopted the "2030 Agenda for Sustainable Development", proposing 17 Sustainable Development Goals (SDGs). The second goal is "Zero Hunger", and improving food production capacity contributes to achieving the global "Zero Hunger" target. The "2024 State of Food Security and Nutrition in the World" points out that the world is still far off track to achieve Sustainable Development Goal (SDG) 2, Zero Hunger, with the global prevalence of undernourishment persisting at nearly the same level for three consecutive years after having risen sharply in the wake of the COVID-19 pandemic. Between 713 and 757 million people faced hunger in 2023, one out of eleven people in the world, and one out of every five in Africa [3]. The global food security situation remains grim. With 9% of the world's arable land and 6% of its freshwater resources, China feeds nearly one-fifth of the world's population, and its food security has a direct impact on global food security [4]. According to the report on the Work of the Chinese Government in 2024, "We must be strengthen the steady production and supply of grain and important agricultural products, and all regions must be in charge of national food security".

Conceptually, food security is a complex system that covers the entire food chain, including prenatal preparation, agricultural production, food processing, product distribution, consumption, and utilization, and the complex relationships among the environmental, economic, and social components involved. In the food security system, agricultural production is the cornerstone of the food security system. Therefore, the concept of "food security" put forward by the FAO in 1974 emphasized that the food "quantity is sufficient" and that countries should strive for a food self-sufficiency rate of more than 95% [5]. In China, the research and policy implementation of "food security" are also centered on agricultural production [5], and the current food security strategy is "basically self-sufficiency in grains and absolutely safe in rations".

The Yellow River Basin, accounting for 30.3% of the country's population [6], is a significant grain-producing area in China [7], supplying nearly one-third of the country's grain and meat [8]. However, in the Yellow River Basin, the production space has been squeezed by living and ecological spaces over a span of 15 years (from 1995 to 2010) [6]. From 1990 to 2021, the Yellow River Basin saw a net transfer of 1.8351 million hectares of arable land to other main agricultural uses, with a rate of non-agricultural cultivation of 4.9% [9]. The ecological efficiency of land use in the main grain-producing areas of the Yellow River Basin is continuously declining [10], and sustainable land use is severely constrained. At the same time, the coordinated development of "water–energy–food" in the Yellow River Basin is facing multiple challenges, including the mismatch of the spatial distribution of resource elements, water scarcity, complex urban interconnections, and uncoordinated departmental management [11]. Consolidating the national grain status of the Yellow River Basin is of great significance to China's food security and the achievement of SDGs.

At present, there has been extensive research on food security, and studies on the food security of the Yellow River Basin have primarily been carried out at the provincial and municipal levels [8], or among some county-level farmers [12], with relatively few evaluations of county-level food security. Yang and Xue evaluated from the aspects of water resource carrying capacity and policy, both at the provincial and county levels, showing that the agricultural water resources of the Yellow River Basin are overburdened, with Ningxia in a state of emergency, and the agricultural water-saving policies have a positive effect on increasing grain production [13]. Yin evaluated the interactive effects and coupling mechanisms between land use transformation and food security in 74 cities of the Yellow River Basin, considering that the driving effect of natural factors is higher than that of socio-economic factors at the scale of the entire basin [14]. Yin, Xi, Lu et al. have conducted research from the perspective of land use, while Yang, Xue et al. have analyzed from the aspects of water resource carrying capacity and policy. Li, F. proposed a micro-level, county-level, and provincial-level spatial scale food security risk assessment model based on the production capacity, accessibility, availability, and stability of grain [13–15]. Fan, Y. et al. evaluated the impact of land use and land cover change on the total arable land production capacity at the county level during the period from 1990 to 2010 and concluded that changes in land use led to a decrease in the county-level arable land production capacity [16]. Methods have been used in the present research, such as using the coupling coordination model to measure food security in major grain-producing areas [16], utilizing the BLS (Bureau of Labor Statistics) to assess global grain production and the number of hungry people [17], and applying system dynamics to simulate the conversion of planting areas for the three major crops, thereby accounting for the consumption of water and soil resources [18]. In terms of research subjects, some studies focus on food security from the perspective of global food demand and supply [19,20]; others propose suggestions for efficient agricultural production from an environmental impact perspective [21], and there are also those that aim to ensure food security by enhancing land use efficiency through the globalization of land use [22]. In the assessment of food security, Fahad, S. and others have calculated the impact of drought on crop yields [22], Challinor predicted crop yields under climate change [23], and Li, G.J. and others used the input–output method to assess the resource and environmental effects of food loss and waste [24]. In terms of influencing factors of food security, Gohari, A. stated that rigorous water demand management can temporarily alleviate water stress in a basin that is essentially governed by the Limits to Growth archetype [18]. Challinor, A.J. proposed that even moderate warming may reduce temperate crop yields in many locations, and through simulation, it was found that crop-level adaptability could increase yields by an average of 7–15% [23]. Jägermeyr, J. showed that replacing surface systems with sprinkler or drip systems could reduce non-beneficial consumption at the river basin level by 54 and 76%, respectively, while maintaining current crop yield levels [25]. In the research on food security in the Yellow River Basin, Zhang Baifa analyzed the spatiotemporal pattern of land use in the Yellow River Basin to elucidate the relationship between land use and food security [26], Pang Ying measured the scale and structure of grain output in the Yellow River Basin based on a non-parametric dual-output model [27], and Wang Yaqiu constructed an index system based on the water–energy–food nexus to assess the total factor productivity of grain production in the Yellow River Basin [28]. With the changing impacts of extreme climate and international situations, the demand for research on food security in the Yellow River Basin has become increasingly urgent. Evaluating regional food security helps to identify the food security status of a particular area. The evaluation results at the county level are more accurate than at the provincial level and are more efficient than at more microscopic scales [16]. Therefore, constructing a food security evaluation index system at the county level for the Yellow River Basin, along with an analysis of the main driving factors, can help in finding strategies to alleviate food security issues in the Yellow River Basin.

As the only region in China that is entirely within the Yellow River Basin and is ecologically fragile, Ningxia has some potential in sharing the responsibility for food security [29]. However, with the continuous advancement of industrialization and urbanization, the declining comparative benefits of grain cultivation, coupled with water scarcity and the impact of uncontrollable factors such as climate change, the region's food supply is in a tight balance. Analyzing and summarizing the solutions for Ningxia's food security can provide a path to achieving food security for ecologically fragile areas in large river basins and offer a reference for similar regions globally to achieve the SDGs.

This study proposes a set of county-level food security evaluation indicators, using publicly available data for statistical analysis, and evaluates the food security of all counties under the jurisdiction of Ningxia from 2013 to 2022. It conducts a spatio-temporal differentiation analysis and further explores the driving factors of food security. The food security evaluation index system for county-level food security in the Yellow River Basin provided by this study can offer a scientific reference for future measurements of food security. The results can provide a basis for the coordinated management of grain production, land use, territorial spatial planning, and water resource utilization at the county level in the Yellow River Basin.

2. Materials and Methods

2.1. Study Area

The Ningxia Hui Autonomous Region is located in the northwest of China, covering an area of 66,400 square kilometers, accounting for 0.69% of China's land area (Figure 1). The region governs 5 prefecture-level cities, namely Yinchuan, Shizuishan, Wuzhong, Guyuan, and Zhongwei, as well as 22 counties. It is one of the smaller provincial-level administrative regions in China. It is mainly divided into the northern Yellow River irrigation area, which includes 11 counties (districts), namely Xingqing, Xixia, Jinfeng, Yongning, Helan, Lingwu, Dawukou, Huinong, Pingluo, Litian, and Qingtongxia; the central arid area, which includes 5 counties (districts), namely Hongsibao, Yanchi, Tongxin, Shapotou, and Zhongning; and the southern mountainous area, which includes 6 counties (districts), namely Yuanzhou, Xiji, Longde, Jingyuan, Pengyang, and Haiyuan. Ningxia currently has approximately 1.2 million hectares of arable land, including 538,667 hm^2 of paddy fields and irrigated land and 662,667 hm^2 of dry land. As the only province in China that is entirely within the Yellow River Basin, Ningxia plays a significant role in national grain production as an important commodity grain base. In terms of crop types, Ningxia hosts a diverse range of grain production, including both rice and wheat cultivation.

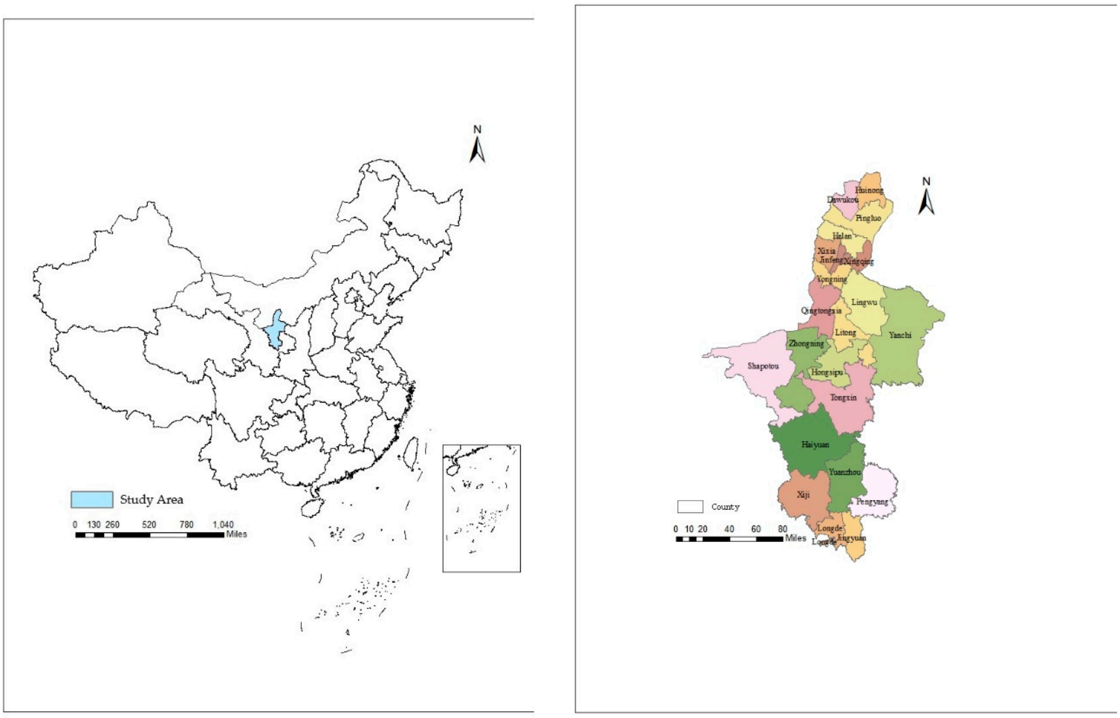


Figure 1. Study area.

This study uses the ArcGIS 10.8 and selects Ningxia as the research subject to explore the spatio-temporal differentiation at the county level within the Yellow River Basin and its driving mechanisms, aiming to provide decision-making references for achieving food security in the Yellow River Basin.

2.2. Methodology

2.2.1. Evaluation Index System

Under the SDGs, grain production needs to consider not only the total output but also the environmental impact during the production process. It is essential to minimize environmental damage while increasing production efficiency. According to China's sustainable development index database involving grain production [30], combining the evaluation of China's food security coefficient [31,32] with the green transformation of arable land utilization [33], it is crucial to construct a county-level food security index system [34]. This county-level evaluation indicator system compares multiple counties over a long time series and under conditions that maximize the elimination of policy impacts. It takes into account the security of arable land and grain cultivation areas while also considering labor efficiency, economic efficiency, and land efficiency. Most importantly, it incorporates ecological elements, allowing for a more sustainable development-oriented assessment of county-level food security [8,35–39]. This index system is typically composed of three main parts (Table 1):

Table 1. Description of county (district) food security indicators.

Level 1	Index Item	Indicator Interpretation	Attribute
Total quantity guarantee	Per capita cultivated area	Cultivated area/total population of the area (hm^2/person)	+ (positive indicator)
	Grain planting rate	Grain sown area/total sown area of crops (%)	+ (positive indicator)
Efficiency guarantee	Per capita annual output of grain	Grain output/total regional population (tons/person)	+ (positive indicator)
	Total output value of per-land planting	Total output value of planting industry/cultivated land area (10,000 yuan/hm^2)	+ (positive indicator)
	Grain yield per unit area	Total grain output/grain sown area (tons/hm^2)	+ (positive indicator)
Ecological security	Non-point source pollution of chemical fertilizer in soil	Application amount of agricultural fertilizer/cultivated area (tons/hm^2)	− (negative indicator)
	Water consumption of gross agricultural product of 10,000 yuan	Agricultural water consumption/total output value of planting industry (m^3/10,000 yuan)	− (negative indicator)

Total Quantity Guarantee: This part of the indicators focuses on the total foundation of food production, including the per capita arable land area, which reflects the average amount of arable land resources each farmer has, and the grain planting rate, which is the proportion of the grain sowing area to the total sowing area of crops, showing the proportion of grain crops among all crops.

Efficiency Guarantee: This part of the indicators measures the efficiency of food production, including the annual grain output per capita, which indicates the average amount of grain produced per person per year; total agricultural output value per unit area, which is the total output value of the planting industry per unit area of arable land, reflecting the economic efficiency of the land output; and the grain yield per unit area, which is the yield of grain per unit area of arable land, a key indicator of food production efficiency.

Ecological Guarantee: This part of the indicators focuses on the sustainability of food production, including the fertilizer pollution per unit area, which, by calculating the ratio of agricultural fertilizer application to arable land area, assesses the potential impact of fertilizer use on the ecological environment, and water consumption per CNY 10,000 of agricultural total output value, which is the ratio of agricultural water consumption to the total output value of the planting industry, used to evaluate the efficiency of water resource utilization in agricultural production.

Through these indicators, the food security situation of various counties (districts) in Ningxia can be comprehensively evaluated, ensuring that food production not only guarantees the total quantity but also pays attention to production efficiency and the sustainability of the ecological environment. This comprehensive evaluation method helps guide policymaking, optimize resource allocation, and promote green development of agriculture and food security.

When measuring the water consumption per CNY 10,000 of agricultural gross output, since the agricultural water consumption data are only available at the city level from 2013 to 2019, it is believed that within the city's jurisdiction, the agricultural water consumption is significantly related to its technological level, and the differences in agricultural technology among the counties within a city are not significant. Therefore, when converting the county-level agricultural water consumption, it is calculated based on the proportion of the county's arable land area to the city's total arable land area. For the years 2020–2022, the data from the "Ningxia Water Resources Statistical Bulletin" are used.

The total quantity guarantee and efficiency guarantee are used to positively assess the food security indicators. In the context of sustainable development requirements, the ecological guarantee indicator is incorporated as a negative indicator.

2.2.2. CRITIC Method

The CRITIC method is an objective weight assignment method proposed by Diakoulaki [40], which is determined by the comparative intensity and conflict among indicators. Comparative intensity refers to the magnitude of the difference in values between different evaluation schemes for the same evaluation indicator, represented as the standard deviation; the larger the standard deviation, the higher the weight. The conflict is represented by the correlation coefficient; if two evaluation indicators have a strong correlation, it indicates that the conflict is less, and the weight is lower [41].

When using the CRITIC method, data standardization is carried out first, positive processing is adopted for dimensional processing of positive indicators, and reverse processing is adopted for negative indicators [42].

For positive indicators,

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (1)$$

For negative indicators,

$$x'_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \quad (2)$$

The expression of the CRITIC method can be expressed as Formula (3):

$$P_j = S_j \sum_{i=1}^{n} (1 - r_{ij}) \quad (3)$$

where P_j represents the information content of the j-th index in the evaluation index system, S_j is the standard deviation of the j-th index, and r_{ij} is the correlation coefficient between the i-th and j-th evaluation indexes.

$$W_j = \frac{P_j}{\sum_{j=1}^{n} P_j} \quad (4)$$

Here, W_j is the objective weight of the j-th index.

In this study, the evaluation unit is the food security index of all 22 county-level administrative regions in Ningxia from 2013 to 2022. The SPSSAU software (https://spssau.com) (accessed on 11 August 2024) is used to process positive and negative indicators separately through min–max normalization and dimensionless treatment. The CRITIC method is applied to calculate the weights of each indicator, and the results are shown in Tables 2 and 3.

From the weights of the county-level food security indicators (Table 3), among the seven indicators, all have a weight exceeding 10%. The highest weight is for the grain yield per unit area, at 19.53%, followed by the per capita arable land area (15.77%). The lowest weight is for the water consumption per CNY 10,000 of agricultural gross output, at 11.42%. The weights for the annual grain output per capita, fertilizer pollution per unit area, and total planting industry output value per unit area are quite similar, at 13.78%, 13.65%, and 13.51%, respectively, with the grain planting rate accounting for a weight of 12.33%.

Table 2. Descriptive statistics of county (district) food security indicators.

Index Item	Sample Size	Average	StDev
MMS_Per Capita Arable Land Area	220	0.291	0.246
MMS_Grain Planting Rate	220	0.628	0.201
MMS_Annual Grain Output Per Capita	220	0.399	0.256
MMS_Gross output value of per land planting	220	0.297	0.206
MMS_grain yield per unit area	220	0.527	0.281
NMMS_land-homogenized fertilizer non-point source pollution	220	0.771	0.183
NMMS_water consumption of gross agricultural product of ten thousand yuan	220	0.82	0.183

Table 3. Weight of county (district) food security indicators.

Index Item	Indicator Variability	Index Conflict	Amount of Information	Weight
MMS_grain yield per unit area	0.281	6.81	1.917	19.53%
MMS_Per Capita Arable Land Area	0.246	6.29	1.548	15.77%
MMS_Annual Grain Output Per Capita	0.256	5.273	1.352	13.78%
NMMS_land-homogenized fertilizer non-point source pollution	0.183	7.309	1.339	13.65%
MMS_Gross output value of per land planting	0.206	6.441	1.325	13.51%
MMS_Grain Planting Rate	0.201	6.015	1.209	12.33%
NMMS_water consumption of gross agricultural product of ten thousand yuan	0.183	6.114	1.121	11.42%

2.2.3. Geodetector

The geodetector is a tool for detecting and utilizing spatial heterogeneity. This article primarily employs the geographical detector (GeoDetector_2015) as a differentiation and factor detector to explore the spatial heterogeneity of Y, as well as to detect to what extent a certain factor X explains the spatial differentiation of attribute Y [43].

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \quad (5)$$

Here, $h = 1, \ldots, L$ represents the stratum of the variable Y or factor X in the classification or partitioning; N_h and N are the numbers of units in stratum h and the entire region, respectively; and σ_h^2 and σ^2 are the variances of the Y values in stratum h and the entire region, respectively. The range of q is [0, 1]; the larger the value, the more significant the spatial heterogeneity of Y. If the stratification is generated by the independent variable X, a larger q value indicates that the explanatory power of X for the attribute Y is stronger, and vice versa. In extreme cases, a q value of 1 indicates that the factor X completely controls the spatial distribution of Y, while a q value of 0 indicates that the factor X has no relationship with Y. The q value indicates that X explains $100 \times q\%$ of Y.

The food security index is closely related to the ecological, living, and ecological space within the region. Factors such as altitude, slope, temperature, precipitation, economy, and population have a significant impact on food security [44,45]. To comprehensively assess the factors affecting food security, we selected 10 indicators from domestic and international research (Table 4), as follows:

Economic Factors:

Per capita GDP: Reflects the level of regional economic development, affecting the input of food production factors.

General public budget expenditure: Government investment levels are a critical factor that directly affect the efficiency of food production.

Disposable income of rural residents: Affects the enthusiasm of farmers for planting food and the input in food production.

Social Factors:

Urbanization rate: Measures the process of urbanization, affecting the transfer of the rural population to urban areas and the conversion of agricultural land to industrial land.

Climatic Factors:

Temperature: Affects the growth cycle and yield of crops.

Precipitation: Affects the water supply and growth conditions of crops.

Sunshine duration: Affects the photosynthesis and energy acquisition of crops.

Land Factors:

Normalized Difference Vegetation Index (NDVI): Reflects the coverage and growth condition of vegetation.

Land use: Involves the types of land, such as arable land and forest land, and their changes.

DEM (digital elevation model): Reflects the impact of terrain and topography on agricultural production.

The selection of these indicators is based on their direct or indirect relationship with food production and security [46]. For instance, economic factors directly affect the efficiency of agricultural production inputs and outputs; social factors, such as the urbanization rate, affect the distribution of labor and land use patterns; climatic factors are directly related to crop growth conditions; and land factors involve the basic resources for agricultural production.

By integrating these indicators, the current situation and trends in food security can be more accurately assessed and analyzed, providing a scientific basis for policymaking and resource allocation [21].

Table 4. Influencing factors of food security.

Type	Drivers	Variable Code
Economic factors	GDP per capita	X1
	General public budget expenditure	X2
	Rural residents' disposable income	X3
Social factors	Urbanization rate	X4
Climatic factors	Temperature	X5
	Precipitation	X6
	Sunshine duration	X7
Land factors	Normalized Vegetation Index (NDVI)	X8
	Land use	X9
	DEM	X10

2.3. Data

In this study, we utilized data from the "China Statistical Yearbook," "Ningxia Statistical Yearbook", "Yinchuan Statistical Yearbook", "Shizuishan Statistical Yearbook", "Wuzhong Statistical Yearbook", "Guyuan Statistical Yearbook", and "Zhongwei Statistical Yearbook" from 2014 to 2023. Additionally, the "China Water Resources Bulletin", "Ningxia Water Resources Bulletin", and statistical bulletins from various cities in Ningxia, as well as statistical yearbooks from counties (districts) within Ningxia, served as significant sources of data for the article. Remote sensing data on land use in China, the Chinese NDVI (Normalized Difference Vegetation Index), and DEM (digital elevation model) grid data were obtained from the "Resource and Environment Science Data Platform" (www.resdc.cn) (accessed on 13 July 2024).

3. Results

3.1. The Changes in the Food Security Index of Various Counties (Districts) in Ningxia

Overall, the food security index in Ningxia has shown an upward trend. The annual average of the food security index for the 22 counties (districts) increased from 0.4970 in 2013 to 0.5446 in 2022 (Figure 2), indicating that over the past decade, the food security in various counties of Ningxia has significantly improved, mainly due to two reasons. On the one hand, there has been an improvement in the efficiency of grain production across Ningxia. The total planting output value per unit area increased from 2.0943 CNY 10,000/hm^2 in 2013 to 3.7843 CNY 10,000/hm^2 in 2022, a growth of 80.69%; at the same time, the grain yield per unit area also increased from 4.6582 tons/hm^2 to 5.4287 tons/hm^2, a growth of 16.54%. On the other hand, improvements in two ecological indicators have contributed to this trend. The fertilizer pollution per unit area decreased from 0.8482 tons/hm^2 to 0.7758 tons/hm^2, a reduction of 8.54%; the water consumption per CNY 10,000 of agricultural gross output reduced from 1165.52 m^3/CNY 10,000 to 661.78 m^3/CNY 10,000, a decrease of 43.22%. Under the dual influence of increased grain production efficiency and positive ecological indicators, the food security index in Ningxia has shown an upward trend.

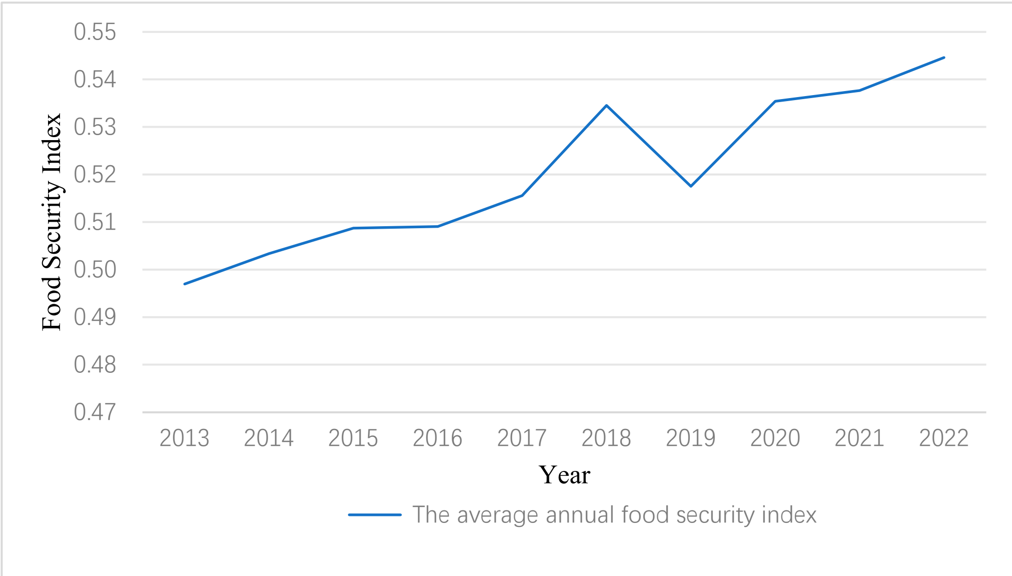


Figure 2. The average annual food security index of 22 counties (districts) from 2013 to 2022.

The internal structure of the food production safety index among the 22 counties (districts) in Ningxia reveals significant disparities. On the one hand, the number of counties with an index higher than the annual average has decreased. In 2013, the annual average of the food safety index for the 22 counties (districts) was 0.4970, with 12 counties above the annual average and 10 below it, whereas in 2022, there were 10 counties above the annual average and 12 below it. On the other hand, the gap in the food safety index among the counties (districts) has widened (Figure 3). In 2013, the highest-ranking county was Yongning with an index of 0.6154; in 2014, the highest was Pengyang (0.6276); from 2015 to 2018, the highest was, again, Yongning (0.6373, 0.6388, 0.6517, 0.6323); in 2019 and 2020, the highest was Pingluo (0.6179, 0.6482); and in 2021 and 2022, the highest was Qingtongxia (0.6695, 0.6909). From 2013 to 2014, the lowest ranking was Dawukou (0.353, 0.3731), and from 2015 to 2022, the lowest food safety index was consistently in Jingyuan, with values of 0.3718, 0.3643, 0.3494, 0.3415, 0.2691, 0.3127, 0.3132, and 0.3469, respectively. It can be seen that the difference between the highest and lowest values in 2013 was 0.2623, while in 2022, the difference was 0.3440, indicating a significant increase in disparity. Qingtongxia is located in the northern part of Ningxia in the Yellow River irrigation area and is one of the national commodity grain bases. In 2021, Ningxia implemented the construction of the original grain reserve production base, with Qingtongxia as one of the bases, which has seen a significant increase in arable land area, grain output, and the total output value of agriculture. At the same time, the use of chemical fertilizers was reduced, providing momentum for the improvement of Qingtongxia's food safety.

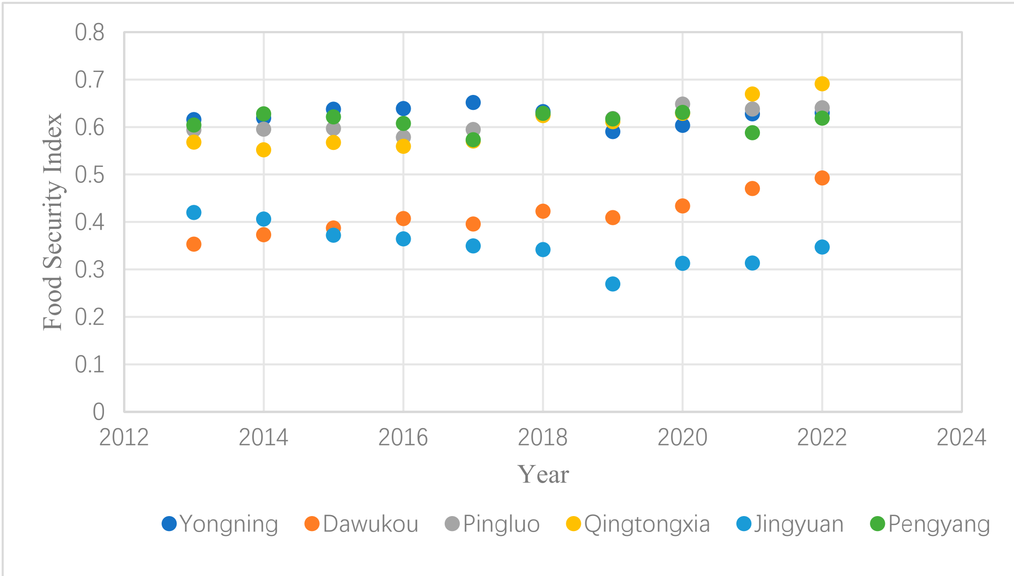


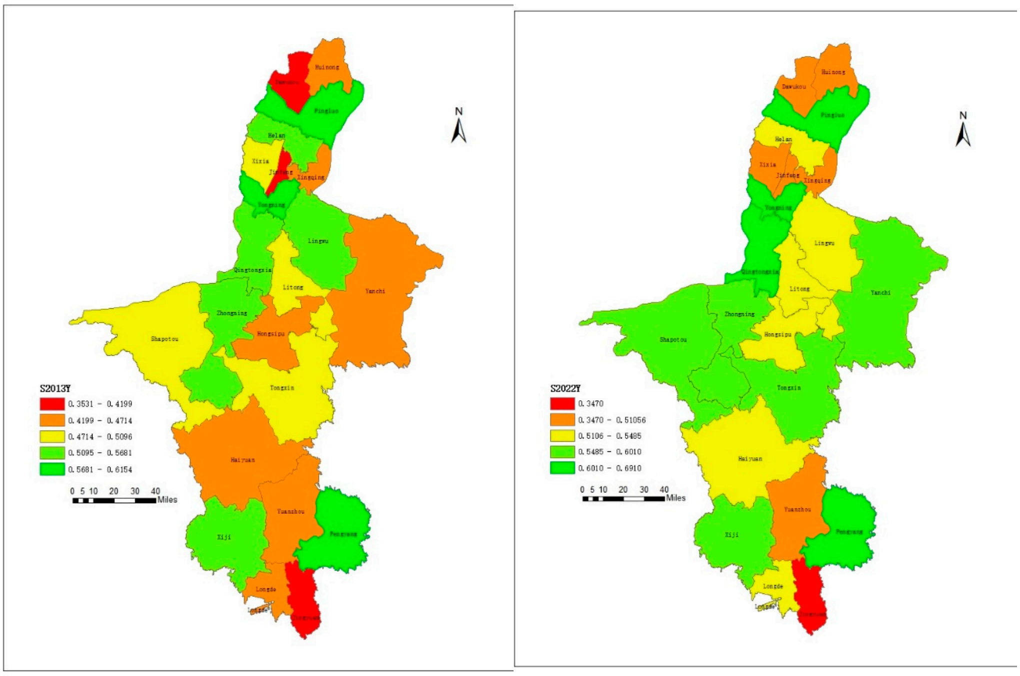
Figure 3. Graph showing annual high and low values of county (district) food security index from 2013 to 2022.

In terms of the trend, only two counties (districts) have seen a decline in the food security index. In 2022, among the 22 counties (districts) in Ningxia, Jingyuan and Helan were the two counties where the food security index was lower than that of 2013. Specifically, Jingyuan had an average annual food security index of 0.3495 over the decade, with six years below the annual average, and for nine consecutive years from 2014 to 2022, it remained below the food security index of 2013. Helan had an average annual food security index of 0.5521 over the ten years, with five years below the annual average.

3.2. Spatio-Temporal Differentiation in Food Security Among Counties

The food security index of the administrative centers is relatively low (Figure 4). Jinfeng, Dawukou, Lingtong, Yuanzhout, and Shapotout are the districts where the municipal governments of Yinchuan, Shizuishan, Wuzhong, Guyuan, and Zhongwei are located, respectively. Except for Shapotou, the remaining four counties have been below the annual average food security index of the 22 counties (districts) in the past five years. Jinfeng, Dawukou, and Yuanzhou have been below the annual average throughout the decade.

There is a significant difference in food security between the counties under the Yellow River irrigation area and the southern mountainous areas, while the food security index in the central arid region is gradually improving. From 2013 to 2022, the counties with the highest and lowest food security indexes were all located in the Yellow River irrigation area and the southern mountainous areas. In nine of those years, the county with the highest food security index was in the Yellow River irrigation area, and for nearly eight years, the county with the lowest food security index was in the southern mountainous area. Moreover, in the last two years, all counties (districts) with food security indexes above the annual average were in the Yellow River irrigation area and the southern mountainous areas. In the central arid region, which includes five counties (Figure 5), Zhongning and Tongxin have had food security indexes above the annual average over the decade. Shapotou only slightly fell below the annual average of 0.5034, with a 2014 index of 0.4877, and has been above the average in other years. Hongsibao has had a food security index above the annual average since 2019, and Yanchi's food security index has also been above the average in the last two years. In 2021 and 2022, all counties (districts) in the central arid region had food security indexes above the annual average. It is evident that there has been a significant improvement in grain production in the central arid region, especially in Yanchi, which jumped from 19th place in 2013 to 8th place in 2022.



(**a**) (**b**)

Figure 4. (**a**) 2013 food security index, (**b**) 2022 food security index.

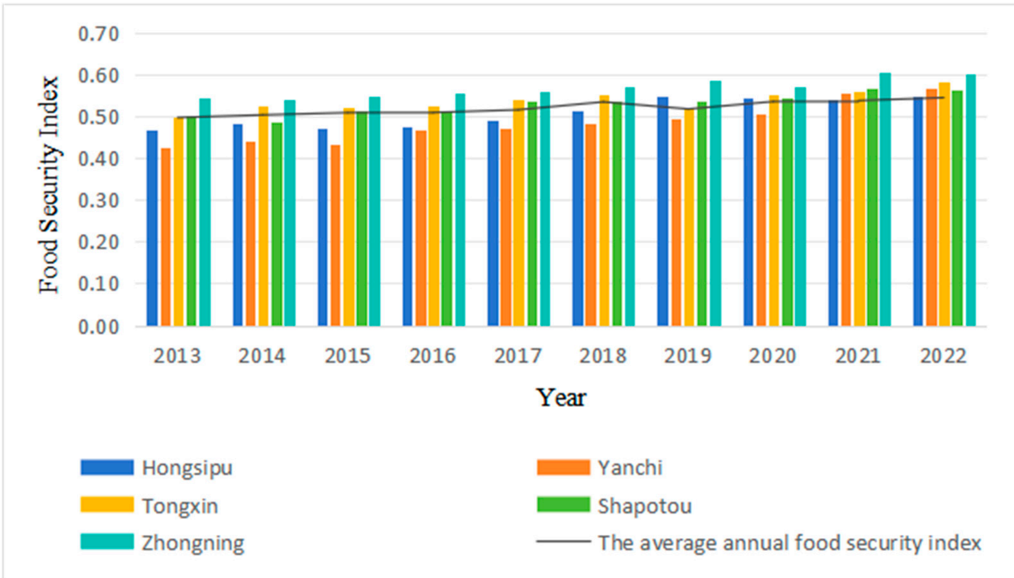


Figure 5. Graph of food security index in the central arid region from 2013 to 2022.

3.3. Driving Factors of Food Security in Ningxia Counties (Districts)

3.3.1. Single-Factor Detection Analysis

The factor detection in the geodetector was applied to explore the driving force of each driving factor on the food security of 22 counties (districts) in Ningxia from 2013 to 2022, with results shown in Table 5. (1) All driving factors have a significant impact. The 10 influencing factors of food security in the 22 counties of Ningxia from 2013 to 2022 are significant at the less than 1% level, indicating that economic, social, climatic, and land factors greatly affect food security. (2) In terms of economic factors, from 2013 to 2022, per capita GDP had a strong driving force on food security; additionally, the disposable income of rural residents rapidly increased its driving force on food security, while the driving force of general public budget expenditure on food security is weakening. Regarding social factors, the driving force of the urbanization rate on food security is weakening but still has a strong impact. Looking at climatic factors, precipitation has the strongest driving force on food security, while temperature and sunshine duration also have significant driving effects. In terms of land factors, NDVI, land use, and DEM have a minor driving effect on the spatial differentiation of food security.

Table 5. 2013, 2017, and 2022 factor detection results.

Factors	2013		2017		2022	
	q-Value	**Rank**	**q-Value**	**Rank**	**q-Value**	**Rank**
GDP per capita (X1)	0.3583	3	0.1585	5	0.2805	3
General public budget expenditure (X2)	0.2717	5	0.3306	2	0.0271	10
Rural residents' disposable income (X3)	0.1341	8	0.1482	6	0.4102	1
Urbanization rate (X4)	0.5109	1	0.2846	3	0.1893	4
Temperature (X5)	0.2810	4	0.3736	1	0.1520	6
Precipitation (X6)	0.4172	2	0.2305	4	0.3815	2
Sunshine duration (X7)	0.2573	6	0.1297	8	0.1653	5
NDVI (X8)	0.2021	7	0.0627	10	0.0609	9
Land Use (X9)	0.0503	10	0.0816	9	0.0814	8
DEM (X10)	0.1275	9	0.1378	7	0.0874	7

3.3.2. Interaction Detection Analysis

Interaction detection is used to explore whether the interaction between two influencing factors affects the explanatory power of single factors on the dependent variable (Figure 6).

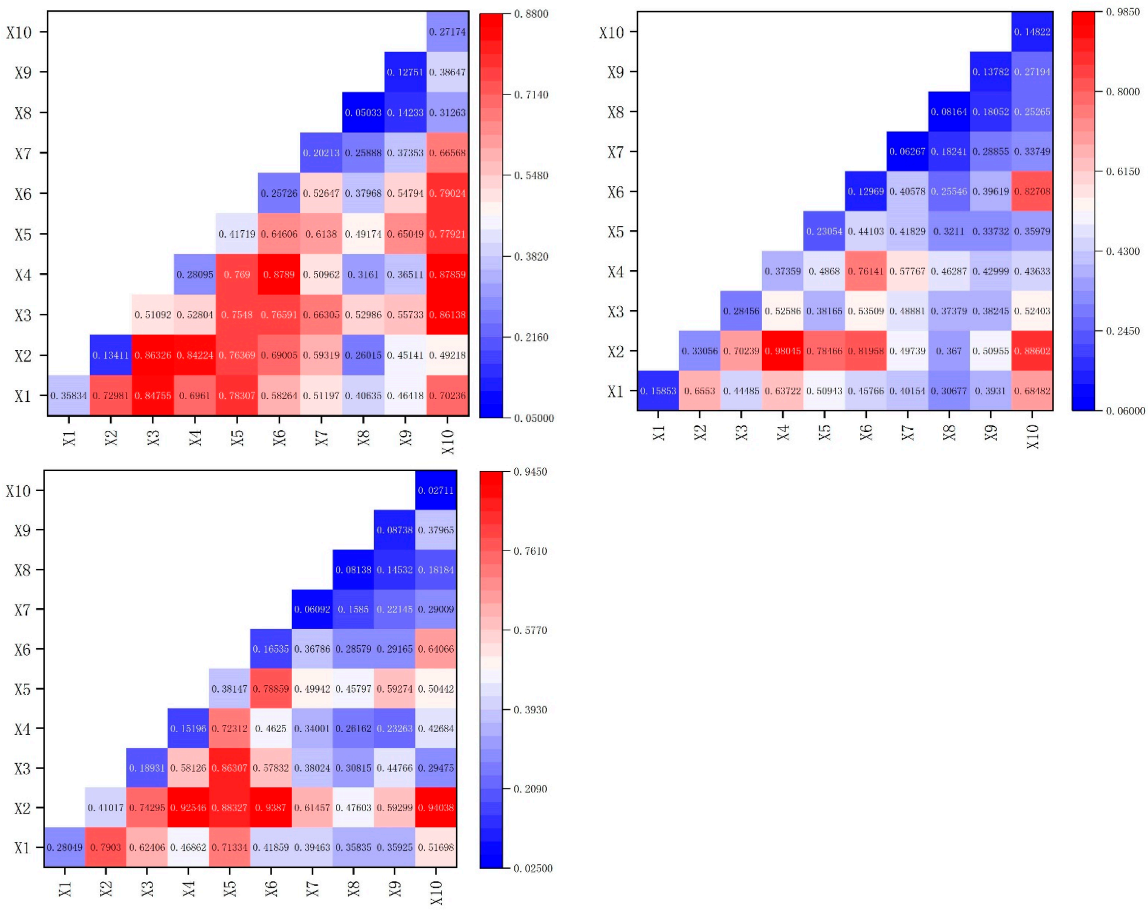


Figure 6. Heatmap of driving factor interactions for the years 2013, 2017, and 2022.

The specifics are as follows: (1) From 2013 to 2022, factor interactions all show dual-factor enhancement and nonlinear enhancement, indicating that the changes in the food security index of the 22 counties in Ningxia are the result of the combined effects of multiple factors, and the interactions between two factors play a positive reinforcement role in driving food security. At the same time, as time progresses, the number of nonlinear enhancement types gradually increases, indicating that the interaction effects of driving factors are gradually strengthening, and the joint effect of various factors is becoming more prominent. (2) With the advancement of time, the explanatory power of the general public budget expenditure (X2) improved after interacting with other factors. The interactive effect of the urbanization rate (X4) with temperature (X5) and precipitation (X6) shows a downward trend in explaining food security. The interaction of precipitation (X6) and sunshine duration (X7) also shows a decreasing trend in explaining food security. The explanatory power of other factors decreases after interaction, which also confirms that food security is greatly influenced by climate, urbanization, and land patterns, and under the influence of economic factors, they jointly promote the emergence of spatial differentiation in food security.

3.3.3. Risk Detector Analysis and Ecological Detector Analysis

A risk detector is used to determine whether there is a significant difference in the mean attributes between two sub-regions. In 2013, for GDP per capita (X1), general public budget expenditure (X2), rural residents' disposable income (X3), temperature (X5), precipitation (X6), sunshine duration (X7), and DEM (X10), there were significant differences in the food security index between the two sub-regions for each single factor, and this situation has been changing over time. By 2022, for GDP per capita (X1), general public budget expenditure (X2), rural residents' disposable income (X3), urbanization rate (X4), temperature (X5), precipitation (X6), and sunshine duration (X7), there were significant differences in the food security index between the two sub-regions for each single factor.

An ecological detector is used to compare whether there are significant differences in the spatial distribution impact of two factors on attribute Y. At different times, the impact of two factors on the spatial distribution of the county-level food security index varies. In 2013, the impact of the general public budget expenditure (X2), combined with rural residents' disposable income (X3), urbanization rate (X4), temperature (X5), precipitation (X6), sunshine duration (X7), and DEM (X10) on the spatial distribution of the county-level food security index showed significant differences. However, by 2022, the situation had changed, revealing significant differences in the impact of the general public budget expenditure (X2) combined with GDP per capita (X1) on the spatial distribution of the county-level food security index.

4. Discussion

4.1. Main Factors Affecting Food Security in Ningxia

Land resource conditions are fundamental factors for food security. Grain production relies on arable land as the carrier, which supports grain production and ensures the survival of humanity through its use as a basic resource. It is the essential element for guaranteeing agricultural production and achieving SDG2 [47]. The relationship between arable land in Ningxia and food security is positively correlated. The results of this study show that arable land plays a significant positive role in the level of food security in Ningxia, contributing positively to the enhancement of grain production capacity and the realization of the United Nations' sustainable development goal of "Zero Hunger". In terms of quantity, the area of arable land has a decisive effect on food security. For example, in 2018, Jingyuan had 17,411 hectares of arable land, which decreased to 7902 hm^2 in 2019, and the food security index also dropped from 0.3415 in 2018 to 0.2691 in 2019. The quality of arable land resources also directly affects food security. The Yellow River irrigation area is one of the ancient large-scale irrigation regions in China. Since the founding of China, large-scale transformations and expansions have been carried out in the Yellow

River irrigation area, along with a series of soil and water conservation projects, which have improved agricultural production conditions. The efficiency of arable land resource utilization in this area has subsequently increased [48]. The Yellow River irrigation area is the region with the best land cultivation conditions among the 22 counties (districts), and the counties with the highest food security index are also concentrated in this area.

Climate change has a significant impact on food security. Climate change is causing countries around the world to suffer from increasingly severe floods, droughts, storms, and heatwaves, along with adverse effects such as changes in precipitation patterns, water scarcity, and rising sea levels. These factors exert tremendous pressure on plant cultivation, forestry, and fisheries, posing a serious threat to global food security [49]. The Intergovernmental Panel on Climate Change (IPCC) has stated that humanity is facing the risk of a collapse of food systems related to warming, drought, floods, precipitation variability, and extreme events [50]. The results of this study show that temperature, precipitation, and sunshine duration can affect the spatial differentiation of food security. The impact of precipitation remained in the second position in both 2013 and 2022, while sunshine duration rose from the sixth position in 2013 to the fifth position in 2022, and the impact of temperature on food security once jumped to the first position in 2017. For a long time, water resources have been a significant factor affecting food security in Ningxia, and the uncertainty of rainfall increases the risk of grain production. It can also be seen that the irrigation facilities, water-saving technologies, and climate-smart agricultural technologies in Ningxia need further improvement.

Ecological security policy and the advancement of urbanization can have a counterproductive effect on food security. As ecological security increasingly gains attention, the constraints of ecological security on the use of arable land are becoming more severe, posing a potential threat to the stable use and productive capacity of arable land resources [51]. Under the national strategy of "poverty alleviation" and the ecological protection policy of "converting farmland back to forest and grassland", the arable land area in Jingyuan, Ningxia, has been significantly reduced, while the area of infrastructure land, forest land, and grassland has been greatly increased. For instance, in 2018, the arable land area in Jingyuan was 17,411 hm^2, which decreased to 7902 hm^2 in 2019. Concurrently, the land area for forest land, grassland, transportation, water areas, and water conservancy facilities increased from 79,507 hm^2, 668 hm^2, 754 hm^2, and 26 hm^2 in 2018 to 94,756 hm^2, 2963 hm^2, 1752 hm^2, and 841 hm^2, with increases of 19.78%, 343.56%, 132.36%, and 3134.62% respectively. The food security index also dropped from 0.3415 in 2018 to 0.2691 in 2019.

The different factors interact with each other and jointly affect food security. GDP per capita and general public budget expenditure can affect the intensity of financial support in agricultural technology, which in turn can enhance crops' adaptability to temperature and precipitation changes. A high urbanization rate may reduce arable land, but it may also compensate for this impact by increasing agricultural production efficiency. NDVI and land use directly reflect the growth conditions of crops and the efficiency of land use, while DEM affects the arability of land. These factors together form a complex system that influences the stability and sustainability of food security.

4.2. Spatial Differentiation Characteristics of Food Security Index in Ningxia

There is a trend of overall improvement with local pressures. Ningxia has high-quality arable land, and there is still room for improvement in the degree and efficiency of arable land use. The overall outlook for food security is good, but the food security situation in Yinchuan and Jingyuan is not optimistic. This study constructs a county-level indicator system and evaluates that the annual average value of the food security index of the 22 counties (districts) is on an upward trend, and the overall food security in Ningxia is guaranteed. However, the food security index in some areas is relatively low, and since 2015, Jingyuan's food security index has been at the lowest position; in 2022, among the six counties (districts) under the jurisdiction of Yinchuan, the food security index of the five counties (districts) other than Yongning is below the annual average. This trend is related to Ningxia's policy of coordinating grain production across the region. Different areas have different resource endowments; for example, the southern mountainous areas, which are not suitable for rice production, do not produce rice. The production efficiency of various factors is inconsistent, and in areas with a higher degree of industrialization and urbanization, the opportunity cost of producing grain is higher, resulting in a lower food security index, such as the counties (districts) of Jinfeng, Xingqing, Xixia, Helan, and Lingwu under the jurisdiction of Yinchuan.

Areas with a high level of urbanization tend to have a lower food security index. The urbanization rate in this region has a negative impact on grain production, while the increase in the urbanization rate of adjacent areas has a positive effect on local grain production that exceeds the direct effect [47]. The impact of the urbanization rate on food security is also the case in the middle and lower reaches of the Yellow River, specifically in the Henan section [52]. The results of this study show that the impact of the urbanization rate on food security ranks in the top 5, and the food security index in areas such as Jinfeng, Dawukou, Lingtong, and Yuanzhou, which serve as administrative centers, is lower than in surrounding areas. Over the decade, the food security index of Jinfeng District, Dawukou District, and Yuanzhou District has consistently been below the annual average food security value of the 22 counties (districts). The advancement of the urbanization process will absorb rural labor from the surrounding areas. At the same time, urbanization requires a large amount of land for industry, commerce, and residential use, which can have a displacement effect on arable land, thereby affecting food security within the region. From 2013 to 2022, in areas with high urbanization, the per capita arable land area has been on a declining trend. In Jinfeng District, it decreased from 0.0588 hectares to 0.0274 hectares; in Litoug District, it decreased from 0.076 hectares to 0.0649 hectares; and in Yuanzhou District, it decreased from 0.2487 hectares to 0.178 hectares.

Areas with concentrated government support for grain production tend to have a higher food security index. Intensive production guided by policy plays a positive role in food security. Similarly, the governments of the 28 EU member states also influence food security through their support for agricultural research and development [53]. Globalization of land use can improve land use efficiency, increase grain output, and ensure food security. This study has calculated that the food security index in counties under the jurisdiction of the original grain reserve production base is relatively high, which is closely related to its intensive management policies. In 2021, Ningxia initiated the construction of the original grain reserve production base in major grain-producing counties such as Yongning, Pingluo, Qingtangxia, and Zhongning, where approximately 6666 hm^2 of production bases for reserve wheat and high-quality rice reserves are established each year. At the same time, a "five unities" management approach was implemented, which includes unified planting varieties, unified soil testing and fertilization, unified field management, unified technical guidance, and unified mechanical harvesting. These policies have played a significant role in enhancing food security in these areas. In 2021 and 2022, the food security index of Yongning, Pingluo, Qingtangxia, and Zhongning all ranked in the top 5 among the 22 counties (districts). Guided by policies, intensive use of land resources can greatly enhance grain production efficiency, thereby increasing the food security index.

4.3. Policy Recommendations

This study identified several factors affecting food security, including intensive land use, climate conditions, ecological restoration, and urbanization processes. To ensure the sustainable capacity of food security and promote the achievement of the SDGs, the following policy recommendations are proposed: (1) Coordinate the use of land resources. There are significant differences in land resources among the counties of Ningxia, and it is necessary to coordinate grain production at the provincial level, reorganize resources across administrative regions, concentrate high-quality arable land, promote the construction of high-standard farmland, strengthen technical guidance, optimize planting space, and improve the efficiency of land resource use. (2) Improve the level of grain planting technology.

Climate conditions such as precipitation, temperature, and sunlight hours have a significant impact on the food security of the counties in Ningxia. By improving agricultural technology, enhancing soil fertility, and increasing the coverage of artificial irrigation facilities, the over-reliance of grain production on climate conditions can be reduced, thereby increasing the food security index. (3) Scientifically manage the relationship between ecological restoration and food security. Ningxia is an ecologically fragile region with a heavy task of ecological restoration. The ecological restoration in the southern mountainous areas has occupied part of the arable land area. After the ecological carrying capacity is improved, it is possible to consider increasing the intensity of agricultural production in the southern mountainous areas, expanding the area of grain production and ensuring food security.

5. Conclusions

Land resources, climate conditions, and policy orientation all have a significant impact on food security. In this study, we constructed a county-level food security evaluation index system, assessed the food security index of 22 counties (districts) in Ningxia from 2013 to 2022, described the evolutionary characteristics of the spatial pattern of county-level food security in Ningxia, and analyzed its influencing factors. The study concludes as follows: (1) Food security is driven by multiple factors. In the 22 counties (districts) of Ningxia, food security is jointly driven by various factors such as economy, society, climate, and land resources, and the driving force of each factor varies under different spatio-temporal conditions. (2) The food security index is lower in the administrative centers. In counties (districts) where the government agencies of the prefecture-level cities are located, due to the higher opportunity cost of land elements and a proportionately higher non-agricultural population, these areas have a lower food security index than surrounding areas. (3) Areas with a higher food security index are concentrated in the Yellow River irrigation area. The Yellow River irrigation area has convenient water conservancy facilities, long-term good irrigation conditions, and high arable land production efficiency, and the major grain-producing counties responsible for food security in Ningxia are concentrated in this area. Based on the conclusions of this study, it is recommended to optimize the main influencing factors of food security to enhance it.

Exploring the spatio-temporal evolution characteristics and driving mechanisms of food security at the county level in ecologically fragile areas is crucial for ensuring food security in these regions. This study takes the evaluation of food security at the county level in Ningxia as a starting point to explore its spatio-temporal evolution and driving mechanisms but still has certain shortcomings. (1) The geodetector model used in this study can only test the magnitude of the explanatory power of food security driving factors but cannot determine the direction of the driving force. (2) This study only conducted an empirical study in one province, Ningxia, and did not reveal the spatio-temporal evolution laws and driving mechanisms of food security from a larger region with similar resource endowments. (3) When using water consumption data, due to the inability to obtain specific data on water consumption for grain production at the county level for the first 8 years, the calculation was made using the proportion of arable land, and the accuracy of the data still needs to be further improved.

In response to the above shortcomings, follow-up studies should select more accurate models to reflect the explanatory power of various factors, incorporate a more comprehensive and diverse set of driving factors, and utilize a variety of research methods to obtain more precise data. Analyses should be conducted at multiple scales to provide policy support for food security in ecologically fragile areas.

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