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Research article

The impact of climate change on China's central region grain production: evidence from spatiotemporal pattern evolution

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Abstract: Under the influence of global climate change, the climatic conditions of China's major agricultural regions have changed significantly over the last half-century, affecting regional grain production levels. With its favorable conditions for agricultural activities, China's central region has been a strategic location for grain production since ancient times and has assumed an essential responsibility for maintaining national grain security. However, the key concerns of this study are whether the national grain security pattern is stable and whether it might be affected by global climate change (especially climate instability and increased risks in recent years). Therefore, the present study collected grain production data and used descriptive statistical and geospatial analyses to reveal the trend and spatiotemporal pattern of grain production in China's central region from 2010 to 2020. Then, a further analysis was conducted by combining meteorological data with a geographically weighted regression (GWR) model to investigate the relationship between spatial differences in the output per unit of the grain sown area (OPUGSA). The findings were as follows: (1) The overall development trend of grain production in China's central region from 2010 to 2020 revealed a positive overall trend in grain production, with notable differences in growth rates between northern and southern provinces. (2) Most regions in the southern part of the central region from 2015 to 2020 showed varying degrees of total output of grain (TOG) and OPUGSA reduction, possibly affected by the effects of the anomalies for global climate change and a strong El Niño effect in 2015. (3) Low-low (L-L) clusters of TOG and OPUGSA indicators were consistently in the northwest part (Shanxi) of the central region, and high-high (H-H) clusters of TOG were consistently in the central part (Henan and Anhui) of the central region, but H-H clusters of OPUGSA were not stably distributed. (4) The fitting results of the GWR model showed a better fit compared to the ordinary least squares (OLS) model; it was found that the annual average temperature (AAT) had the greatest impact on OPUGSA, followed by annual sunshine hours (ASH) and annual precipitation (AP) last. The spatiotemporal analysis identified distinct clusters of productivity indicators. It suggested an expanding range of climate impact possibilities, particularly in exploring climate-resilient models of grain production, emphasizing the need for targeted adaptation strategies to bolster resilience and ensure agricultural security.

Keywords: grain production; climate change; pattern evolution; spatiotemporal analysis; geographically weighted regression (GWR); China's central region

1. Introduction

Goal 2: Zero hunger is one of the seventeen global sustainable development goals (SDGs) set by the United Nations (UN) in 2015 with a focus on eradicating hunger, achieving food security, improving nutrition, and promoting sustainable agriculture [1]. Ensuring the survival and progress of humanity is a worldwide concern, with grain security and nutrition serving as fundamental elements in tackling environmental challenges and ensuring the universal right to basic survival and development for every individual [2]. However, according to a report by the UN, the current trend indicates that the world will face resource scarcity and grain security problems, and it is estimated that about 660 million people globally will be impacted by food insecurity until 2030 [3]. Academician Yuan Longping of China, the Father of Hybrid Rice, once said that grain could save a country or trip it up, particularly emphasizing that China's grain security must be mastered in the hands of the Chinese themselves, thus demonstrating the importance of grain security to the people of China and even the world. Since ancient times, China has been a major agricultural country, and its grain resources have provided an essential material basis for economic development among different regions, ensuring the livelihood of nationals and the stability of social order [4]. At present, the relationship between grain security and climate change is becoming more complex as the recovery of the world economy shows obvious vulnerability, and the challenge of climate change is becoming increasingly prominent [5,6]. In addition, the worsening of global warming has also severely affected China in terms of the frequent occurrence of natural disasters and risks in recent years, which directly posed severe challenges to grain production [4]. The instability of climate change, as one of the significant threats to the global agricultural sector, covers the devastating impacts on agricultural production from changes in temperature, rainfall patterns, seawater levels, and atmospheric carbon dioxide concentrations [7].

Against the above background, this study's key concerns are whether China's grain security pattern is stable and whether it might be affected by global climate change (especially climate instability and increased risks in recent years). With its favorable conditions for grain production, China's central region has traditionally been an essential grain production site and has assumed the critical responsibility of maintaining national grain security [8,9]. As an important cornerstone for stabilizing China's grain food security, its importance in China's grain production is self-evident, so the empirical study of this research area has significant empirical value as well as practical significance. Therefore, this study selects China's central region (six provincial administrative units) as the study area. After collecting grain production data, descriptive statistical and geospatial analyses were used to reveal the trends and spatiotemporal patterns of grain production in China's central region from 2010–2020. The geographically weighted regression (GWR) model was then used with meteorological data to further explore the relationship between spatial differences in the output per unit of grain sown area (OPUGSA) indicators in China's central region and reveal the impact of climate change on grain production. This study analyzes the spatial and temporal relationships of grain production in China's central region, and the study findings could help stakeholders to better understand the status of grain security and the impact of climate on it, thereby contributing to the stabilization and improvement of agricultural production activities in the region.

2. Literature review

As more emphasis is given to understanding the risky changes in global climate and the urgent need for a great sustainable transition, more academic scholars shift their focus to the spatial and temporal characteristics of climate change in different regions [10,11], as well as natural ecological and agri-environmental areas under the influence of climate change, including vegetation phenology [12], crop production [13,14], agricultural investment [15], environmental pollution [16], and grain security [17,18]. Specifically, in the field of grain security, some scholars have explored the relationship between climate change and food security, and studies have revealed the possible adverse effects of climate change on agricultural commodity prices, as demonstrated by the fact that climate change has exacerbated the tendency of grain prices to rise and caused a sharp increase in the number of famished groups within a short time [19]. Some scholars have considered exploring the dynamics of spatiotemporal patterns of non-grain cropland production (it is usually more profitable to grow cash crops) to reveal its threat to overall grain safety and explore corresponding mechanisms to alleviate the pressure on grain security reserves [19–21]. Some scholars have studied the trends in the evolution of spatiotemporal patterns and influential factors of agriculture and grain-related indicators through the use of geospatial analyses (remote sensing monitoring or geographic information systems) concerning the evolution of farmland [22], dynamics of grain supply, demand, and equilibrium [23,24], crop cultivation [25], rice (crop) productivity [26,27], and efficiency of grain production [22,28–30]. In addition, in terms of climate change perspectives, some scholars have routinely conducted statistical analyses and proposed countermeasures and recommendations on grain yields [31,32], crop production [33], and agricultural development [34,35] based on empirical data and climate change conditions in different regions.

China's enormous population shows higher standards and requirements for grain security than other countries, and the problem of grain security in China remains severe today [36]. Some scholars have systematically sorted out the characteristics of China's grain security under the influence of global climate change by constructing a macro research perspective of food security [37]. Based on the research perspective of combining natural and social sciences, some scholars have systematically studied the climate change risk of grain production, clarified the specific impacts of climate change impacts on grain production, and proposed new directions [38]. Some scholars have refined the climate change impact factors and composed specific indexes, aiming to use them to measure the climate sensitivity of regional climate in different geographical distribution contexts [39,40]. Some scholars have explored the possible impacts of climate change characteristics on grain production by taking China's major grain-producing areas (at the scale of provincial administrative units) as the study object [41].

After a comprehensive literature review, this study finds most scholars were likely to pay more attention to the impacts of climate change on the spatiotemporal patterns of regional grain production at the national scale and to make full use of the large-scale scope of the study area to reinforce the differences in the impacts of climate change on different regions. To some extent, it shows the research gap in the field of research on the relationship between climate change and grain security at relatively meso- or microscales. Therefore, this study focuses on the trend of grain production and its impacts on climate change from the mesoscale perspective (prefecture-level administrative units in the central region of China), aiming to fill the gap in this research area and direction.

3. Materials and methods

3.1. Description of the study area

China's central region, including Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan provinces, is located in the interior hinterland of China and has the advantages of bearing the east to the west and connecting the south to the north, with the terrain mainly dominated by the plains (North China Plain and Yangtze Plain, Middle and Lower) and abundant water resources through the water system (see Figure 1). With its large population, plentiful resources, and apparent advantages in agriculture, especially grain production, this region has historically been an essential grain production location in China [8]. Moreover, the central region, encompassing roughly 10.7% of the nation's landmass, sustains approximately 28.1% of the population and contributes around 20% to the GDP [42]. This designation positions it as China's densely populated area, economic hub, and pivotal market, crucial to China's geographical division of labor [42]. According to grain production statistics, the central region accounts for about 40% of the country's total grain production, and the development of the central region not only guarantees China's grain security but eases the constraints on the supply of its energy resources (the abundance of coal resources in the provinces of Shanxi, Henan, Anhui, and Jiangxi), which reflects the region's crucial strategic position [42].

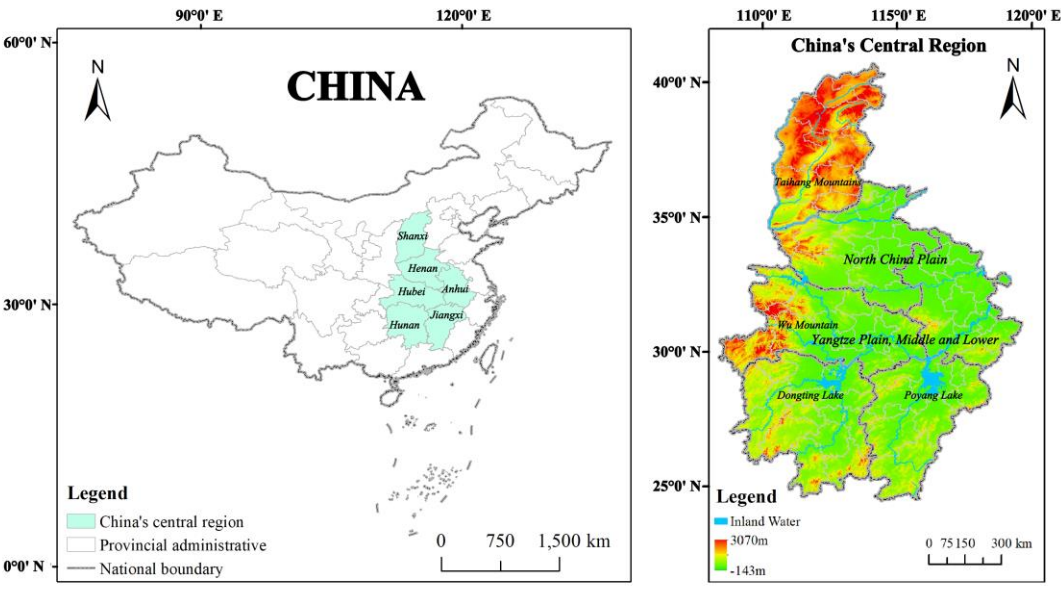

Figure 1. Location and topography of China's central region.

3.2. Data collection

Adjustment of administrative divisions could cause changes in the spatial structure of cities. On August 22, 2011, Anhui Province, China, announced that they would abolish the prefecture-level administrative unit of Chaohu (one district and four counties under the jurisdiction of the county-level unit) to make corresponding adjustments, separately allocated to the jurisdiction of the already existing three prefecture-level administrative units in Hefei, Wuhu, and Maanshan [43]. Therefore, between 2010 and 2020, 88 prefecture-level administrative units were under all provincial administrative units in China's central region in 2010 and 87 in 2011–2020 (only Chaohu was abolished). Since it involves the adjustment of administrative divisions, this study refers to the prefecture-level administrative divisions in Chinese drawing review No: GS (2023) 2762 to adjust the prefecture-level administrative divisions in 2010 (only Chaohu was abolished). This study assigns the data of the five county-level administrative units of the old Chaohu (one district and four counties under the prefecture-level administration) to the prefecture-level administrative units to which they belonged after the adjustments. Specific adjustments are detailed in Appendix 1.

The administrative divisions in this study are based on the prefecture-level administrative divisions in Chinese drawing review No: GS (2023) 2762 for data analysis, and this study uses the WCG_GCS_1984 geographic projection coordinate system for data processing (see Figure 2). There is a lag in the data statistics, and generally, the data for the previous year are released in the latter year. Therefore, the grain production data from 2010 to 2020, including the sown area of grain crops (SAGC), total output of grain (TOG), and output per unit of the grain sown area (OPUGSA), are derived from the corresponding China Statistical Yearbook and Provincial Statistical Yearbook (Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan). Some of these missing data were aggregated by collecting Statistical Yearbooks (prefecture-level administrative units) and Statistical Communique of National Economic and Social Development (prefecture-level administrative units). Meteorological data measuring climate change in various regions, including annual average temperature (AAT), annual precipitation (AP), and annual sunshine hours (ASH) indicator data, are processed and summarized by China's surface meteorological observations V3.0 (spatial interpolation based on point data from each regional meteorological observation station) released by the China Meteorological Data Service Centre (National Meteorological Information Centre) [44]. However, by performing an initial check, there is an issue of multicollinearity between some of the data involved in the construction of the model; therefore, some data are preprocessed (Z-score normalization) with the aim of resolving the multicollinearity problem in this study. Specific steps are detailed in Appendix 2.

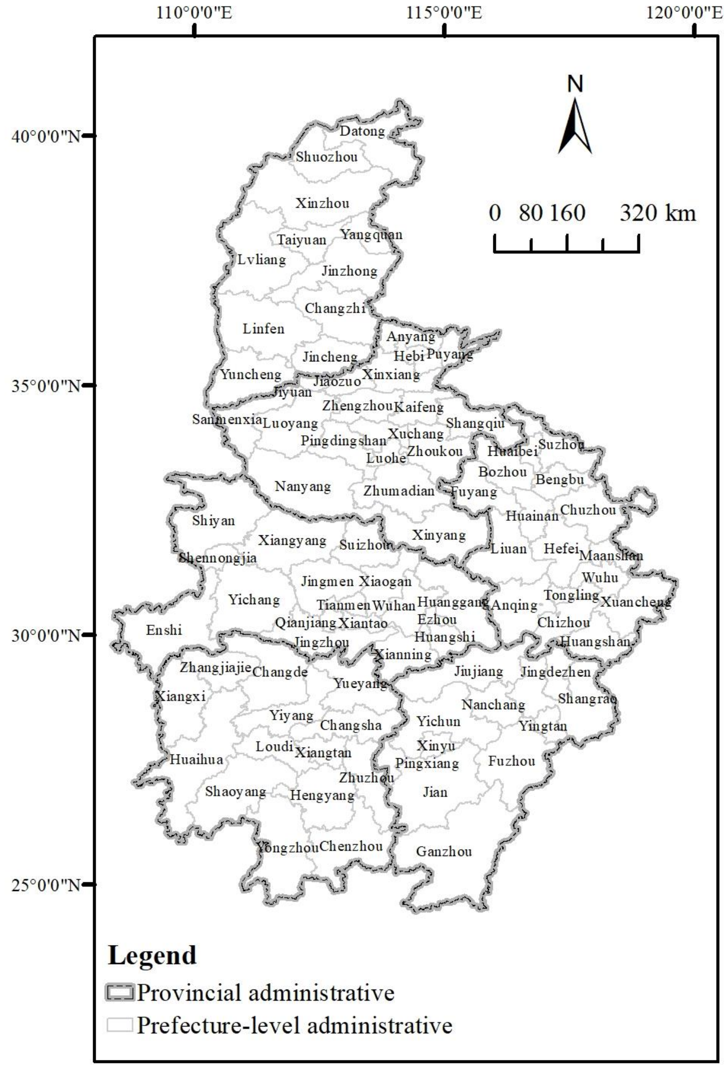

Figure 2. China's central region administrative units within the provincial jurisdiction (location of prefecture-level administrative units).

3.3. *Design of the study*

This study selected six provincial administrative units (87 prefecture-level administrative units) in China's central region as the study scope. With its favorable conditions for grain production, this region has been an important grain production location in China and is responsible for maintaining national grain security [8,9]. It is essential to investigate the historical grain production in China's central region, the evolution of spatial patterns, and the impact of climate change on it. Specifically, this study collects grain production data and employs descriptive statistical analysis and geospatial analysis (a spatial autocorrelation model) to reveal the trends and spatiotemporal patterns of grain production in China's central region (global and local) during the 2010–2020 period.

The spatial autocorrelation model generally consists of global spatial autocorrelation and local spatial autocorrelation, which are used to explore the global and local characteristics of the distribution location of the research indicator values in geographical regions [45–47]. Global autocorrelation describes the whole distribution of a certain geographic phenomenon within a regional unit to determine whether the phenomenon is spatially clustered or dispersed, and the commonly used test statistical index is Global Moran's I index [48]. Its value range is typically between [−1, 1], and the index values can be used to assess the overall spatial pattern of grain production and characteristics in China's central region [49,50]. Global Moran's I > 0 indicates a positive spatial correlation, which means that the indicators of grain production in the central region show clustered characteristics. Meanwhile, Global Moran's I < 0 indicates a negative spatial correlation, which means that the indicators of the distribution of grain production in the central region show dispersed characteristics. Lastly, Global Moran's I = 0 indicates spatial irrelevance, which means that the indicators of grain production in the central region show random characteristics.

To further refine the local characteristics of the metrics in a geographical region, local autocorrelation analysis could be used to measure the similarity or difference of the neighboring regions centered on each of the selected spatial unit objects [49,51,52]. Therefore, the grain production indicators in China's central region were used for the geospatial identification of grain production agglomeration types with the help of local autocorrelation analysis (Anselin Local Moran's I) [53]. In this study, local indicators of spatial association (LISA) were used to classify 87 prefecture-level administrative units within China's central region into a high-high (H-H) cluster, high-low (H-L) cluster, low-high (L-H) cluster, and low-low (L-L) cluster based on the results of the indicator calculation.

In addition, studies have shown that AAT, AP, and ASH, as important climate indicators, could significantly impact regional grain production [54,55]. To further reveal the impact of climate change on grain production in China's central region, this study simulated the spatial difference relationship of grain production based on OPUGSA indicators (which measure the ability of grain production) and meteorological data (AAT, AP, ASH). GWR constructs these independent equations by combining the dependent and explanatory variables of the features that fall within the bandwidth of each target feature [56]. The shape and size of the bandwidth depend on the core type, bandwidth method, distance, and number of neighbors entered by the user. GWR is an extension of ordinary least squares (OLS) regression, i.e., it is used to explore the spatial changes and related factors of the research object at a certain scale by establishing local regression equations for each point in the spatial scale [54,57]. In particular, severe model design errors or errors used to indicate that a local equation has not included a sufficient number of neighboring elements usually indicate that the regression has a global or local multicollinearity problem [56]. To determine where problems are occurring, it is necessary to run the OLS model before using GWR and then examine the variance inflation factor (VIF) values for each explanatory variable [56]. If some of the VIF values are large (e.g., greater than 7.5), global multicollinearity prevents GWR from running and fails to output results [56]. The flow chart and framework roadmap for this study are as follows (see Figure 3).

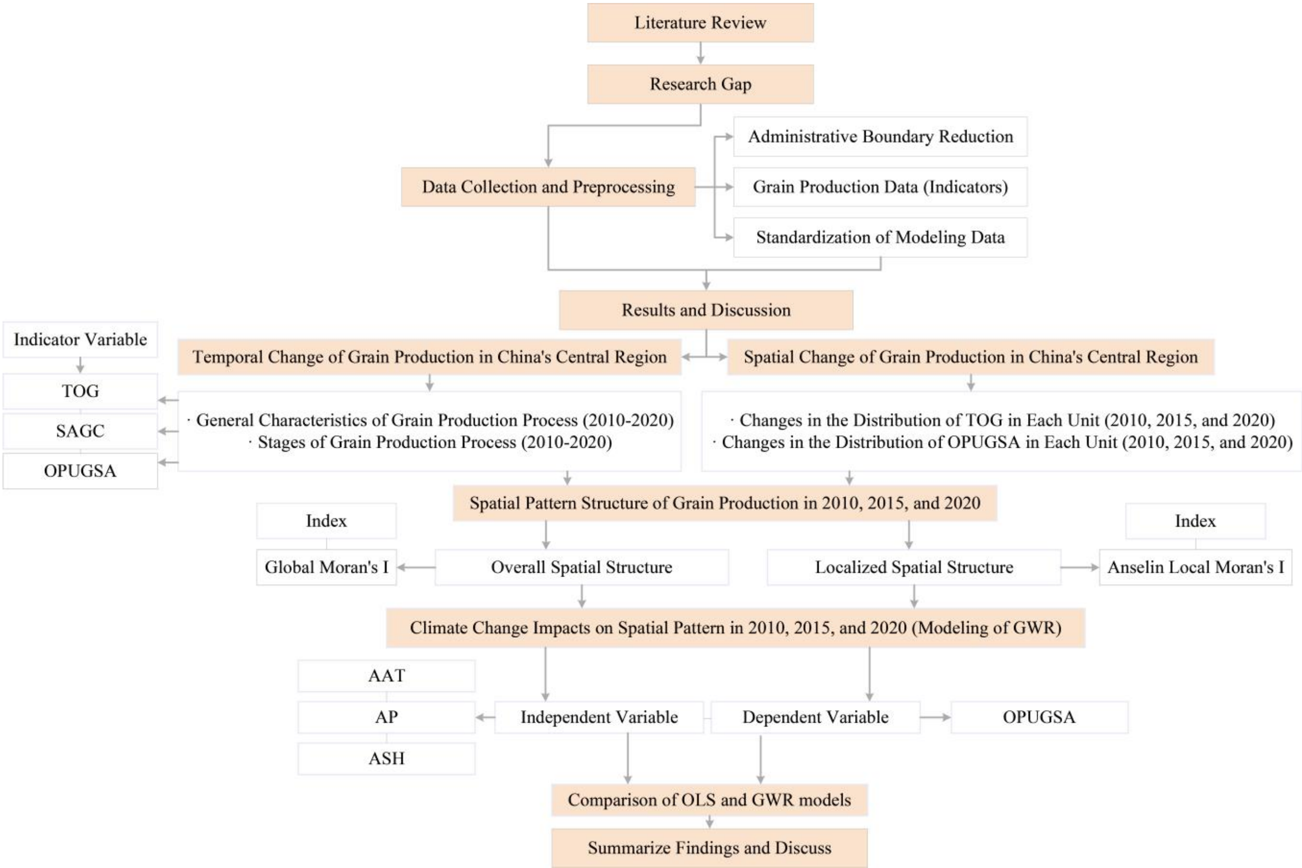

Figure 3. Research framework roadmap.

4. Results and discussion

4.1. Temporal change of grain production in China's central region

4.1.1. General characteristics of the grain production process from 2010 to 2020

The overall development trend of grain production in the central region in 2010–2020 is positive, and the sown area of grain crops (SAGC), total output of grain (TOG), and output per unit of the grain sown area (OPUGSA) showed growth (see Figure 4). In terms of growth rate, TOG increased from 16720.66 (unit: 10,000 tons) in 2010 to 20175.70 (unit: 10,000 tons) in 2020, with an average annual growth rate of 1.90% (see Figure 4a). SAGC increased from 32112.42 (unit: 1,000 hm²) in 2010 to 34330.80 (unit: 1,000 hm²) in 2020, with an average annual growth rate of 0.67% (see Figure 4b). OPUGSA increased from 5207 kg/hm² in 2010 to 5877 kg/hm² in 2020, with an average annual growth rate of 1.22% (see Figure 4c). By comparing the average annual incremental rates of the three indicators, TOG showed a faster growth rate than OPUGSA and SAGC.

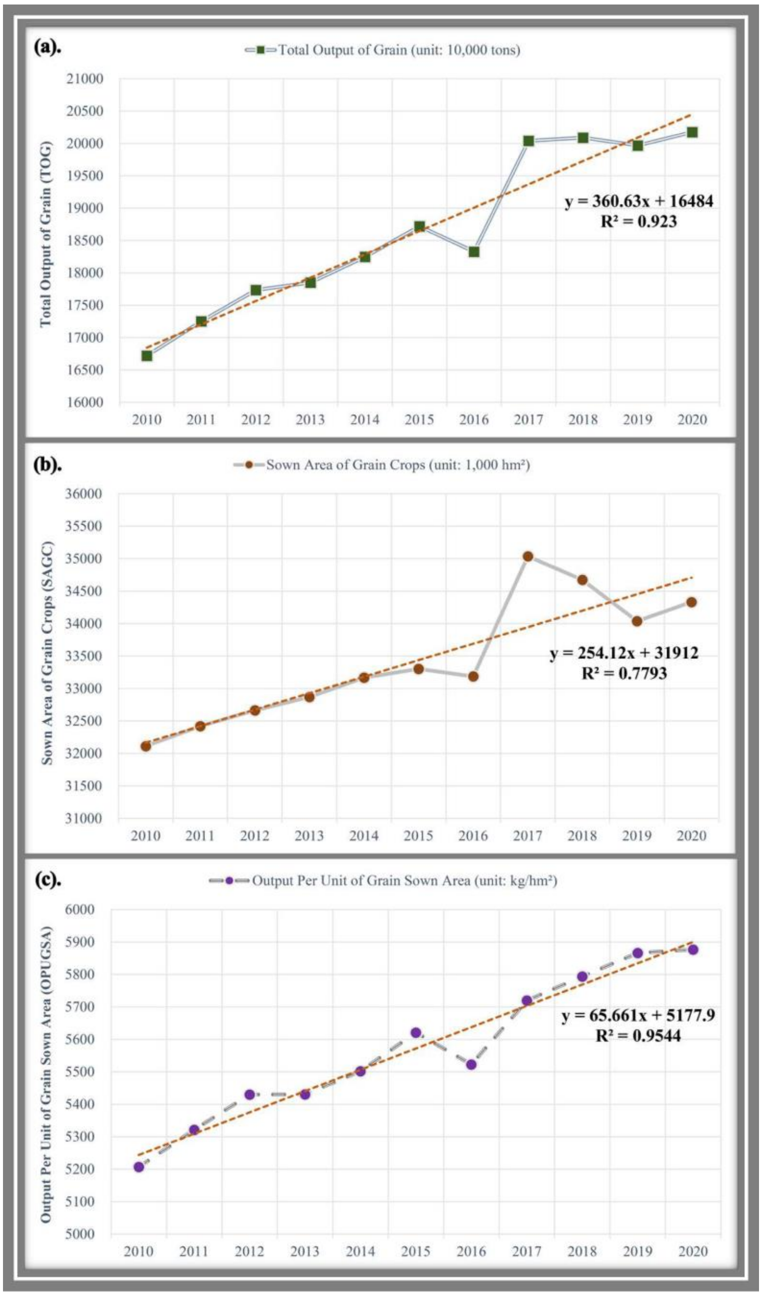

Figure 4. Changing trends of three indicators of grain production (TOG, SAGC, and OPUGSA) in China's central region from 2010 to 2020.

4.1.2. Stages of the grain production process from 2010 to 2020

In Figure 4, from the perspective of stage changes, the grain production process in China's central region from 2010 to 2020 had two stages of change characteristics: (1) 2010–2015 showed a sustained growth trend in grain production, with SAGC, TOG, and OPUGSA showing continuous growth, with average annual growth rates of 0.73%, 2.28%, and 1.54%, respectively, and TOG and OPUGSA showed a rapid growth trend. (2) 2015–2020 showed a fluctuating growth trend in grain production, with average annual growth rates of SAGC, TOG, and OPUGSA being 0.61%, 1.51%, and 0.89%, respectively. In comparison, the growth rate was significantly lower than that from 2010 to 2015. There has also been a decreasing trend in different years, especially in 2015–2016, when SAGC, TOG, and OPUGSA showed negative growth.

4.2. Spatial change of grain production in China's central region

Besides the temporal characteristics, this study also focuses on the spatial characteristics of grain production in China's central region from 2010 to 2020. The overall trends of SAGC, TOG, and OPUGSA in different regions were identified from the national average, the average of the central region, and the respective average of each province in the central region (see Figure 5). The results showed that TOG and OPUGSA showed positive growth in all regions except for SAGC, which showed negative growth in Shanxi and Hunan. Changes in SAGC might be controlled by the Chinese government's strict regulations, including China's strict requirement to ensure a red line (the cordon sanitaire) of at least 1800 million mu of arable land reserve, which is the minimum arable land area standard to ensure self-sufficiency in grain supply for all people in China when the country is facing external pressures and embargoes.

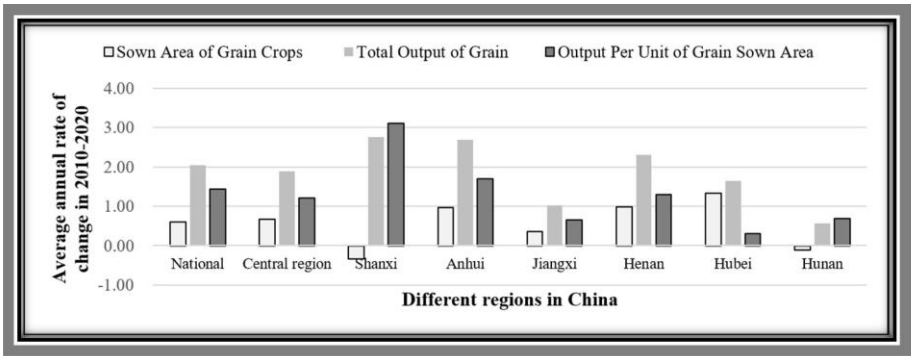

Figure 5. The average annual rates of change in grain production indicators for the nation, the central region, and each province within China's central region from 2010–2020.

The Chinese government proposes strictly controlling arable land, especially converting permanent basic farmland to non-agricultural construction land or other agricultural land, to ensure that permanent basic farmland is used for grain production [58]. Therefore, given the minor differences in SAGC in China's central region between 2010 and 2020, as well as the restrictive nature of the strict control by government authorities at all levels, this study stopped considering the SAGC indicator in the subsequent study and further used the TOG indicators and OPUGSA indicators to explore the characteristics and trends of grain production distribution in 2010, 2015, and 2020 for prefecture-level administrative units.

During 2010–2020, the distribution of TOG indicators in the central region showed significant spatial differences, and the spatial distribution pattern was roughly characterized by a small-scale concentration in the center but a low concentration in the surrounding area (see Figure 6). The high grain-producing areas have been distributed in the southeastern region of Henan (the terrain is mainly in the plains), while the low grain-producing areas are distributed in the northern part of Shanxi and the western part of Hunan (the terrain is mainly in the mountains). In addition, the provinces with faster average annual TOG growth are Shanxi, Henan, and Anhui, and their growth rates are all higher than the national average and the central region average (see Figure 5). In general, overall TOG of the central region showed an increasing trend between 2010 and 2020, and the growth rate of TOG from 2010 to 2020 was higher in the three provinces in the northern part of the central region than in the three provinces in the southern part. However, most of the prefecture-level administrative units in the southern part of the central region from 2015 to 2020 showed varying degrees of TOG reduction.

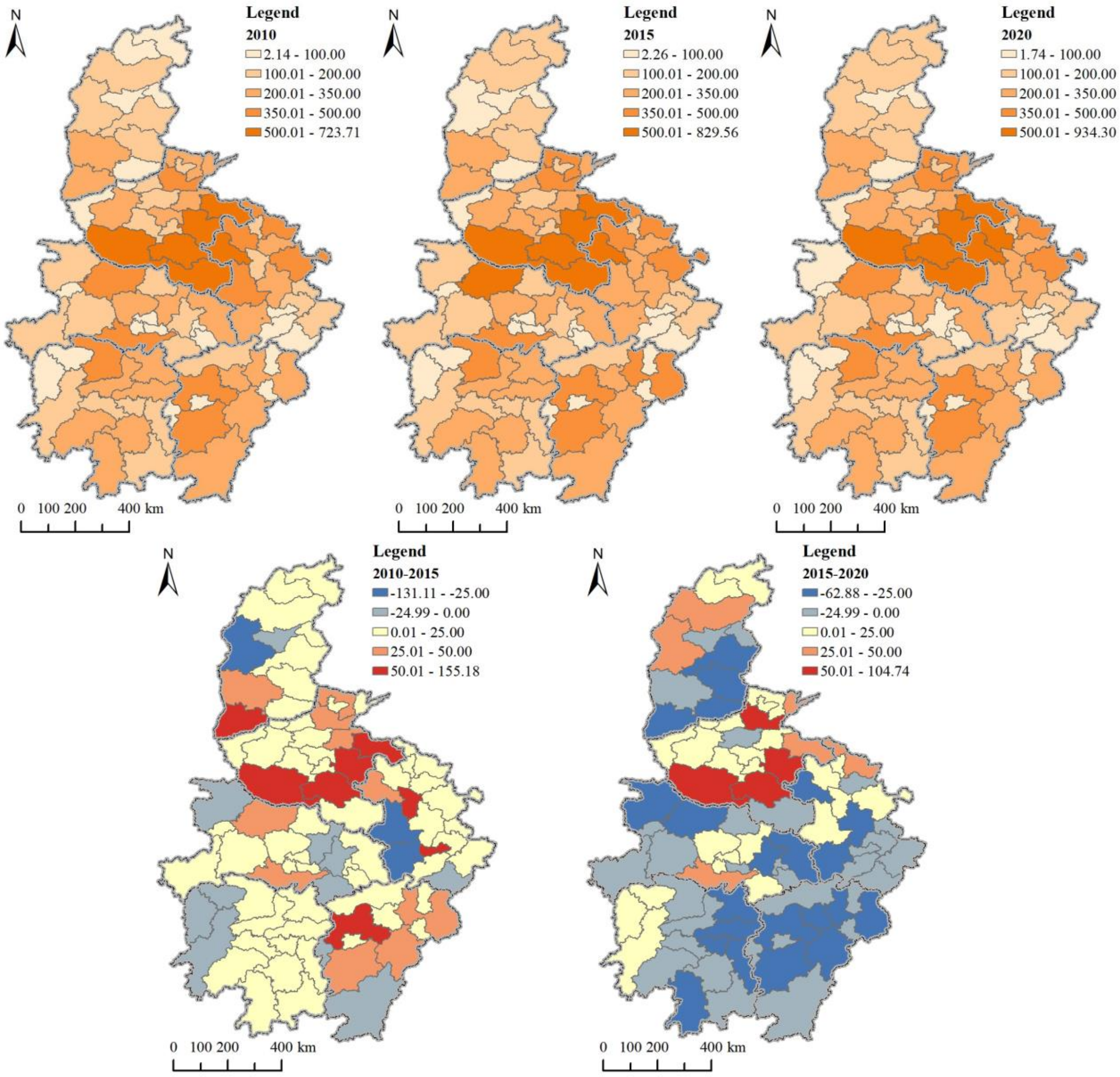

Figure 6. Changes in the distribution of TOG (unit: 10,000 tons) in each prefecture-level administrative unit within China's central region in 2010, 2015, and 2020.

From 2010 to 2020, the distribution of OPUGSA indicators in the central region showed significant spatial differences. Compared with the TOG indicators, the OPUGSA indicators are distributed in many different regions, and the high grain-producing areas extend from the North China Plain, from north to south into the Yangtze Plain, Middle and Lower, with the spatial distribution pattern roughly in the shape of a band (see Figure 7). In addition, the provinces with faster average annual growth in OPUGSA are Shanxi, Henan, and Anhui, and their growth rates are all higher than the national average and the central region average (see Figure 5). In general, overall OPUGSA of the central region showed an increasing trend between 2010 and 2020, and the growth rate of OPUGSA from 2010 to 2020 was higher in the three provinces in the northern part of the central region than in the three provinces in the southern part. However, most of the prefecture-level administrative units in the southern part of the central region between 2010 and 2020 showed varying degrees of OPUGSA reduction, with the reduction trend expanding from 2015 to 2020.

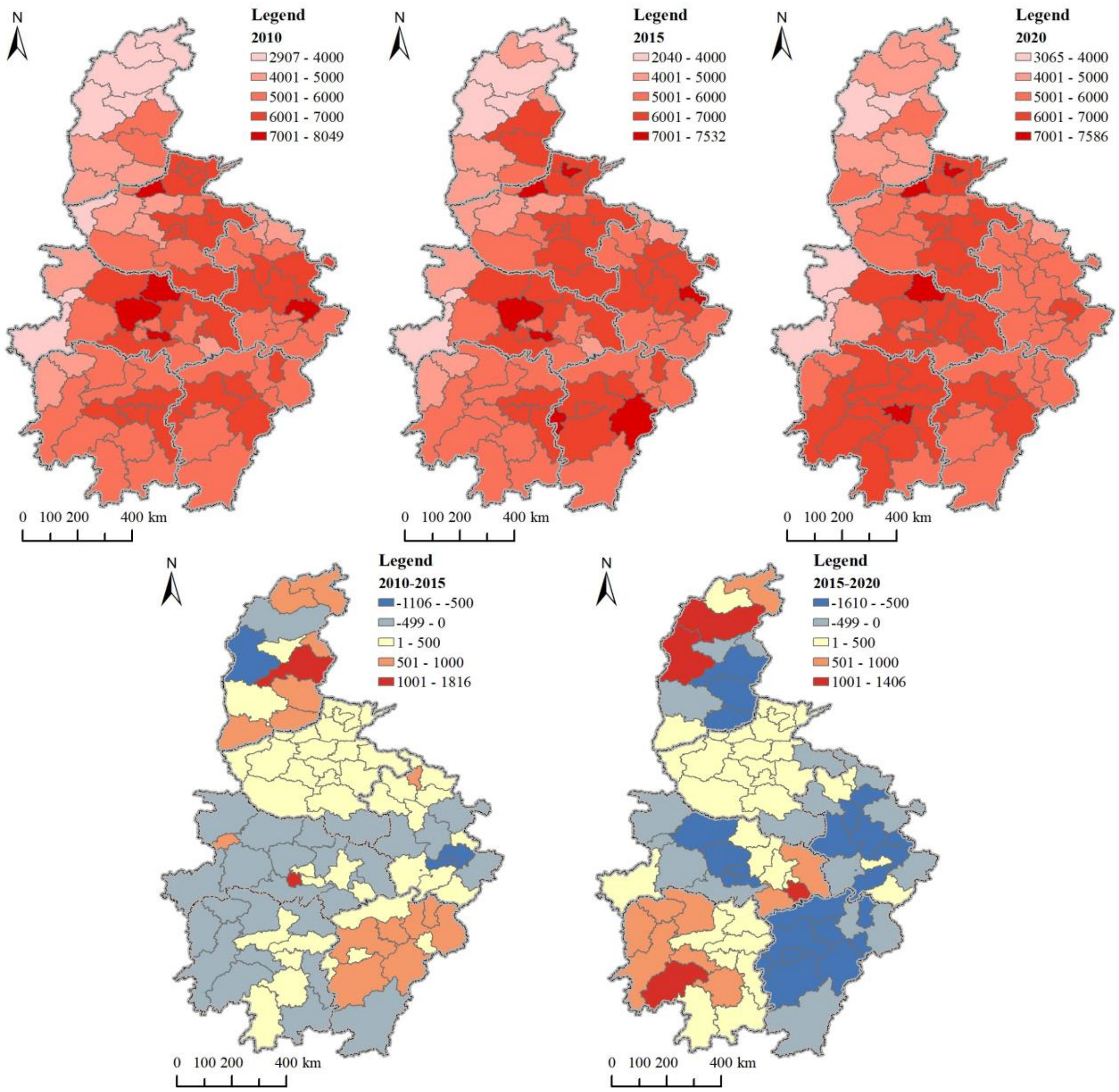

Figure 7. Changes in the distribution of OPUGSA (unit: kg/hm²) in each prefecture-level administrative unit within China's central region in 2010, 2015, and 2020.

4.3. Spatial pattern structure of grain production in China's central region

This study applies the spatial autocorrelation analysis methods (global autocorrelation and local autocorrelation) to focus on the spatial structural relationship and changing trend of the TOG and

OPUGSA indicators from 2010, 2015, and 2020. This is done to determine the spatial distribution relationship of grain production in the central region and reveal the spatial structure of each indicator.

4.3.1. Overall spatial structure of grain production in the central region

In 2010, 2015, and 2020, the Moran's I index for both indicators of grain production was greater than 0, and the P-value passed the 1% significance level test, indicating that the overall structure of grain production among the various prefectural administrative units showed a spatial clustered structure (see Table 1). The Moran's I index for each indicator of grain production generally improved, indicating that the spatial spillover effect (positive) of grain production in the central region increased and that the deepening of the role in the spatial relationship between neighboring prefectural administrations within the central region might further lead to the trend of more spatial differentiation and polarization. Overall, the results of global spatial autocorrelation indicate that both TOG and OPUGSA indicators of grain production in the central region show spatial clustering and the trend of clustering has increased.

Table 1. Global spatial autocorrelation results of grain production for China's central region in 2010, 2015, and 2020.

Indicators for measuring grain production	Year	Moran's I	Z-score	P-value
Total Output of Grain (TOG)	2010	0.288143	4.171843	0.000030
	2015	0.304046	4.411410	0.000010
	2020	0.347310	5.050842	0.000000
Output Per Unit of Grain Sown Area (OPUGSA)	2010	0.361696	5.173448	0.000000
	2015	0.355186	5.105714	0.000000
	2020	0.396082	5.653448	0.000000

4.3.2. Localized spatial structure of grain production in the central region

After evaluating the overall spatial structure of grain production in 2010, 2015, and 2020 using global spatial autocorrelation, this study uses local spatial autocorrelation to assess the structural characteristics of TOG and OPUGSA indicators of grain production on local scales. The high-high (H-H) clusters of TOG are significant and are roughly distributed in southwestern Henan and northwestern Anhui (see Figure 8).

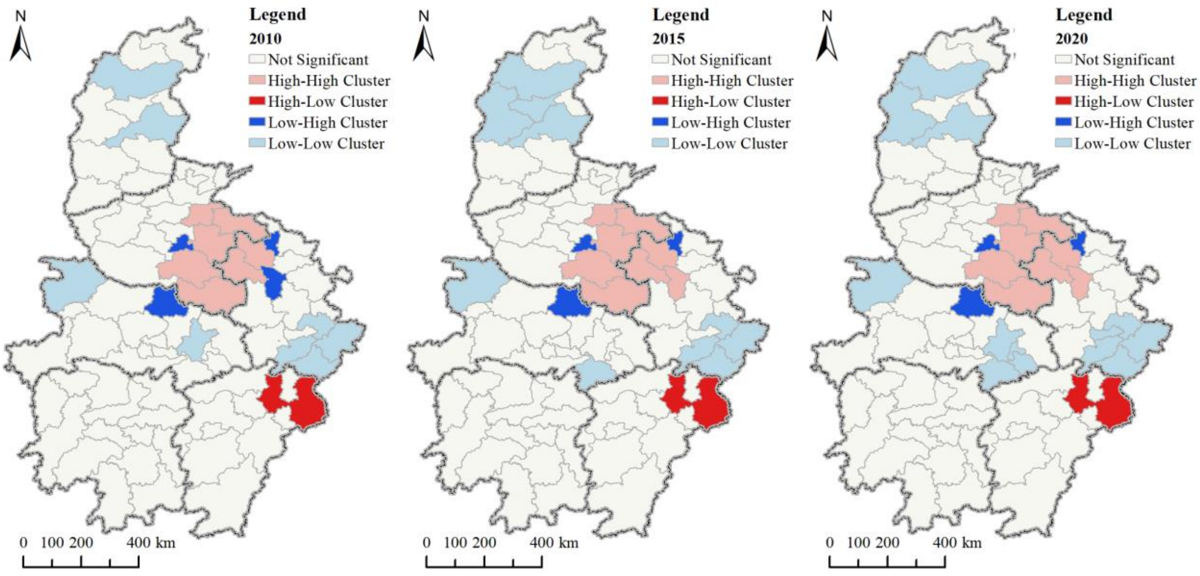

Figure 8. LISA results of TOG in China's central region in 2010, 2015, and 2020.

The low-low (L-L) clusters of TOG are roughly located in southeastern Anhui, southeastern Hubei, and central Shanxi. Moreover, the H-H clusters of OPUGSA are generally located in the central, eastern, and southern parts of China's central region, although it is changing (see Figure 9). The L-L clusters of OPUGSA are roughly distributed in the western and northwestern parts of China's central region.

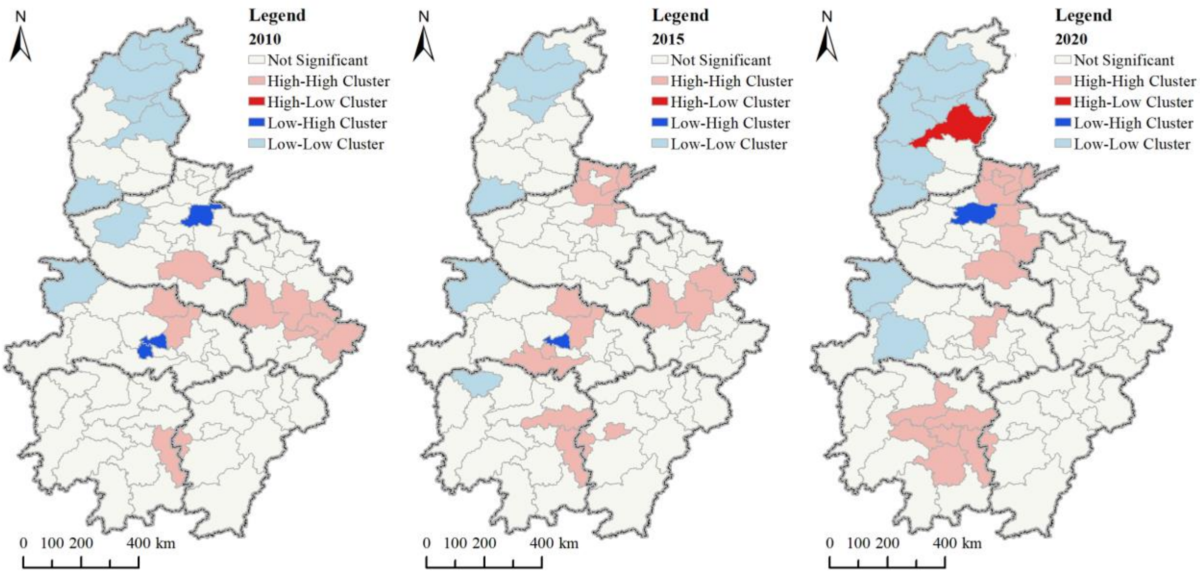

Figure 9. LISA results of OPUGSA in China's central region in 2010, 2015, and 2020.

In general, the results of local spatial autocorrelation indicate that both TOG and OPUGSA in the central region show that grain production in northwest Shanxi and northwest Hubei are low-value clustered areas, indicating that the natural topography of the mountainous region influences grain production to some extent. The TOG results indicate that the topography in the south of the North China Plain is favorable for the formation of high-value clustered areas of grain production. However, the high-value clustered areas of OPUGSA are characterized by unstable distribution compared with those of TOG.

4.4. Climate change impacts on the spatial pattern of grain production in China's central region

Based on the results and findings above, this study found that the spatial pattern of TOG indicators in grain production of the central region was relatively stable and had little fluctuation. However, compared with the TOG indicator, the OPUGSA was a better measure of regional grain production capacity because it considers the unit arable land area indicator. In addition, it was found that the spatial pattern of the OPUGSA indicator was characterized by unstable distribution, which prompts a need to discuss and explain the pattern of the OPUGSA indicator further. Existing studies have shown that AAT, AP, and ASH, as important climate indicators, might significantly impact regional grain production capacity under the current natural conditions of climate change and further increase instability risk [54,55]. Therefore, the OPUGSA indicator was selected to measure grain production capacity, three climate indicators, AAT, AP, and ASH, were chosen to represent the conditions of climate change and a spatial model was conducted based on GWR to analyze the influencing factors of grain production in China's central region. However, the indicators used to construct GWR had the issue of multicollinearity; therefore, the data of variables were standardized in this study (see Appendix 2). After standardization and before constructing the GWR model, the VIF values of the indicators were examined using the OLS model (see Table 2), and the indicators were examined to have the basic conditions for conducting GWR. The model with the smaller Akaike's information criterion with a corrected (AICc) value is the better model (that is, taking into account model complexity, the model with the smaller AICc provides a better fit with the observed data) [56].

Table 2. Summary of OLS model results (data standardized).

Statistical Indicators		2010	2015	2020
VIF	AAT	3.983773	5.789656	4.658099
	AP	2.291269	3.311648	2.296644
	ASH	3.924145	4.341664	6.089373
AICc		233.805641	251.074874	218.147009
R^2		0.321636	0.111135	0.214178
Adjusted R^2		0.297117	0.079007	0.185775
Joint F-Statistic		13.117759**	3.459158*	7.540630**
Joint Wald Statistic		51.334550**	11.124058*	30.949858**
Koenker BP Statistic (Koenker's Studentized Bruesch-Pagan Statistic)		6.199677	8.915975*	11.326558*
Jarque-Bera Statistic		0.045072	2.814748	2.333910

Note: ** and * indicate 1% and 5% significance levels, respectively.

Based on the description of the above situation, this study uses the GWR model, selects OPUGSA of prefecture-level administrative units in China's central region as the dependent variable, and uses AAT, AP, and ASH as the independent variables to construct a geographical spatial relationship model to explain the spatial relationship between the dependent and independent variables. The results of the GWR model and its parameters are shown below (see Table 3). The results of the GWR model show the goodness-of-fit values in 2010 (R^2 = 0.543), 2015 (R^2 = 0.481), and 2020 (R^2 = 0.515). There is a significant improvement in the goodness-of-fit of GWR compared to the OLS model, and the lower AICc value of the GWR model provides a better fit with the observed data. Overall, even though R^2 is not particularly high and the overall explanatory power of the model is mediocre, it still reflects the impact of climate change factors on grain production in some regions.

Table 3. GWR model results (comparison with OLS model results).

Indicator parameters	2010		2015		2020	
	GWR	OLS	GWR	OLS	GWR	OLS
AICc	217.699881	233.805641	211.782527	251.074874	194.412476	218.147009
R^2	0.543025	0.321636	0.481009	0.111135	0.515227	0.214178
Adjusted R^2	0.457227	0.297117	0.428465	0.079007	0.423488	0.185775

Nevertheless, the GWR model provided some explanations for the effects of changes in AAT, AP, and ASH indicators on OPUGSA, and this study further spatially visualized the results of the regression coefficients of the model with the natural breakpoint method (see Figure 10). In general, by comparing the magnitude of the regression coefficients of the respective variables in 2010, 2015, and 2020, it was found that AAT had the greatest impact on OPUGSA, followed by ASH and AP last. Among them, AAT had the greatest impact on OPUGSA in 2010 and 2020, with the highest impact coefficients of 2.53 and 3.37, respectively, while ASH had the greatest impact in 2015, with the lowest impact coefficient of −2.07. The anomalous results of the data in 2015 reflect the anomalies of climate change (average AAT in the central regions for 2015 was about 5°C higher compared to 2010 and 2020), which was affected by the combined effects of the local climate change and a strong El Niño effect in 2015 [59]. In addition, AAT, AP, and ASH all have obvious regional differences in their impacts on OPUGSA, and the areas of high impact coefficients as a whole are characterized by changes advancing from southeast to northwest. In particular, the range of the high-value area of the AAT regression coefficient is gradually expanding. Therefore, changes in average temperatures have positive benefits for increased grain production in the western part of China’s central region but might lead to reduced grain production in the southeastern part of China’s central region. Overall, the changes in the AAT indicators have significantly impacted the spatial pattern of grain production in the central region and, accordingly, speculate on the possible changes to the world’s grain production, which could significantly affect the grain provision and food security in various countries.

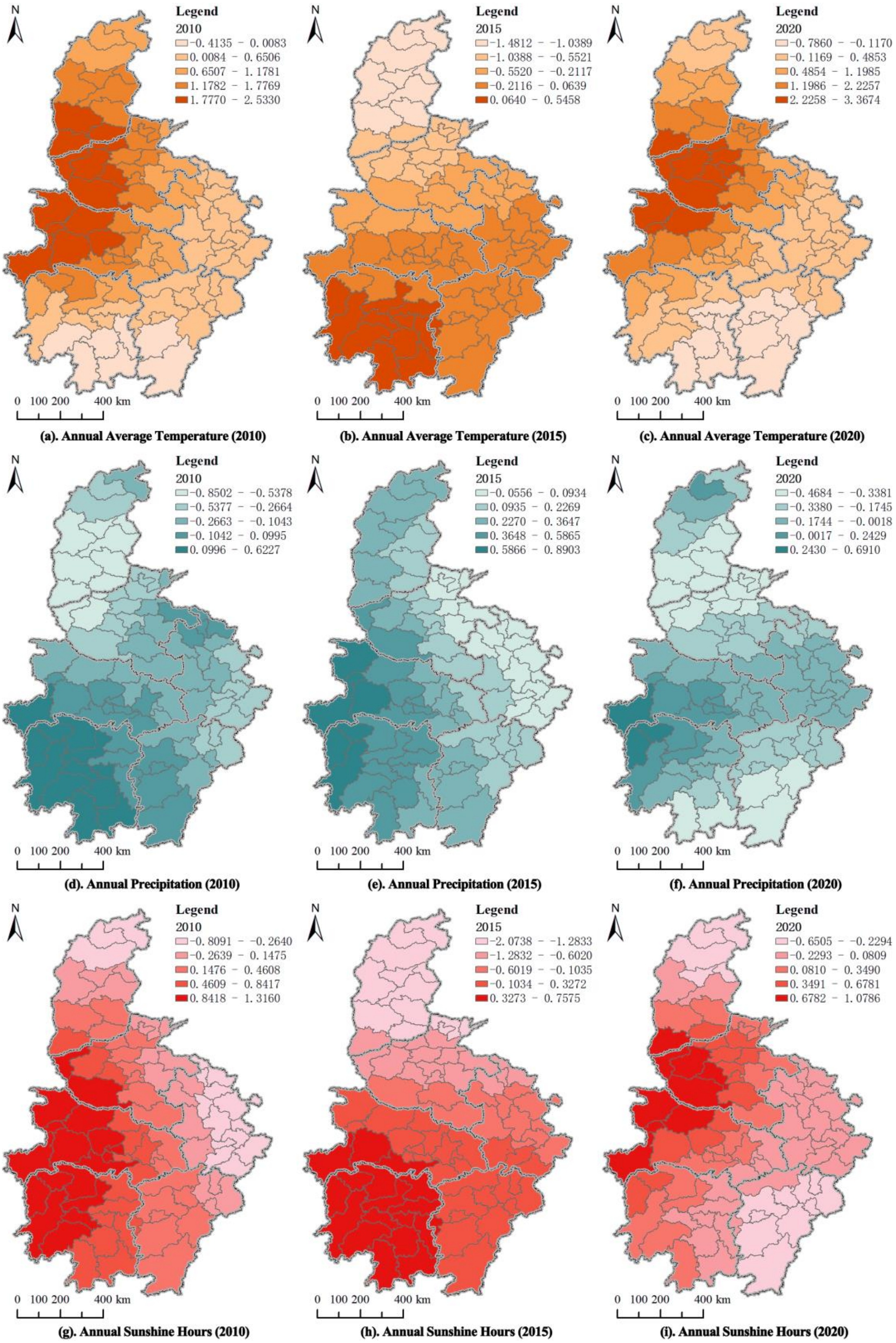

Figure 10. Visualization of regression coefficient results from GWR models for 2010, 2015, and 2020.

In addition to the findings of the central region shown earlier, the impacts of climate change on China's grain production have both advantages and disadvantages, and their impacts vary by region, crop, and time of occurrence. Favorable conditions include the crop planting belt moving northward, multiple-cropping systems with different combinations of crops that will lead to more diversified crop varieties and rising temperatures that will reduce the damage caused by freezing in winter. Meanwhile, unfavorable conditions include persistent drought disasters, high temperature and heat damage, flooding caused by heavy rainfall, large-scale outbreaks of pests and diseases, and extreme weather climates caused by climate change [60,61].

China is one of the sensitive areas that has had a significant impact on global climate change. To record, China's temperature increased by an average of 0.3°C per decade between 1961 and 2020, which is significantly higher than the global average during the same period. In addition, annual precipitation increased by an average of 5.1 millimeters per decade, showing a trend of the rainfall belt expanding to the north [62]. Studies have shown that global climate change, whether warming or cooling, as well as changes in greenhouse gas concentrations, will contribute to changes in the spatial and temporal distribution patterns of water and heat resource elements in China's main grain-producing areas, inducing changes in grain crop varietal resources and their resilience, and exacerbating the formation of catastrophic elements in localized areas [63]. Therefore, as a major challenge to humankind, climate change in the medium and long term has significant impacts on all aspects of human activities, especially on agricultural production and grain production security, which are essential for human survival [61,64].

Embracing the medium- and long-term climate change and the threat of frequent extreme weather events, targeted adaptation strategies should be adopted with an emphasis on the agricultural development objectives and climatic constraints of different regions to guarantee the security of grain production effectively. Due to the large differences between the north and south of China and the diversity of crop varieties and cropping systems, climate change affects different seasons and regions to different degrees. In China's central region, which is the focus of this study, climate change is generally showing a warming and humidifying trend, with both floods and seasonal droughts worsening and an increase in high-temperature ambient droughts, floods and typhoon-induced extreme weather events of heavy rainfall. Therefore, improving disaster prevention and mitigation capabilities, developing climate change adaptation technologies, and establishing a sound agricultural production security system should be the focus of climate change adaptation in this region [64]. Farmers are adjusting their agricultural methods through diverse approaches, considering the climate change challenges confronting China's mountainous areas, which has led to farmers' struggles in cultivating crops and raising livestock. This includes modifying cropping strategies to incorporate biodiversity, diversifying crops suitable for mountainous terrain, and exploring resilient farming practices tailored to withstand climatic shifts in mountainous regions [65].

5. Conclusion

In the context of global climate change, especially climate warming and increasing atmospheric carbon dioxide concentration, the spatial and temporal distribution patterns of climatic resource conditions of temperature, light, water, and heat in the major agricultural regions of China (Northeast China, North China, the middle and lower reaches of the Yangtze River, and South China) have changed significantly over the last half-century [65]. In this study, one of the vital grain production regions in China (i.e., China's central region) was selected as the study area to investigate its historical grain production, the evolution of spatial patterns, and the impact of climate change on grain production. The results showed that the overall development trend of grain production in China's central region from 2010 to 2020 was favorable, and the three important indicators of grain production, SAGC, TOG, and OPUGSA, showed a growth trend. The grain production in China's central region experienced a two-stage characteristic from 2010 to 2020, i.e., a continuous growth trend from 2010 to 2015 and a fluctuating growth trend from 2015 to 2020. In terms of spatial changes from 2010 to 2020, the distribution of TOG indicators in the central region showed significant spatial differences, and the spatial distribution pattern was roughly characterized by a small-scale concentration in the center but low in the surrounding area; however, the OPUGSA indicators were distributed in several different regions, with the high grain-producing areas extending from the North China Plain to the Yangtze Plain, Middle and Lower from the north to the south, and the spatial distribution pattern was roughly band-like. Overall, the results of measuring the growth rates of TOG and OPUGSA from 2010 to 2020 showed that the three provinces in the northern part (Shanxi, Henan, and Anhui) of the central region had higher growth rates than the three provinces in the southern part (Hubei, Hunan, and Jiangxi) of the central region. However, most of the prefecture-level administrative units in the southern part of the central region from 2015 to 2020 showed varying degrees of TOG and OPUGSA reduction.

The results of global spatial autocorrelation of grain production in China's central region showed that both TOG and OPUGSA indicators of grain production in the central region showed spatial clustering, and the trend of clustering has increased. The results of local spatial autocorrelation showed that both TOG and OPUGSA indicators of grain production in central China showed that grain production in northwest Shanxi and northwest Hubei was L-L clusters, indicating that the natural topography of the mountainous areas affects grain production to some extent. However, the H-H clusters of OPUGSA were characterized by an unstable distribution compared with TOG's. In addition, the fitting results of the GWR model showed a better fit compared to the OLS model; it was found that AAT had the greatest impact on OPUGSA, followed by ASH and AP last. Overall, the changes in the AAT indicators have significantly impacted the spatial pattern of grain production in the central region, which could significantly affect the grain provision and food security in various countries.

This study analyzed the spatiotemporal pattern of grain production in China's central region from 2010 to 2020 and constructed the GWR model at the climate level to explore its impact on grain production, which doubles as a reference for formulating scientific grain security policies in localized regions. Global climate change, whether warming or cooling, will affect changes in the spatiotemporal distribution patterns of water and heat resources in China's main grain-producing areas and exacerbate the formation of localized catastrophic elements. Therefore, targeted adaptation strategies should be adopted to effectively guarantee the safety of grain production from medium- and long-term climate change and the frequent threat of extreme weather. Adaptation strategies should also include upgrading disaster prevention and mitigation capabilities, researching and developing climate-change-adaptive technologies, establishing a sound agricultural production guarantee system, and exploring climate-resilient grain farming systems [64,65]. However, this study has limitations, including focusing only on the spatial trends in 2010, 2015, and 2020 without analyzing year-by-year data. Moreover, the fitting effect of the GWR model constructed in this study was average, and future research could focus on richer climate impact factors or other natural and socioeconomic indicators, aiming to contribute more comprehensively to the national grain production and security and stability issues.

Use of AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare that the research has no financial or personal relationships with other people or organizations that can interfere with it.

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