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Spatio-Temporal Differentiation of Non-Grain Production of Cropland and Its Influencing Factors: Evidence from the Yangtze River Economic Belt, China

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Abstract: Food security is important to guarantee national security and people's livelihoods, but the increasingly serious problem of non-grain production (NGP) on croplands has exacerbated the risk of food security and directly affected the sustainable development of the national economy and society. This study adopted 130 cities (states) in the Yangtze River Economic Belt as the research units and used ArcGIS10.8, GeoDA1.22, and Origin2022 software and spatial autocorrelation, standard deviational ellipse, and GeoDetector methods to conduct analyses. This study explored the spatial evolution patterns and factors influencing cropland NGP in the Yangtze River Economic Belt. The results show, firstly, that the NGP rate of cropland in the Yangtze River Economic Belt increased from 35.85% in 2006 to 38.62% in 2022. The number of cities (states) with mild and moderate NGP decreased, while the number of cities (states) with severe NGP increased significantly. Secondly, the spatial distribution of the rate of cropland NGP in the Yangtze River Economic Belt had a strong positive correlation, with "high–high agglomeration" tending to be dispersed, "low–low agglomeration" tending to be concentrated, and the overall trajectory of the center of gravity migrating from the northeast to the southwest. Thirdly, the single-factor detection found that the per capita food possession, slope, elevation, and average annual precipitation had strong explanatory power regarding the spatial difference in cropland NGP in the Yangtze River Economic Belt, and the interaction of any two influencing factors showed nonlinear enhancement. The results of this study can help to precisely identify the spatial and temporal evolution characteristics of cropland NGP in the Yangtze River Economic Belt, which is of great significance for supporting the country in controlling the risk of NGP cultivation, promoting the sustainable development of the Yangtze River Economic Belt, and guaranteeing food security.

Keywords: cropland; non-grain production; spatio-temporal differentiation; influencing factors; Yangtze river economic belt

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1. Introduction

Croplands are the foundation of agricultural production, and food security is important to guarantee national security and people's well-being [1]. With the continuous advancement of urbanization and industrialization and the modernization of agriculture and rural areas, China's rural labor force loss has intensified, industrial structure adjustment has been strengthened, the land transfer market has become increasingly active, and the comparative returns of agricultural grain cultivation have been low, which causes the problem of NGP of cropland to be more prominent [2–4]. The NGP of cropland not only affects food security, but also poses great risks in terms of rural social imbalance, the fragmentation of agricultural landscapes, and the degradation of ecosystems, thus seriously affecting the sustainable development of regional economies. In the face of the uncertainty brought about by changes in the international situation, it is even more urgent to prevent the NGP of cropland and firmly guard national food security. How to solve the problem of cropland NGP has become the focus of attention of the government, scholars, and the public [4–7]. In November 2020, the General Office of the State Council issued the Opinions on Stabilizing Food Production by Preventing the "Non-Grain" Production of Cropland, emphasizing that strong measures should be taken to prevent the "non-grain" production of cropland and that cropland resources should be prioritized for food production so as to effectively stabilize food production and safeguard national food security. Guaranteeing national food security, Document No. 1 of the Central Government in February 2024 clearly stated that areas sown with grain should be stabilized, and the policy of subsidizing grain cultivation should continue to be implemented to ensure national food security. Therefore, how to stabilize areas sown with grain and prevent excessive cropland NGP areas has become an urgent issue of national food security.

In recent years, along with extensive public attention, the protection of cropland, remediation of NGP, and ensuring food security have become focuses of current academic research. In terms of research content, the conceptual definition [8,9], quantitative measurement [4,9], food security [8], spatial and temporal patterns [10,11], influencing factors [12], and preventive and curative measures [13] of cropland NGP have been addressed. In terms of research scales, national [3,11], functional grain areas [14], provincial [1,11], municipal [15], and county, town, and village [16] scales have also been studied. However, fewer studies have focused on balanced grain production and marketing areas, the main grain marketing areas and non-centers of grain production areas at the provincial level. In terms of research methods, statistical analysis and econometric modeling are mainly used. The main methods used include the use of a spatial autocorrelation model to portray spatial characteristics based on Geoda, ArcGIS, and other software [17,18]. The random forest model [4], multiple linear regression analysis [19], and logistic regression [20] are used to explore the driving mechanism of NGP of cropland from a socio-economic point of view. To summarize, many academic studies have focused on cropland NGP, but there are many aspects that deserve further in-depth exploration. Firstly, in terms of the research scale, the current research focuses more on the provincial scale of the main grain-producing areas. However, research on the main production areas, the main marketing areas, and the balance of production and marketing areas within the functional areas of China's grain production is still insufficient. At the same time, the spatial differences within the provinces of the three major functional zones have been overlooked. Secondly, in terms of influencing factors, many current studies start from unilateral socio-economic or natural conditions, which is one-sided. However, fewer studies have examined the construction of an indicator system of influencing factors from multiple perspectives, such as social, economic, natural, and production conditions. Thirdly, in terms of research content, horizontal comparisons of cropland NGP while exploring the main production areas, main marketing areas, and balance of production and marketing areas have not yet been completed, and the spatial shift of the gravity of cropland NGP is yet to be explored in depth. In view of this, based on a multi-scale perspective, we explore the time series change characteristics of cropland NGP in the Yangtze River Economic Belt, aiming to provide theoretical guidance for exploring cropland protection and food security in the Yangtze River Economic Belt. Second, based on the combined use of spatial autocorrelation and standard deviational ellipse models, we explore and verify the spatial evolution pattern of cropland NGP in the Yangtze River Economic Belt via the integration of multiple methods to compensate for the shortcomings of this current study.

The Yangtze River Economic Belt spans three major regions in Eastern, Central, and Western China, with large differences in natural conditions between the East and West, including the Yunnan–Guizhou Plateau, the middle and lower Yangtze River plains, six major grain-producing areas, three grain-production and marketing balance areas, two major grain marketing areas, and cropland accounting for about one-third of the country. Agriculture provides important support for the Yangtze River Economic Belt and is an important area necessary to guarantee China's food security. However, responsible for only 30.07% of the country's grain production in 2022, the risk of cropland NGP is high due to socio-economic development.

Based on this, this study selected the Yangtze River Economic Belt as the study area, examining it from the three scales of cities (states); functional grain areas; and the upper, middle, and lower reaches of the Yangtze River Basin. Based on three periods of geospatial data and socio-economic and natural statistics in 2006, 2015, and 2022, spatial autocorrelation analysis, a standard deviational ellipse model, and a geoprobe were used to analyze the spatial and temporal evolution characteristics of cropland NGP in the Yangtze River Economic Belt and its causes to provide a reference for controlling cropland NGP and ensuring food security in the region.

2. Analysis Framework

2.1. Definition of Concepts

Clarifying the concept of cropland NGP is an important prerequisite for recognizing and controlling the phenomenon of cropland NGP. In conjunction with previous studies, cropland NGP, in a narrow sense, mainly refers to the cultivation of cash crops, such as vegetables, fruits, and flowers, on cropland [8,21]. In contrast, the broader definition of cropland NGP refers to non-food crop cultivation on cropland [22,23]. However, in terms of the quantitative measurement of NGP, current scholarly research mainly uses the "grain-to-crop ratio" and the "ratio of non-food sown area to sown area of crops" to quantitatively measure the NGP of cropland and uses the NGP rate of cropland to measure the level of NGP in a region. Based on the openness, authoritativeness, and data availability of the relevant research materials, and in accordance with the Opinions on Preventing the "Non-Grain Production" of Cropland and Stabilizing Food Production issued by the General Office of the State Council and the relevant research studies, in this study, food crops are defined as cereals, wheat, miscellaneous grains, pulses, and yams, and the act of sowing crops other than these is defined as NGP. This definition can accurately be used to measure the degree of NGP of cropland in the Yangtze River Economic Zone and provide a scientific basis for the formulation and implementation of relevant policies. The ratio of the sown area of non-food crops to the sown area of crops was used to measure the degree of NGP of cropland in the Yangtze River Economic Zone, as follows:

$$F = (1 - L/P) \times 100\%$$

where F is the rate of non-grain production of cropland (the NGP rate), L is the area sown for food crops, and P is the area sown for agricultural crops. The advantage of the conceptualization in this study is that there are precise and authoritative statistics for all of the above indicators.

2.2. Research Framework

The emergence of cropland NGP is closely related to the natural environment, economic level, social development, and production conditions, and the combined effect of different factors has a greater impact on cropland NGP. At the macro level, rapid economic development accelerates the adjustment of the social and industrial structures, and the constraints of the natural environment greatly reduce productivity and lead to inefficiencies in the benefits of growing food, thus contributing to the development of non-agricultural industries (Figure 1). The analytical framework of this study is as follows: firstly, data were collected and organized to form a database on cropland NGP. Secondly, in the ArcGIS10.8 software (https://www.esri.com, accessed on 2 February 2024), the natural breaks (Jenks) method was utilized to explore the characteristics of the time period changes of cities (states); functional grain areas; and the upper, middle, and lower reaches of the Yangtze River Basin in the Yangtze River Economic Belt. Then, spatial exploration tools were used to explore the spatial evolution characteristics of cropland NGP in the Yangtze River Economic Belt based on spatial autocorrelation and standard deviational ellipse bispace analysis models. Finally, based on Geodetectors, this study explored the factors influencing the current spatial differences in the NGP of cropland in the Yangtze River Economic Belt and the proposed countermeasures.

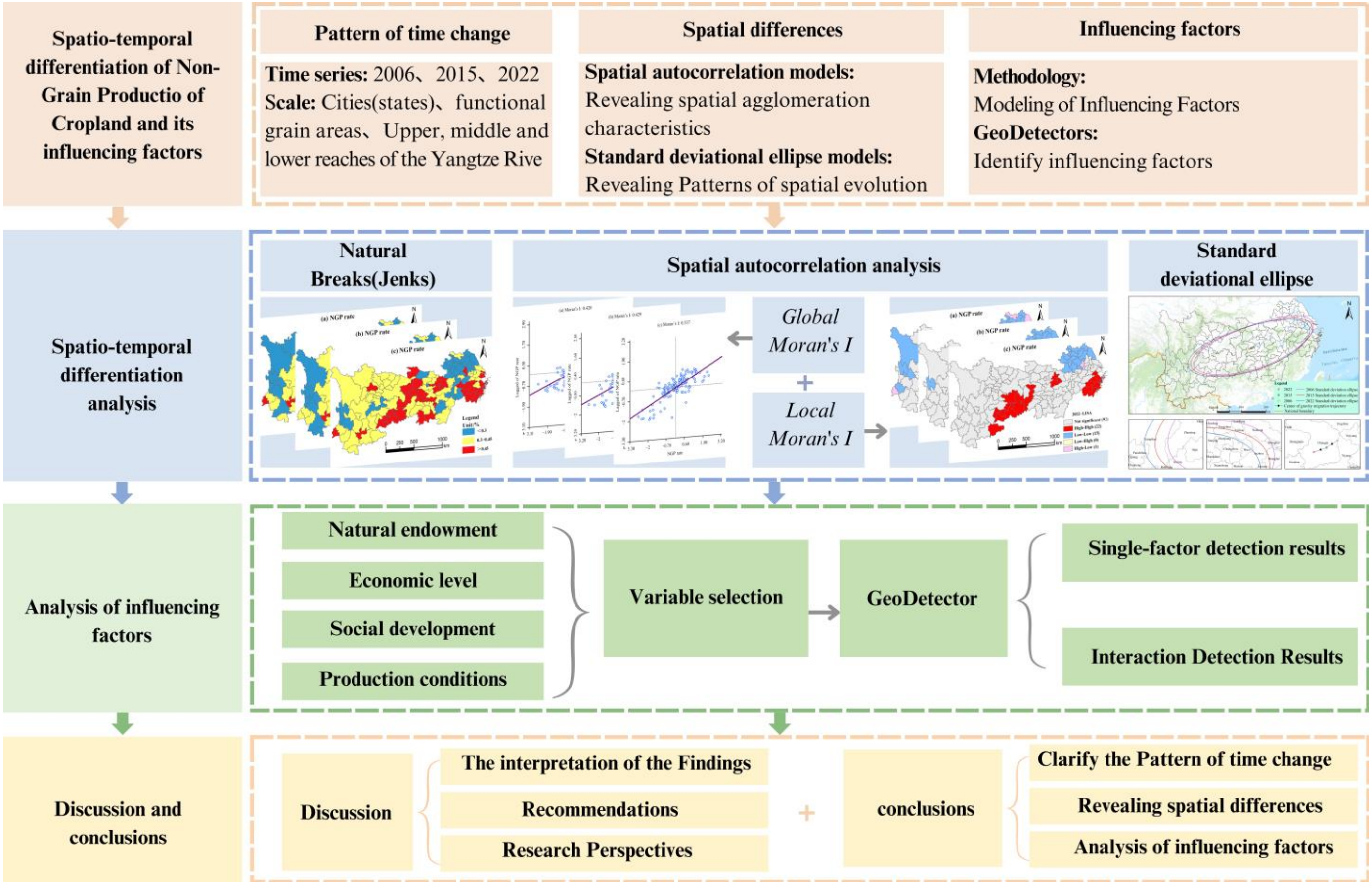

Figure 1. Research framework.

3. Materials and Methods

3.1. Overview of the Study Area

The Yangtze River Economic Belt spans 3 major regions in China, namely Sichuan, Yunnan, Guizhou, and Chongqing in the upper reaches of the Yangtze River Basin; Hubei, Hunan, and Jiangxi in the middle reaches of the Yangtze River Basin; and Anhui, Jiangsu, Zhejiang, and Shanghai in the lower reaches of the Yangtze River Basin, with a total of 11 provincial-level administrative units, including 6 major grain-producing areas, 3 grain-production and marketing balance areas, and 2 major grain-marketing areas (Table 1). Its land area is 205.23 km^2, accounting for 21.4% of the country's total area. By the end of 2022, the economic belt had a population of 524 million, accounting for 37.14% of the country's total population, while its GDP accounted for 42.01% of the country's GDP, demonstrating strong economic momentum. The geomorphological types are rich and diverse, with high terrain in the west and low terrain in the east. The steepest average slope within the territory is located in the western Yunnan Province Nujiang Lisu Autonomous Prefecture, at 28.11°; the highest average elevation within the territory is located in the western Sichuan Province Ganzi Tibetan Autonomous Prefecture, at 4186.02 m, with an average slope of 0.45 °and elevation of 1.34 m. The lowest point is east of the Yellow–Huai-Hai Sea Plain in Yancheng City, Jiangsu Province. Geographical differentiation is obvious, with both economically developed and underdeveloped regions, and national-level city clusters, such as the Yangtze River Delta, the city cluster in the middle reaches of the Yangtze River Basin, and the Chengdu–Chongqing city cluster, as well as small- and medium-sized city clusters in Qianzhong and Yunnan, which relatively lag behind the others (Figure 2).

Table 1. The Yangtze River Economic Belt functional grain production zone.

Functional Grain Areas	Provinces
Major grain-producing areas	Jiangsu, Anhui, Jiangxi, Hubei, Hunan, Sichuan
Major grain-marketing areas	Shanghai, Zhejiang
Grain production and marketing balance areas	Guizhou, Yunnan, Chongqing

Note: Data on China's functional grain areas.

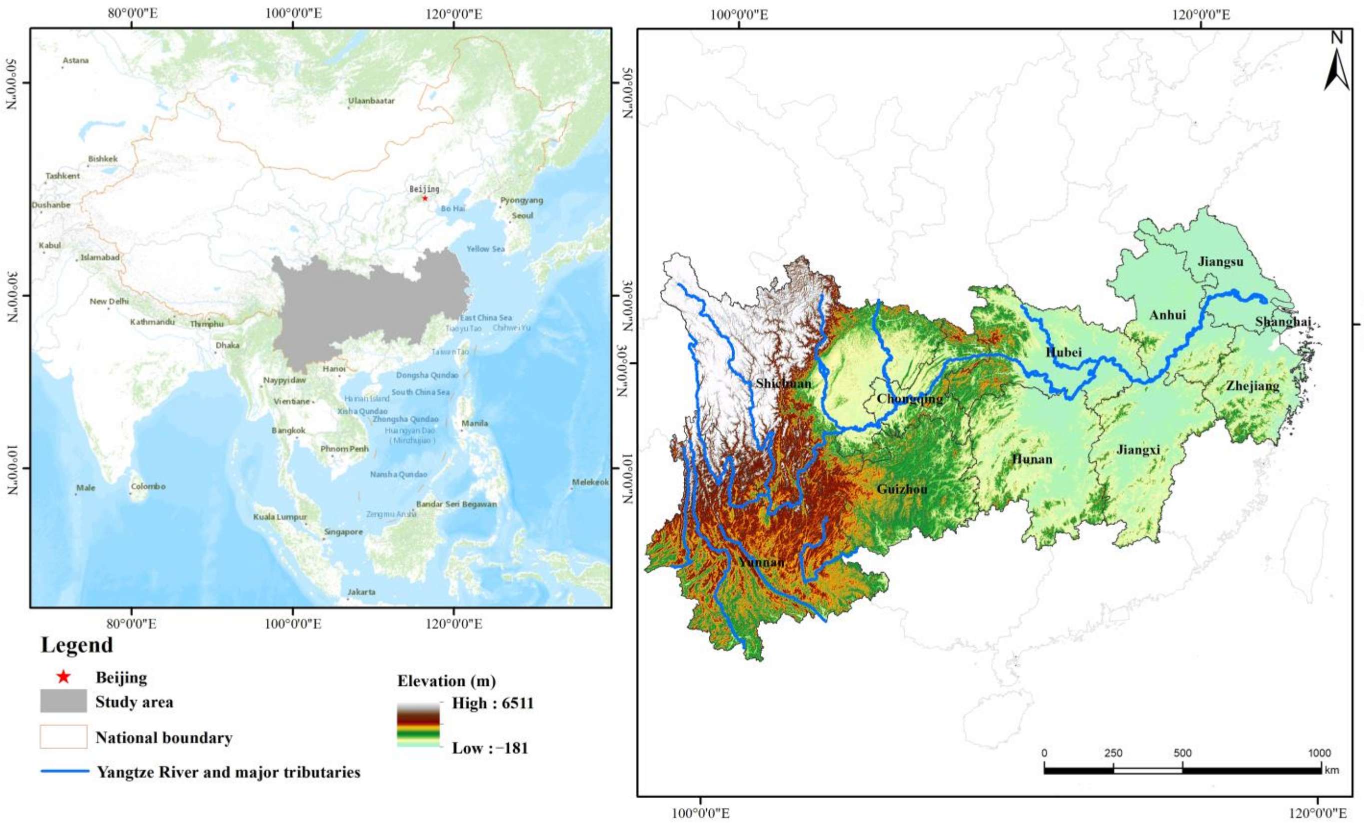

Figure 2. The location of the study area.

3.2. Data Sources

The administrative boundaries of the provinces and cities (states) of the Yangtze River Economic Belt were obtained from the National Center for Basic Geographic Information (http://www.ngcc.cn/, accessed on 13 January 2024). The Yangtze River Economic Belt covers a total of 130 municipal units (including 2 municipalities directly under the Central Government). It should be noted that the municipal units are based on 2022, during which the phenomenon of merging municipal units and splitting was carried out via raw data processing. The DEM data were obtained from the Geospatial Data Cloud Platform (http://www.gscloud.cn/, accessed on 13 January 2024), with a spatial resolution of 30 m. The average slope was obtained using the DEM data and processed using ArcGIS tools. The grain crop sown area, crop sown area, and socio-economic statistics were obtained from the provincial cities' (states) statistical yearbooks for 2007, 2016, and 2023 (https://www.stats.gov.cn/sj/ndsj/, accessed on 20 January 2024) and cities' (states) statistical bulletins for 2006, 2015, and 2022.

3.3. Research Methodology

3.3.1. Spatial Autocorrelation Models

The Moran's I index was used to test the spatial autocorrelation of element distributions, including global spatial autocorrelation and local spatial autocorrelation, which can be applied to identify agglomerated areas and accurately reflect whether the spatial distribution of an attribute in the regional scope is correlated with the neighboring areas and the degree of correlation [24–27]. This study used Global Moran's I to explore whether there was a clustering or dispersion of cropland NGP in the Yangtze River Economic Belt as a whole using the following formula:

$$I_g = \frac{n \times \sum_{i=1}^{n} \sum_{j=1}^{n} \omega_{ij} (x_i - \overline{x}) (x_j - \overline{x})}{\sum_{i=1}^{n} \sum_{j=1}^{n} \omega_{ij} \sum_{i=1}^{n} (x_i - \overline{x})^2} \quad (1)$$

where n is the total number of cities (states) in the study area; x_i and x_j are the observed values of units i and j, respectively; $\overline{x}$ is the average mean value of all cities (states) in the study area; and ω_{ij} is the spatial weight matrix of the study unit. The range of I_g is $[-1, 1]$; $I_g > 0$ is a positive correlation, and spatial elements are agglomerated; $I_g < 0$ is a negative correlation, and spatial elements are dispersed; and $I_g = 0$ is a random distribution.

Global Moran's I mainly presents the distribution characteristics of the cropland NGP rate in each city (state) of the Yangtze River Economic Belt. However, it is difficult to present spatially localized clustering and spatial differences using this metric [28]. Therefore, Local Moran's I needs to be further adopted to determine the spatial clustering characteristics of high and low values of the cropland NGP rate and clarify the spatial differences between local areas and their surroundings. The formula is as follows:

$$I_l = \frac{(x_i - \overline{x}) \sum_{j=1}^{n} \omega_{ij} (x_j - \overline{x})}{\frac{1}{n} \times \sum_{i=1}^{n} (x_i - \overline{x})^2} \quad (2)$$

where $I_l > 0$ reflects that the difference between city (state) No. 1 and its neighboring cities and states is less significant, with stronger homogeneity and agglomeration; conversely, the difference is more significant, with weaker homogeneity and agglomeration.

3.3.2. Standard Deviational Ellipse Models

The standard deviational ellipse (SDE), first proposed by Lefever in 1926 [29], is a statistical method used to reveal the characteristics of the spatial distribution of geographic elements, which can accurately reveal the center of the spatial distribution of geographic elements, as well as discrete and directional trends [30], and has been widely used in the fields of demography [31], economics [32], ecology [33,34], etc. This study adopted the standard deviational ellipse and center of gravity migration analyses to reveal the spatial evolution characteristics of the NGP cropland in the Yangtze River Economic Belt and calculated the relevant parameters based on the spatial statistics module of ArcGIS10.8. The specific formulas are as follows:

$$SDE_x = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \overline{X})^2}{n}} \quad (3)$$

$$SDE_y = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \overline{Y})^2}{n}} \quad (4)$$

$$tan\theta = \frac{\left(\sum_{i=1}^{n} \overline{x_i}^2 - \sum_{i=1}^{n} \overline{y_i}^2\right) + \sqrt{\left(\sum_{i=1}^{n} \overline{x_i}^2 - \sum_{i=1}^{n} \overline{y_i}^2\right)^2 + 4(\sum_{i=1}^{n} \overline{x_i y_i})^2}}{2\sum_{i=1}^{n} \overline{x_i y_i}} \quad (5)$$

$$\sigma_x = \sqrt{2}\sqrt{\frac{\sum_{i=1}^{n}(\overline{x_i}cos\theta - \overline{y_i}sin\theta)^2}{n}} \quad (6)$$

$$\sigma_y = \sqrt{2}\sqrt{\frac{\sum_{i=1}^{n}(\overline{x_i}cos\theta + \overline{y_i}sin\theta)^2}{n}} \quad (7)$$

where SDE_x and SDE_y are the center of the ellipse of the study object; x_i and y_i are the spatial locations of the study object; x_i and y_i are the coordinates of the ith study unit; $\overline{x}$ and $\overline{y}$ are the coordinates of the center of gravity; n is the total number of cities (states); θ is the angle of the ellipse, which denotes the angle formed by a clockwise rotation of the due north direction to the long axis of the ellipse; σ_x and σ_y are the standard deviations of the sum axis; and $\overline{x_i}$ and $\overline{y_i}$ are the coordinates of the location of the respective study object to the center of the mean deviation.

3.3.3. Modeling of Influencing Factors

The Yangtze River Economic Belt spans the three steps of China's geography, and there is significant spatial heterogeneity in the region's natural environment, socioeconomic development, and production conditions. Referring to the existing studies on cropland NGP [3,18,20,35,36], combining the characteristics of regional development and data availability, 14 indicators were selected from 4 dimensions, namely the natural environment, economic level, social development, and production conditions, in order to study the influencing factors of spatial differences in cropland NGP in the Yangtze River Economic Belt (Table 2). The natural endowment was mainly from the point of view of topography and climate, and four indicators were selected: average annual temperature, average annual precipitation, average slope, and average elevation. The economic level was selected from the perspectives of economic development, industrial development, urban–rural development, and people's consumption levels, with four indicators: GDP per capita, consumption level per capita, the ratio of secondary and tertiary industries, and the ratio of urban and rural incomes. Social development was based on three indicators: the urbanization rate, comparative efficiency of agriculture, and food per capita, selected from the perspective of farmers' own factors and the state of social development. Production conditions were mainly constructed from the perspectives of the mechanization level, cropland resources, and output efficiency using three indicators: the total mechanical power per unit of cropland area, per capita cropland area, and land productivity.

Table 2. Indicators of impact factors.

Standardized Layer	Factors	Unit	Definitions	Mean	Max	Min	Standard Deviation
Natural endowment	Average annual temperature (X_1)	°C	Mean annual air temperatures in the study unit, reflecting farming air temperature conditions in the study area.	17.36	21.60	7.60	1.96
	Average annual precipitation (X_2)	mm	Mean annual precipitation in the study unit, reflecting farming water endowment in the study area.	1096.85	1978.50	490.90	295.94
	Slope (X_3)	°	Average slope of the study unit, reflecting the steepness of the terrain and ease of cultivation in the study area.	9.65	28.11	0.45	6.74
	Elevation (X_4)	mm	Average elevation of the study unit, reflecting the actual elevation of the study area.	644.54	4186.02	1.34	819.94
Economic level	GDP per capita (X_5)	CNY	Ratio of the annual gross product to the total population in the study unit, reflecting the level of economic development in the study area.	77,695.14	198,404.00	27,168.23	38,560.23
	Per capita consumption level (X_6)	CNY	Ratio of the resident population to total consumer goods in the study unit, reflecting the level of consumption of the people in the study area.	28,532.88	82,523.73	2318.06	14,428.08
	Ratio of secondary and tertiary industries (X_7)	%	Ratio of secondary and tertiary output to GDP of the study unit, reflecting the degree of industrial development.	88.43	99.78	69.27	6.60
	Ratio of urban and rural incomes (X_8)	%	Eatio of the disposable income of rural residents to the disposable income of urban residents, reflecting the urban–rural gap.	2.15	3.57	1.56	0.38

Table 2. *Cont.*

Standardized Layer	Factors	Unit	Definitions	Mean	Max	Min	Standard Deviation
Social development	Urbanization rate (X_9)	%	Ratio of the urban resident population to the total population in the study unit, reflecting the current level of urbanization.	59.41	89.30	31.92	12.14
	Comparative efficiency of agriculture (X_{10})	%	Ratio of agricultural output to total agriculture, forestry, livestock, and fisheries output in the study unit, reflecting the efficiency of agricultural output and the propensity of farm households to make agricultural choices.	62.24	95.56	3.50	14.18
	Food possession per capita (X_{11})	kg/per	Ratio of the resident population to food production in the study unit, reflecting regional food holdings.	454.57	1500.41	20.15	275.37
Production conditions	Total mechanical power per unit of crop (X_{12})	kW/ha	Ratio of the cropland area in the study unit to the total mechanical power in the agricultural industry, reflecting regional production conditions.	12.62	82.88	0.35	8.28
	Cropland area per capita (X_{13})	ha/per	Ratio of the cropland area to the resident rural population in the study unit, reflecting the amount of cultivated land resources per capita	0.07	0.19	0.02	0.04
	Land productivity (X_{14})	CNY/ha	Ratio of primary sector output to the area sown for crops in the study unit, reflecting the output efficiency of cropland.	71,321.57	1,082,963.90	6543.56	93,723.85

3.3.4. GeoDetectors

GeoDetectors are a set of statistical methods used for detecting spatial dissimilarities and revealing the driving forces behind them [37]. The core idea is that, if an independent variable has an important effect on a dependent variable, then the spatial distribution of independent variable X and dependent variable Y should be similar [38,39], and the analysis results consider geographical attributes. In this study, the main influencing factors and interaction characteristics of the cropland NGP were determined using the NGP rate of cropland in each city (state) of the Yangtze River Economic Belt as the dependent variable and the influencing factors as the independent variables, as well as by using a GeoDetector. The q statistic in the factor detector can be used to determine the strength of X's explanation of Y. The range of q is [0, −1], with q of 0 reflecting that X has no explanation of Y, and q of 1 reflecting that X fully explains Y. The larger the value of q, the greater the explanatory power of X for Y. The formula is as follows:

$$q = 1 - \frac{1}{n\sigma^2}\sum_{d}^{k} n_d\sigma_d^2 \quad (8)$$

where d is the stratification of factors X and Y, $d = 1, 2, \cdots, k$; n_d and n are the stratum d and the number of study units, respectively; and σ_d^2 and σ^2 are the variances in the values of Y for stratum d and the number of study area units, respectively.

Interaction probes can be used to judge the interactions between the influencing factors. After detecting the relationship between q following the superposition of two factors and the q value of the original single factor to identify the interaction between different influencing factors so as to reveal whether there was an interaction between different influencing factors and the intensity of the factor interaction, factor interactions were determined to have a total of five bell types (Table 3).

Table 3. Types of factor interactions.

Standard	Type
$q(x_1 \cap x_2) < Min[q(x_1),q(x_2)]$	Nonlinear weakening
$Min[q(x_1),q(x_2)] < q(x_1 \cap x_2) < Max[q(x_1),q(x_2)]$	Single-factor nonlinear attenuation
$q(x_1 \cap x_2) > Min[q(x_1),q(x_2)]$	Two-factor enhancement
$q(x_1 \cap x_2) = q(x_1) + q(x_2)$	Independent
$q(x_1 \cap x_2) > q(x_1) + q(x_2)$	Nonlinear enhancement

4. Results

4.1. Characteristics of Temporal Changes in the NGP of Cropland

During the period of 2006–2022, the NGP rate of cropland in the Yangtze River Economic Belt showed an increase, and the average value of the NGP rate of cropland increased from 35.85% in 2006 to 38.62% in 2022, an increase of 7.73%. In order to better present the change characteristics of the city (state)-scale cropland NGP in the time series during the three periods, the boundaries were scientifically delineated according to existing studies [15,28,40] and combined with the actual situation of the Yangtze River Economic Belt. Using the ArcGIS 10.8 software, the Natural Break (Jenks) method was used to classify the degree of cropland NGP into three categories: mild NGP (NGP rate < 30%), moderate NGP (30% $\leq$ NGP rate $\leq$ 45%), and severe NGP (45% > NGP rate). Within the time series of this study, 84 cities (states) showed an increase in the rate of cropland NGP, accounting for 64.62% of the total. Among them, the Ganzi Tibetan Autonomous Prefecture in Sichuan Province, Liupanshui City in Guizhou Province, and Qiannan Buyi and Miao Autonomous Prefecture had the largest growth, from 9.56%, 21.97%, and 36.03 in 2006 to 32.49%, 43.21%, and 56.21% in 2022, respectively, representing increases of 22.93%, 21.23%, and 20.18%. In terms of categories, the number of municipalities (states) with light and medium levels of NGP decreased, while the number of cities (states) with heavy levels of NGP increased significantly (Figure 3). Of these, 37 cities (states) showed mild NGP in 2006, accounting for 28.46%; 34 cities (states) showed mild NGP in 2015, a decrease of 3 cities compared with 2006; and only 31 cities (states) showed mild NGP in 2022, a decrease of 6 cities compared with 2006, or 16.22%. The number of cities (states) that showed moderate NGP declined from 71 in 2006 to 59 in 2022, a decrease of 16.90%. The number of cities (states) that showed severe NGP increased from 22 in 2006 to 40 in 2022, an increase of 81.82%.

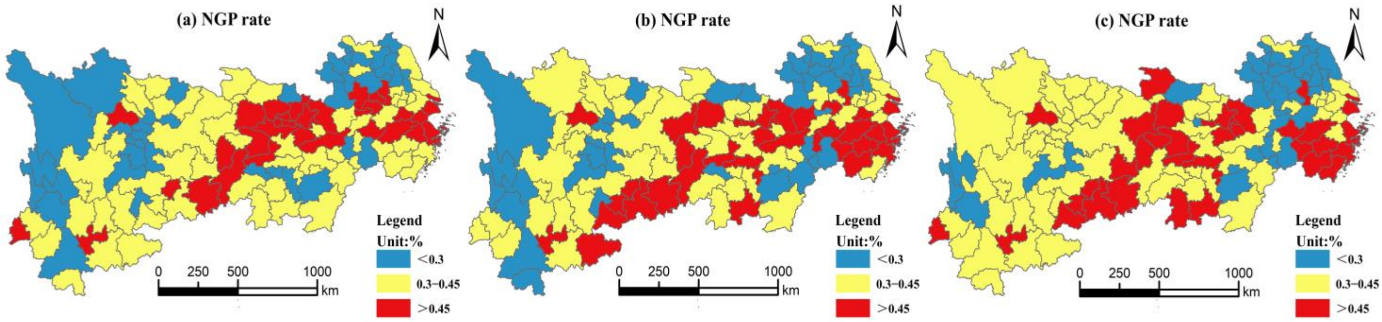

Figure 3. Time series of changes in the degree of cropland NGP: (**a**) represents 2006, (**b**) represents 2015, and (**c**) represents 2022.

Given the trend of changes in functional grain areas, the most serious degree of cropland NGP was in the main marketing area, followed by the balance of production and marketing area, and the main production area had the lowest rate of NGP (Table 4). From the perspective of the specific change trend, the main production area exhibited a small change between 2006 and 2022, around 35%, with a stable food supply, providing an important guarantee of food security. The main marketing area experienced the most severe degree of cropland NGP, and the rate of cropland NGP dropped from 50.56% in 2006 to 49.77% in 2015 and then rose to 52.63% in 2022, which was mainly because the main marketing area's rapid economic development and the small proportion of agricultural activities in the process of socio-economic development led to a high rate of NGP. The NGP rate of cropland in the production and marketing balance area, on the other hand, exhibited a state of rapid increase, from 33.01% in 2006 to 43.77% in 2022, an increase of 32.61%, which mainly stemmed from the fact that Yunnan, Guizhou, and Chongqing are subject to natural constraints and limited production conditions. On the other hand, Yunnan, Guizhou, and Chongqing are all the main battlefields for consolidating and expanding the results of the poverty-alleviation campaigns in the western part of China, and the benefits of growing grains, labor loss, and land transfer together triggered an increase in NGP.

Table 4. Statistics on the NGP rate of cropland in the Yangtze River Economic Belt's functional grain areas and regional subzones.

Year	2006	2015	2022
Main production area	35.13%	35.00%	35.52%
Main marketing area	50.56%	49.77%	52.63%
Balance of production and marketing area	33.01%	39.88%	43.77%
Upper reaches of the Yangtze River Basin	32.06%	38.06%	42.03%
Middle reaches of the Yangtze River Basin	38.49%	39.43%	41.35%
Lower reaches of the Yangtze River Basin	41.81%	39.67%	39.37%

Examining the trend of regional changes in the upper, middle, and lower reaches of the Yangtze River Basin, the degree of NGP in the upper and middle reaches of the Yangtze River Basin increased, while the NGP rate in the lower reaches of the river decreased by a small margin. Meanwhile, the average NGP rate in the study period was as follows: lower reaches > middle reaches > upper reaches (Table 4). Among them, the NGP rate of cropland in the upper reaches of the Yangtze River Basin increased from 32.06% in 2006 to 42.03% in 2022, with an average annual increase of 1.71%. The NGP rate of cropland in the middle reaches of the Yangtze River Basin increased from 38.49% in 2006 to 41.35% in 2022, with an average annual increase of 0.45%. The NGP rate of cropland in the lower reaches of the Yangtze River Basin decreased from 41.81% in 2006 to 39.37% in 2022, with an average annual decrease of 0.38%, mainly because Anhui and Jiangsu provinces in the region, the main grain-producing provinces in China, are located in the Yellow–Huai Hai Plain, which has a flat topography and fertile soil suitable for farming, thus decreasing NGP in the region.

4.2. Characteristics of the Spatial Distribution of Cropland NGP

In order to explore whether there is a spatial characteristic of cropland NGP in the Yangtze River Economic Belt in the study period, a spatial autocorrelation analysis test was performed using the GeoDA 1.22 software (http://geodacenter.github.io/index-cn.html, accessed on 5 March 2024). The Global Moran's I of the Yangtze River Economic Belt in 2006, 2015, and 2022 passed the significance test at the 1% level, indicating that the spatial distribution of the cropland NGP rate in the Yangtze River Economic Belt in the study area had strong positive correlations and tended to be clustered. The Global Moran's I index increased during the study period, but with small changes. Among them, the Moran's I index values were 0.420 in 2006, 0.429 in 2015, and 0.537 in 2022, indicating that the spatial agglomeration characteristics of cropland NGP in the Yangtze River Economic Belt maintained a relatively stable status (Figure 4).

In order to explore the specific distribution areas of cropland NGP in the Yangtze River Economic Belt, LISA clustering was plotted for each year based on Local Moran's I (Figure 5). The types of spatial agglomeration of NGP cropland in the three time periods of 2006, 2015, and 2022 were dominated by "high–high agglomeration" and "low–low agglomeration", and there was obvious spatial heterogeneity in the regional space with the passage of time. Over time, areas of "high–high agglomeration" tended to be decentralized, while areas of "low–low agglomeration" tended to be concentrated. Among them, there were 27 cities (states) with high and high agglomeration in 2006 and 2 agglomeration clusters. They were mainly located in the middle reaches of the Yangtze River Basin in the eastern and southern parts of Hubei Province; the northern part of Hunan Province; and the lower reaches of the Yangtze River Basin in the southeastern part of Anhui Province, Zhejiang Province, and Shanghai. There were 22 cities (states) with high and high agglomeration in 2022 and 4 agglomeration city clusters. They were mainly located in the eastern part of Yunnan Province in the upper reaches, the eastern part of Guizhou Province and the western part of Hunan Province along the middle and upper reaches of the border, the southeastern part of Hunan Province in the middle reaches, and the coastal area in the lower reaches.

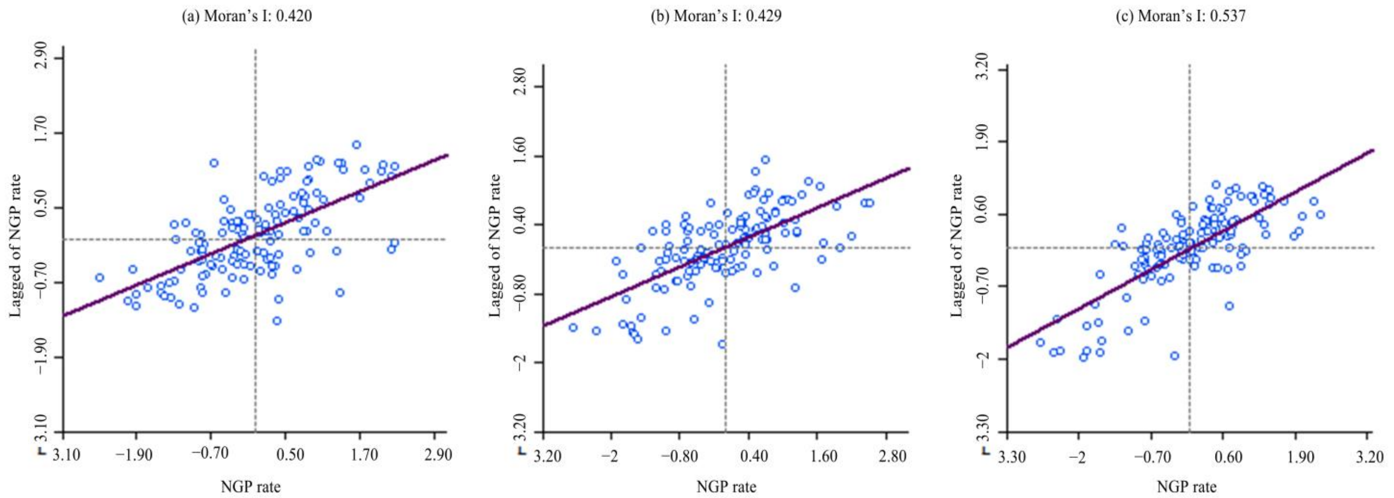

Figure 4. Moran's I scatterplot of the rate of cropland NGP in the Yangtze River Economic Belt in 2006 (**a**), 2015 (**b**), and 2022 (**c**).

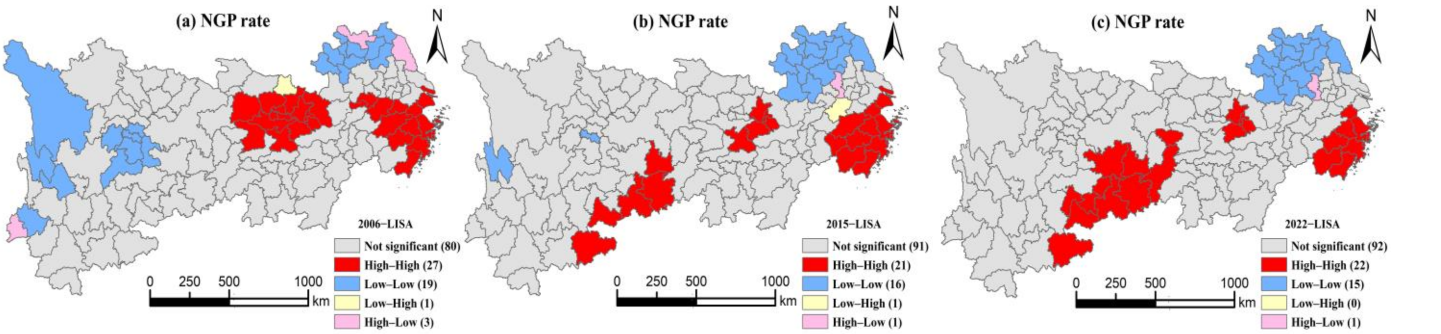

Figure 5. Types of spatial agglomeration of NGP in cropland in the Yangtze River Economic Belt: (**a**) 2006, (**b**) 2015, and (**c**) 2022.

The number of cities (states) with "low–low agglomeration" and the spatial distribution of agglomeration clusters decreased. In 2006, there were 19 cities (states) with low–low agglomeration and 4 agglomeration clusters (Figure 5). They were mainly distributed in the junction areas of western Sichuan Province and northeastern Yunnan Province upstream, the junction areas of eastern Sichuan Province and western Guizhou Province downstream, and the junction areas of Anhui Province and northern Jiangsu Province downstream. There were 15 cities and states with low–low agglomeration and 1 agglomeration cluster in 2022. They were mainly located in the whole of Anhui Province and the northern region of Jiangsu Province, the main downstream grain-producing areas. The "low–high" and "high–low" agglomerations involved fewer cities (states) and had a smaller distribution; in 2006, the low–high agglomeration area comprised Suizhou City in northern Hubei Province. The high–low agglomeration comprised Yancheng City, northern and Xuzhou City in eastern Jiangsu Province, and Dehongzhou City in eastern Yunnan Province in 2022. In 2022, the high–low agglomeration was distributed in Nanjing City in the southwest of Jiangsu Province.

Using the ArcGIS10.8 software, the standard deviational ellipse and spatial center of gravity migration model were used to explore the spatial evolution characteristics of cropland NGP in the Yangtze River Economic Belt and clarify the spatial development tendency of cropland NGP (Figure 6). During the study period, the geographic coordinates of the center of gravity of cropland NTFPs in the Yangtze River Economic Belt ranged between 112°22′ E–111°40′ E and 29°32′ N–29°02′ N, showing a northeast-to-southwest migration. Among them, 112.22 km migrated from northeast to southwest from 2006 to 2015 and 111.83 km from 2015 to 2022. Although the overall migration direction of cropland

NGP changed, the spatial center of gravity of cropland NGP in the Yangtze River Economic Belt was located on the border of Yiyang City and Changde City, Hunan Province, except in 2006, when the center of gravity of cropland NGP was located in Changde City, Hunan Province, in both 2015 and 2022 (Figure 6). Per the standard deviational ellipse analysis, the range of the ellipse was relatively stable during the study period, with small changes in the overall direction of northeast–southwest, which further confirmed the phenomenon of high-and-high agglomeration in western Hunan Province to the southwest along Guizhou. The reason for this is that, although Hunan Province is located in the middle reaches of the Yangtze River Basin, with large topographic differences between the east and west, the western part of Hunan Province bordering Guizhou and Chongqing has large topographic undulations and limited farming conditions. At the same time, the impact of farmers' agricultural planting efficiency led to a decline in the area of grain crops sown, and the rate of cropland NGP continued to rise. The current rate of cropland NGP in Hunan Province is more than 45% of the city (state) in nine cities (states), which account for 64.29% of the province.

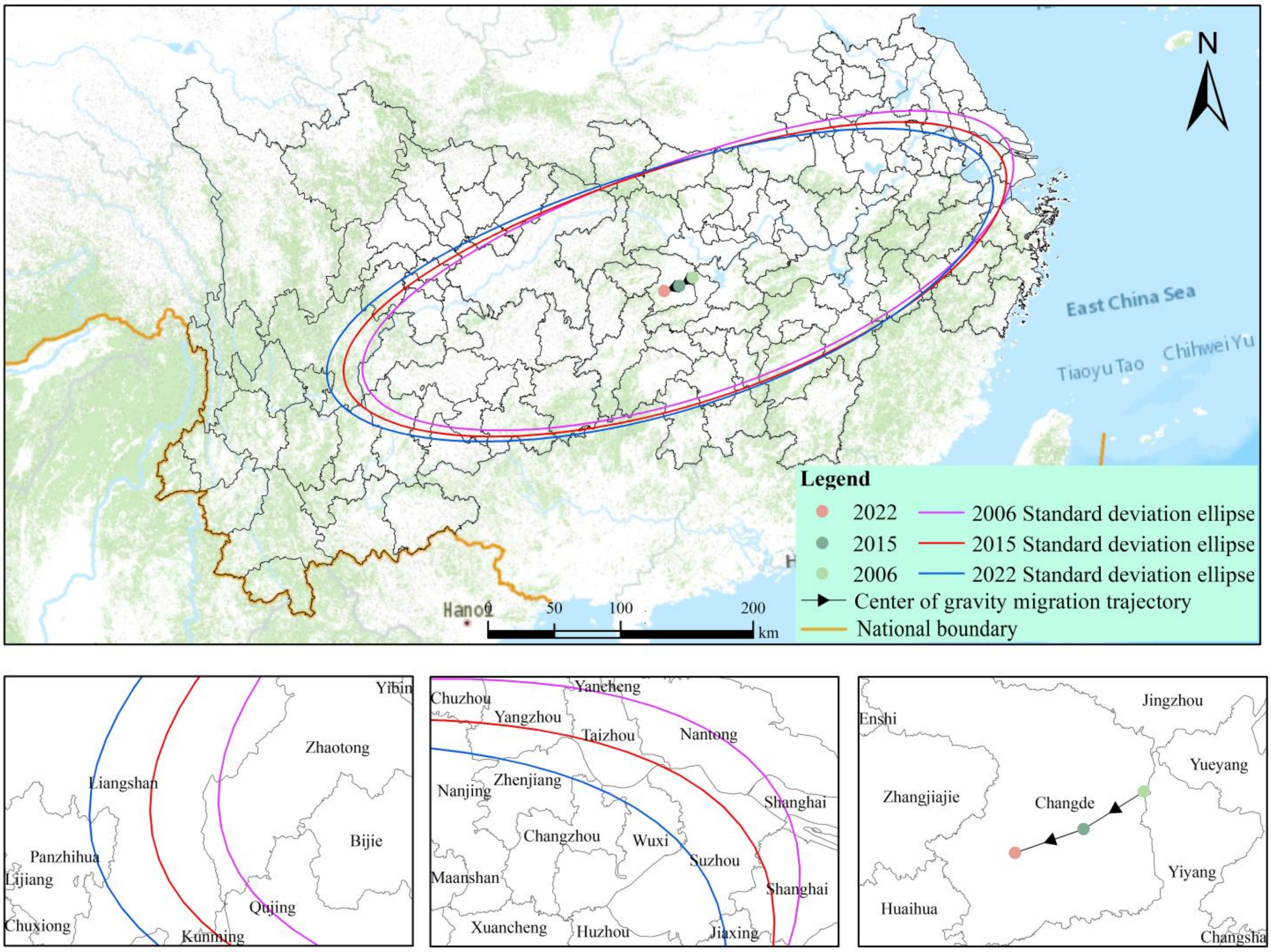

Figure 6. Trend map of the spatial evolution of cropland NGP in the Yangtze River Economic Belt.

4.3. Analysis of Influencing Factors

4.3.1. Single-Factor Detection Results

Using the ArcGIS10.8 software to rasterize the influencing factors of cropland NGP and subsequently reclassify them using the GeoDetector software (http://www.geodetector.cn/, accessed on 20 March 2024) (Figure 7), all 14 impact factors passed the significance test, yielding the detection results (Table 5). The spatial heterogeneity of cropland NGP in the

Yangtze River Economic Belt was affected by several factors. The explanatory strength of each influencing factor according to the q-value was as follows, in descending order: per capita food possession (X_{11}) > slope (X_3) > average annual precipitation (X_2) > per capita cropland area (X_{13}) > elevation (X_4) > per capita consumption level (X_6) > land productivity (X_{14}) > comparative efficiency in agriculture (X_{10}) > ratio of secondary and tertiary industries (X_7) > urbanization rate (X_9) > average annual temperature (X_1) > GDP per capita (X_5) > ratio of urban and rural income (X_8) > total mechanical power per unit of crop (X_{12}). In terms of single factors, five factors—per capita food possession, slope, average annual precipitation, per capita cropland area, and elevation—had the greatest impact on the cropland NGP in the Yangtze River Economic Belt. In the standardized layer, the natural endowment factor had the greatest impact on the cropland NGP. In the standardized layer, the natural endowment factor had the greatest influence on the spatial differences in cropland NGP in the Yangtze River Economic Belt.

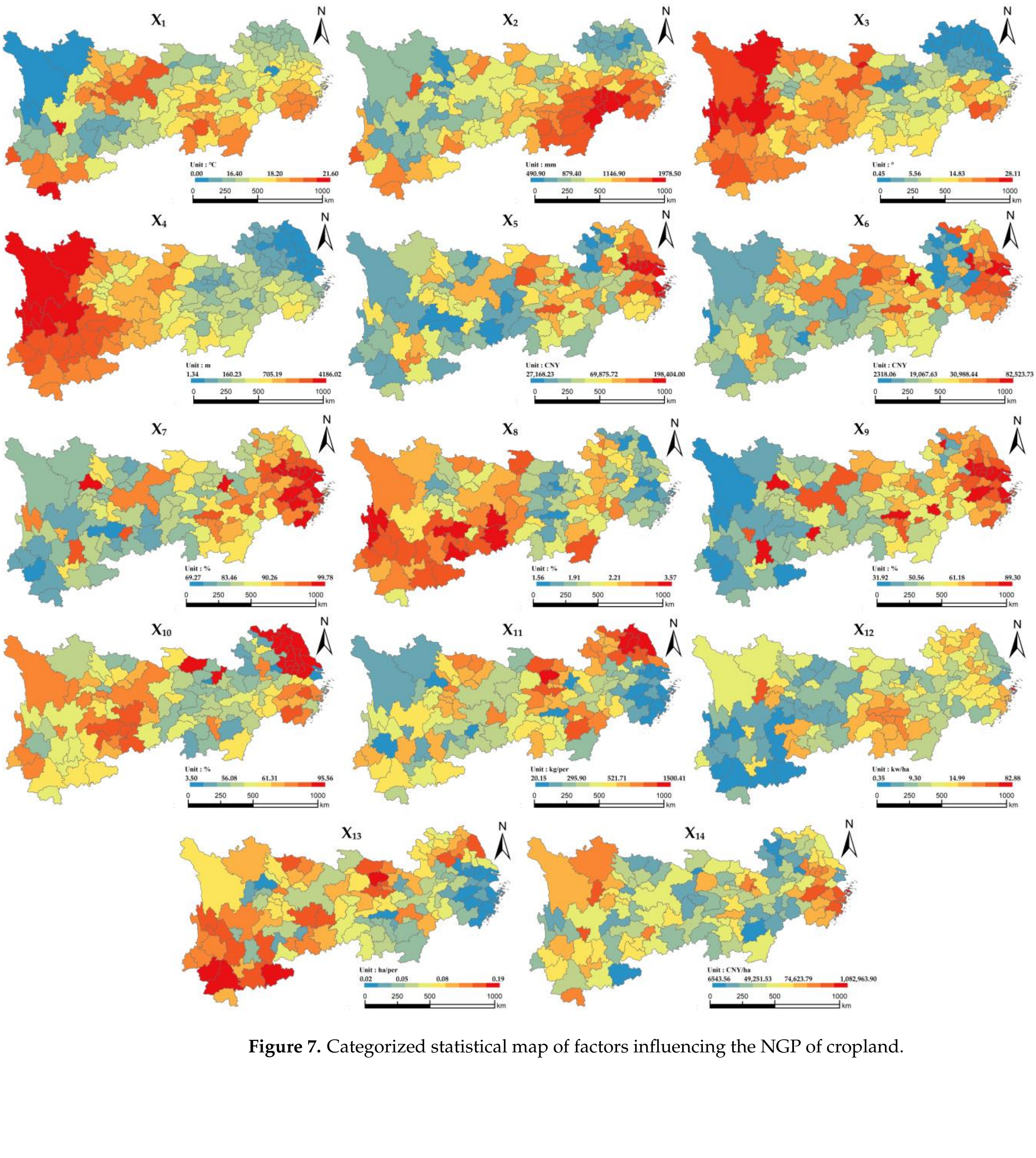

Figure 7. Categorized statistical map of factors influencing the NGP of cropland.

Table 5. Single-factor detection results (q-statistic value).

X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}
0.126	0.269	0.287	0.207	0.116	0.190	0.133	0.077	0.132	0.170	0.353	0.050	0.251	0.188

4.3.2. Factor Interaction Detection Results

Using the GeoDetector software, the interaction of 14 factors was determined, and a heatmap was created using Origin 2022 (https://www.originlab.com/, accessed on 5 March 2024). The interaction of any two factors showed nonlinear enhancement, i.e., any two factors interacted with each other to have strong explanatory power for the spatial differentiation of cropland NGP in the Yangtze River Economic Belt, and most of the interactions had greater explanatory power than that of a single factor (i.e., the interaction of any two factors was greater than that of a single factor) (Figure 8). Among them, the interaction of slope ∩ consumption level per capita ($X_3 \cap X_6$) explained the spatial variation in the cropland NGP in the Yangtze River Economic Belt, with the strongest q-value of 0.786. This was followed by the interactions of elevation ∩ cropland area per capita ($X_4 \cap X_{13}$), elevation ∩ land productivity ($X_4 \cap X_{14}$), slope ∩ land productivity ($X_3 \cap X_{14}$), elevation ∩ consumption level per capita ($X_4 \cap X_6$), average annual precipitation ∩ per capita food possession ($X_2 \cap X_{11}$), annual average precipitation ∩ per capita GDP ($X_2 \cap X_5$), secondary and tertiary industry ratio ∩ per capita cropland area ($X_7 \cap X_{13}$), annual average precipitation ∩ per capita consumption level ($X_2 \cap X_6$), elevation ∩ per capita food possession ($X_3 \cap X_{11}$), and slope ∩ per capita cropland area ($X_3 \cap X_{13}$), which had q-values of 0.7 or more. This indicates that the interaction between the natural environment and production conditions, economic level, and social development had strong explanatory power for the spatial difference of non-food cultivated land in the Yangtze River Economic Belt.

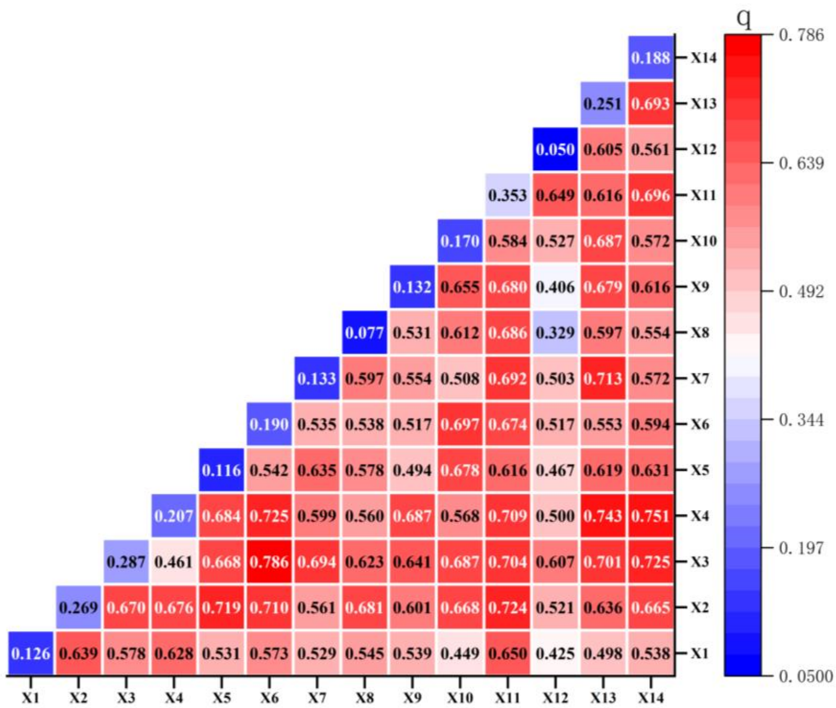

Figure 8. Factor interaction probe results plot.

5. Discussion

5.1. Interpretation of the Findings

In this study, 130 cities (states) in the Yangtze River Economic Belt were selected as the research units, the NGP measurement system was clarified, and the spatial and temporal evolution of cropland NGP in the Yangtze River Economic Belt and the influencing factors were studied in depth. This study has the following innovations: First, this study included a multi-scale exploration of the time-series change characteristics of cropland NGP in the Yangtze River Economic Belt to provide theoretical guidance for exploring cropland protection and food security in the region. Second, spatial autocorrelation and the standard deviation ellipse model were used to jointly explore and verify the spatial pattern of cropland NGP in the Yangtze River Economic Belt and the spatial evolution pattern under multi-method integration, which enhanced the credibility of the research results. The rate of cropland NGP in the Yangtze River Economic Belt increased from 2006 to 2022, the number of cities (states) with mild NGP and moderate NGP decreased, and the number of cities (states) with severe NGP increased significantly. Further, cropland NGP in the balance of grain-producing and marketing areas and the main marketing areas faced serious challenges. In contrast, cropland NGP in the main production areas was relatively stable. With social and economic development, the proportion of the industrial structure has constantly changed, and farmers tend to plant higher-yielding cash crops in pursuit of better economic benefits, resulting in a decline in the sown area of grains and increased cropland NGP. Second, the main marketing area is located in the eastern coastal area, with rapid urban expansion, rapid economic development, and a high proportion of secondary and tertiary industries, resulting in a small area under cultivation, while the production and marketing balance area is located in the upper reaches of the Yangtze River Basin, with great topographical undulations and serious fragmentation of cropland, resulting in limited farming conditions and triggering a higher degree of cropland NGP. The standard deviation ellipse and spatial autocorrelation model both showed that the spatial differentiation of the Yangtze River Economic Belt experienced significant correlation during the study period, and the overall center of gravity migrated from the northeast to the southwest, which is similar to the results found by Chen Fu [3], Meng Fei [11], Cui Jiaxing [41], and Tang Linderng [42]. At the same time, it also revealed that the status quo characteristics of a relatively high rate of NGP were relatively higher in the areas of Guizhou, eastern Chongqing, and western Hunan, and along the coast, which provides effective support for further identifying the extent of NGP in the Yangtze River Economic Belt. The Yangtze River Economic Belt spans three steps in China's geography, with downstream areas, such as Shanghai and Zhejiang, being economically developed, and the degree of cropland NGP in these areas being higher for long periods of time due to historical reasons and the industrial structure. In upstream areas, the terrain is highly undulating, and except for the Chengdu Plain, where the grain sowing of arable land is relatively stable, the degree of cropland NGP in Guizhou, Chongqing, and Yunnan is increasing.

The results of single-factor detection showed that single factors, such as the per capita food possession, slope, elevation, and average annual precipitation, have a large influence on the spatial differentiation of cropland NGP in the Yangtze River Economic Belt. The results of interaction factor detection showed that the interaction of natural endowment and the economic level, natural endowment, and production conditions were the most important influencing factors, and the results of this research were similar to those of Zhang Jie [16], Cheng Xianbo [43], and Zhang Bailin [19] et al. The upper reaches are mainly mountainous, with a low food crop output efficiency. The middle reaches of the plains are the country's main grain-producing areas. Jiangxi, Hubei, and other areas maintained a better state of development and hold an important position as the main grain-producing areas. The lower reaches of the plains, and Jiangsu and Anhui in the Yangtze River Economic Belt, currently feature a low–low concentration of flat topography and abundant water sources are conducive to farming and further solidify the area's status as a main grain-producing area.

The dual spatial exploratory analysis model combining spatial autocorrelation and deviational ellipse models adopted in this study to explore the spatio-temporal evolution pattern of cropland NGP in the Yangtze River Economic Belt, as compared with the single spatial analysis method commonly adopted by other scholars in the spatio-temporal analysis of cropland NGP. This dual-space model can reveal the complex structures and associations in the geospatial data in a more comprehensive and precise way, and it can also capture the spatial autocorrelation of the data, as well as depict the directionality of the data distribution, which accurately reveals the spatio-temporal evolution pattern of cropland NGP in the Yangtze River Economic Belt.

5.2. Recommendations

(1) We first recommend developing production according to local conditions and cultivating technology to enhance efficiency. Firstly, the Yangtze River Economic Belt has a rich and varied topography, with large differences between the east and west, so it is necessary to formulate differentiated cropland utilization policies according to the characteristics of different regions to ensure food production. Secondly, the difference in precipitation leads to an uneven distribution of water resources, and the construction of farmland water conservancy facilities should be strengthened to improve the efficiency of water resource utilization and provide stable water sources for food production. In addition, farmers will be able to increase their incomes with support from scientific planning and management, the rational use of arable land resources in mountainous areas, the accelerated cultivation of grain seed technology, the development of agriculture with special characteristics, and the effective suppression of cropland NGP.

(2) Second, we recommend optimizing the allocation of resources between urban and rural areas and enhancing the comparative returns of agriculture. First, the urban–rural gap and the urbanization process have had a profound impact on how cropland is utilized. Optimizing the allocation of resources between urban and rural areas promotes the development of the rural economy, increases agricultural income, and enhances the incentive for farmers to grow food. Secondly, agricultural subsidy policies should be continuously improved to guide farmers to plant food crops and enhance the comparative efficiency of food, thereby guaranteeing national food security.

(3) Third, we recommend increasing land-improvement efforts and optimizing land use. According to the different farming conditions in the upper, middle, and lower reaches of the Yangtze River Basin, implementing land remediation, actively promoting high-standard farmland construction, and improving the production conditions around the cropland's supporting facilities can enhance farming conditions and output efficiency. Second, the way the land is utilized can be optimized, and actively integrating broken cropland resources can facilitate the mechanization of cultivation so as to enhance the overall income, reduce the cost of production, and enhance the incentive for farmers to grow food.

(4) We finally recommend strengthening sectoral coordination governance to enhance the efficiency of supervision and management. First, a cross-sectoral coordination mechanism, including relevant departments such as agriculture, natural resources, environmental protection, and forestry should be established to clarify the responsibilities and division of labor of each department and to create synergy. Second, information technology, such as remote sensing monitoring and GIS geographic information systems, should be used for the real-time monitoring and dynamic management of arable land and improve the efficiency of supervision.

5.3. Research Perspectives

The advantage of this study lies in the fact that the NGP of cropland levels was measured at multiple scales in 2006, 2015, and 2022 in 130 cities (states) in the Yangtze River Economic Belt, the spatial and temporal evolution of NGP cropland was revealed using spatial analysis models, and the influencing factors were explored in combination with GeoDetector. This study is of great significance for the country to formulate cropland NGP risk control, promote the sustainable development of the Yangtze River Economic Belt, and guarantee food security. However, this study only considered three periods and failed to accurately measure the degree of cropland NGP in consecutive years from 2006 to 2022, and models influencing factors developed did not sufficiently take into account the willingness of individual farmers. In this study, only three periods were considered, namely 2006, 2015, and 2022, to quantitatively measure the spatial and temporal patterns of cropland NGP in the Yangtze River Economic Belt, effectively reflecting the degree of NGP in the three periods. The next step will be to focus on consecutive years in order to explore the characteristics of cropland NGP in the Yangtze River Economic Belt in each time period. Second, the influencing factors were not sufficiently taken into account in considering the willingness of individual farmers to farm food. Thus, the next step will be to analyze it from micro and macro scales using field research so as to provide theoretical support for the precise implementation of policies.

6. Conclusions

In this study, 130 cities (states) in the Yangtze River Economic Belt were selected as the research units. Based on the methods of spatial autocorrelation, standard deviation ellipse, and GeoDetector, the spatial and temporal evolution characteristics of cropland NGP in the Yangtze River Economic Belt and the factors affecting them were empirically examined. The conclusions of this study are as follows:

(1) In 2006–2022, the degree of cropland NGP in the Yangtze River Economic Belt intensified, the number of cities (states) with mild NGP and moderate NGP decreased, and the number of cities (states) with severe NGP increased significantly. In terms of the trend of changes in the functional grain area, the degree of cropland NGP was the most serious in the main marketing area, followed by the balance of production and marketing areas, and the rate of NGP in the main production areas has stabilized at around 35%. In terms of the regional division of the Yangtze River Economic Belt, the degree of NGP of the middle and upper reaches of the Yangtze River Basin continued to intensify, and the NGP rate of the lower reaches declined by a small margin.

(2) Cropland NGP in the Yangtze River Economic area has a strong positive correlation with the spatial distribution. During the study period, the Global Moran's I index increased slightly, and over time, the number of cities (states) with "high–high agglomeration" decreased, but the spatial distribution of agglomerations increased. Further, the number of cities (states) with "low–low agglomeration" and the spatial distribution of agglomerations decreased. Finally, the center of gravity of the cropland NGP showed a northeast-to-southwest migration trajectory.

(3) Per capita food possession in single-factor detection had the strongest explanatory power for the spatial pattern of cropland NGP in the Yangtze River Economic Belt, followed by differences in slope, elevation, and average annual precipitation in natural endowment, which exacerbated the degree of NGP in the upstream area. In the factor interaction detection, the interaction of any two influencing factors showed nonlinear enhancement, and the explanatory power of most of the interactions was greater than that of a single factor, indicating that cropland NGP was influenced by multiple factors.

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