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Spatiotemporal Pattern of Cultivated Land Pressure and Its Influencing Factors in the Huaihai Economic Zone, China

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Abstract: Cultivated land pressure represents a direct reflection of grain security. Existing relevant studies rarely approached the spatiotemporal pattern of cultivated land pressure or the spatial heterogeneity of its influencing factors from the level of economic zones. Taking the Huaihai Economic Zone (HEZ), China for case analysis, this study investigated the spatiotemporal pattern of cultivated land pressure in diverse periods from 2000 to 2018 based on a modified cultivated land pressure index and spatial correlation models. On this basis, it explored the influencing factors of the spatial differentiation of cultivated land pressure in the late stage of the study using geographical detector as well as multi-scale geographically weighted regression model. The results indicated that: 1) in the study period, the global cultivated land pressure index of the study area decreased gradually, but cultivated land pressure increased locally in a significant way, especially in the central and southern Shandong Province; 2) the spatial pattern of cultivated land pressure manifested global clustering features. Hot and secondary-hot spots presented a narrowing and clustering trend, whereas cold and secondary-cold spots manifested a spreading and clustering trend; 3) average slope, the proportion of non-grain crops, population urbanization rate, and multiple cropping index have significant effects on the spatial differentiation of cultivated land pressure. The former three factors were positively correlated with cultivated land pressure, and the last factor was negatively correlated with cultivated land pressure; and 4) the amount of cultivated land has increased in the central and southern Shandong Province through land consolidation which, nonetheless, failed to improve the grain production. In regards to major grain producing areas similar to the HEZ in China, the authors suggest that great importance should be given to the balance of the quality and quantity of cultivated land, the optimization of agricultural production factors and the rational control of non-grain crops, thus providing a powerful guarantee for grain security in China.

Keywords: cultivated land pressure; spatiotemporal pattern; influencing factors; Huaihai Economic Zone; China

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1 Introduction

In China, there exists a saying ‘food is the paramount necessity of the people’. Indeed, cultivated land resources lay a material base for the sustainable development of human society, and quantity and quality vari-

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ations of cultivated land resources greatly affect both grain production and security (Fu et al., 2001; Skinner et al., 2001; Kastner et al., 2012; Uddin and Oserei, 2019). In the context of global urbanization and rapid industrialization, the quantity of cultivated land has been decreasing throughout years, accompanied by a gradual deterioration in its quality. It is estimated that by 2030, 3.7% of the global cultivated land area will disappear as a result of urbanization (Bren D'Amour et al., 2016; Deng et al., 2020). The decrease of basic farmland will pose serious threats to local, regional, and even global grain security. For instance, China with less than 10% of the world's cultivated land produces 25% of the world's grains and feeds 22% of the world population, which is a notable contribution to the grain security of the world (Ma et al., 2021). According to related studies, China's urban expansion is characterized by the encroachment of the most productive cultivated land on large scales. As a result, China will contribute 1/4 of the total cultivated land loss of the world (Bren D'Amour et al., 2016). The issue of grain security in China is continuously drawing attention from policymakers and scholars worldwide. This situation is closely related to the decrease of cultivated land resources in the background of urbanization. In fact, China has lost more than 14.5 million ha of cultivated land between 1979 and 1995 and approximately 8.32 million ha between 1996 and 2008 due to urbanization that followed its reform and opening-up (Lichtenberg and Ding, 2008; Cheng et al., 2015). The Chinese government has brought a series of policies to solve these problems, such as establishing the red line of 1.8 billion mu (120 million ha) for cultivated land and balancing the occupation and replenishment of cultivated land through land consolidation. Nonetheless, studies have shown that many problems still persist, such as the low quality of most newly-reclaimed cultivated land, as well as insufficient reserves of cultivated land (Yang et al., 2010; Xin and Li, 2018; Yu et al., 2020). In addition, the low comparative benefits of agriculture have brought about the abandonment and extensive operation of cultivated land (Zhang et al., 2016; Liao et al., 2019; Lu, 2020). All the above problems present potential ecological risks to cultivated land and undermine China's long-term grain security. The opinions of the CPC Central Committee and the State Council on Implementing the Rural Revitalization Strategy (No. 1 [2018], CPC Central Committee) proposes to deeply implement the strategy of adhering to sustainable farmland use and innovative application of agricultural technology for the purpose of increasing farmland productivity, and to firmly hold the red line of cultivated land. Evidently, guaranteeing grain security has always been an important task for the Chinese government in achieving long-term socio-economic development.

Cultivated land pressure can measure the tension of cultivated land resources in a region, and became a core content of research on grain security globally. Existing studies on cultivated land pressure have been fruitful. Western scholars mainly measured changes in cultivated land pressure from the perspectives of scenario simulation, grain demand, changes in the quantity of cultivated land, *etc*.. They have diverse research perspectives, and their measurement indices are simple. In addition, they have rarely explored how changes in cultivated land pressure vary spatially over longer periods. Peters et al. (2016) measured the bearing capacity of farmland under ten dietary structures through simulation using a biophysical model. Furthermore, Jayne et al. (2014) examined the grain supply pressure faced by cultivated land from the point of increased grain demand caused by continual population growth. Additionally, Bratley and Ghoneim (2018) investigated the threats posed by urban expansion to cultivated land resources in the East Nile Delta region of Egypt mainly from the perspective of changes in the quantity of cultivated land. Empirical studies conducted by Chinese scholars on cultivated land pressure are being progressively deepened and improved. Cai et al. (2002) proposed a cultivated land pressure index model based on the minimum per capita cultivated land area, which served as a representative method for early studies on cultivated land pressure. Nonetheless, this method is confined by its single measurement indices, and lacks consideration of interregional differences in the quality of cultivated land. Later, by continuous innovation of the model, scholars proposed modified cultivated land pressure index model based on the interactions among regions, population, cultivated land and grain, which was accepted by the academic circles and widely applied for regional grain security evaluation (Luo et al., 2015). Overall, existing studies on cultivated land pressure mostly unfold their analysis from a macroscopic perspective at either national or provincial level, but they rarely regard the level of economic zones. Economic zones are regions with mainly consistent natural conditions and economic development directions across administrative districts. Adopting economic zones as spatial units to study the issue of grain security not only materializes spatial scales, but also helps identify the factors influencing the grain security differences across regions with similar levels of economic development, thus providing better practical guidance for guaranteeing regional grain security. Some scholars have investigated the factors driving the spatiotemporal changes of cultivated land pressure, mainly from the socioeconomic perspective, but they were unable to give comprehensive consideration of differences in the natural environment. Moreover, there is an insufficient number of studies that investigate cultivated land pressure from the perspective of the spatial differentiation of influencing factors (Zhang and Wang, 2017). Therefore, in-depth studies should be carried out on the cultivated land pressure at the level of economic zones for the purpose of guaranteeing regional grain security.

The Huaihai Economic Zone (HEZ), China which is adjacent to the Yangtze River Delta Economic Zone and the Bohai Bay Economic Rim, is a potential zone for developing industries from developed areas. Meanwhile, satisfactory water-heat conditions have transformed the HEZ into a major grain producing area in China. In 2018, the HEZ produced 12.72% of China's grains with 7.58% of the country's cultivated land (http://tjj.shandong.gov.cn/; https://tjj.henan.gov.cn/; http://tj.jiangsu.gov.cn/; http://tjj.ah.gov.cn/). Therefore, grain production in the HEZ greatly contributes to national grain security. Is there any contradiction between the urban construction of the HEZ and the goal of guaranteeing grain security from the background of rapid urbanization in China? Considering that Shandong, Henan, Anhui, and Jiangsu provinces rank among the top provinces in China in terms of the scale and quantity of land consolidation, will the implementation of land consolidation projects help to ease the tension of cultivated land resources and assure grain security in the HEZ? Questions like these are in urgent need for empirical answers. However, it is seen that the studies on the cultivated land resources of this region are still incomplete, especially those concerning regional grain security from the perspective of cultivated land pressure.

In view of this, this study took 20 prefecture-level cities in the HEZ as the research objects, modified cultivated land pressure index and spatial correlation models, geographical detector, and multi-scale geographically weighted regression (MGWR) model were adopted to solve the following problems: did cultivated land pressure build up in the HEZ between 2000 and 2018? What were the spatiotemporal evolution features of cultivated land pressure in this period? Which part of the HEZ underwent the highest cultivated land pressure in the late stage of the study period? What were the main factors affecting the spatial differentiation of cultivated land pressure? How did dominant factors cause cultivated land pressure to undergo spatial differentiation? The results of this study can be deemed as a substantial supplement to the existing literature about the grain security of the HEZ. They also provide scientific references for formulating the policy of farmland requisition-compensation balance, conducting the planning and design of land consolidation projects, regulating regional agricultural policies, and promoting the sustainable use of cultivated land resources as well as rural revitalization.

2 Materials and Methods

2.1 Study area

The Huaihai Economic Zone (HEZ) was formally demarcated in 1986. It is located in the central and eastern China, and spans across 20 prefecture-level cities of Shandong, Henan, Anhui, and Jiangsu provinces, including Xuzhou, Lianyungang, Yancheng, Huai'an, Suqian, Suzhou, Huaibei, Fuyang, Bengbu, Bozhou, Heze, Jining, Linyi, Zaozhuang, Rizhao, Tai'an, Laiwu (transformed into Laiwu district of Jinan in 2019), Shangqiu, Kaifeng, and Zhoukou (Fig. 1). The HEZ has prominent location advantages as the eastern bridgehead of the Eurasian Continental Bridge, and plays the role of a hub that radiates in all directions in the macroscopic regional development pattern of the country (Zhang et al., 2020). From the west to the east, the study area can be divided into four parts: eastern Henan, northern Anhui, southern Shandong, and northern Jiangsu. The study area has a total land area of 178 100 km^2, a perennial mean temperature of 15.38°C, and a perennial mean precipitation of 823.56 mm. Its relative elevation differences are above1500 m. Located in the border area between southern and northern China, the study area has a north temperate semi-humid monsoon climate characterized by moderate precipitation and satis-

Fig. 1 The location of Huaihai Economic Zone (HEZ) (a) and digital elevation model (DEM) of the study area (b)

factory number of sunshine hours (Niu et al., 2020). In 2018, the study area had a registered population of 140 million, and a permanent population of 120 million, second only to the Yangtze River Delta economic zone (Meng et al., 2019). Therefore, it is one of the most densely populated areas in China. The cultivated land of the study area was about 10 224.43 ha, which is 56.31% of the total study area. The non-agricultural conversion rate of cultivated land reached about 24.00%. The cultivated land area per capita was 0.07 ha, which is approximately 22.70% lower than the national average. However, the grain yields per capita were was 610 kg, which is 29% higher than the national average (http://tjj.shandong.gov.cn/; https://tjj.henan.gov.cn/; http://tj.jiangsu.gov.cn/; http://tjj.ah.gov.cn/). Furthermore, the study area is also a traditional agricultural area, a production base of farm and sideline products, and a major producing area of wheat, rice and corn in China.

2.2 The connotation and definition of cultivated land pressure

The research core of geography represents human-land relationship system (Wu, 1991). Agricultural geography, as a branch of geography, focuses on agricultural-territorial system (Pretty and Bharucha, 2014; Moseley and Watson, 2016; Pretty et al., 2018). This is a complex system that takes the development and use of cultivated land resources as the basis; the production, consumption, and circulation of crops as the central links; and the satisfaction of people's food demand as the ultimate goal within a certain territorial scope (Clark and Tilman, 2017; Lu et al., 2019a). The core factors affecting the development of agricultural-territorial system are people, land, and industry (Clark and Tilman, 2017). Specifically, people-centered social system is fundamental for agricultural development, and agricultural labor forces provide an essential guarantee for agricultural production. Land-centered natural environmental system constitutes the spatial carrier of agricultural production, and provides a spatial guarantee for the development of other agricultural system factors. Industry-based economic activities, such as urbanization and agricultural production, influence agricultural development through restraining and supporting mechanisms (Fig. 2).

In traditional academic studies, cultivated land pressure refers to the pressure of grain production demand

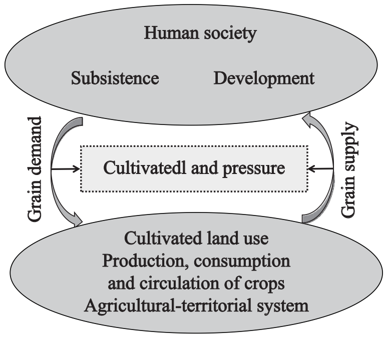

Fig. 2 Formation mechanism of cultivated land pressure

made by people for land necessary for their survival and development. In reference to existing literature, this study holds that cultivated land pressure is a crucial external manifestation of the interactions between the grain demand increased by humans for their survival and development and the grain supply supported by agricultural-territorial system, and a direct reflection of the contradiction between humans and land.

2.3 Data sources

In this study, four years (2000, 2006, 2012 and 2018) were investigated. A total of 1600 entries of data were involved. Demographic, agricultural, and socioeconomic data were mainly extracted from *Prefecture-level Cities Statistical Yearbooks* of Shandong Bureau of Statistics (http://tjj.shandong.gov.cn/), Henan Bureau of Statistics (https://tjj.henan.gov.cn/), Anhui Bureau of Statistics (http://tjj.ah.gov.cn/), and Jiangsu Bureau of Statistics (http://tj.jiangsu.gov.cn/). Data on perennial mean precipitation and perennial mean temperature were acquired from the website of China's Resource and Environment Science and Data Center (http://www.resdc.cn/data.aspx?DATAID=228). Digital elevation data (DEM) were collected from the official website of Geospatial Data Cloud (http://www.gscloud.cn/), with a spatial resolution of 30 m.

2.4 Research methods

2.4.1 Modified cultivated land pressure index model

The cultivated land pressure index can be used to determine the tension of cultivated land resources in a region with a certain population through the interactions between the supply of cultivated land and its demand (Zhang and Wang, 2017). To specify, the demand for cultivated land can be expressed by the minimum per capita cultivated land area guaranteeing grain security; the supply of cultivated land can be obtained by the actual per capita cultivated land area (Cai et al., 2002). In this study, the quality coefficient of cultivated land was introduced to correct the cultivated land pressure index and obtain a modified one. In general, distinct geographical environments cause differences in the use efficiency and quality of cultivated land, i.e., the heterogeneity of cultivated land which represents a basic attribute of cultivated land. The quality coefficient of cultivated land can depict the heterogeneity of cultivated land in diverse prefecture-level cities. In this sense, the modified cultivated land pressure index is a comprehensive pressure threshold that has integrated the quantity and quality of cultivated land, and its results are more valid (Lu et al., 2019b). The index can be calculated from the following equation:

$$K_a = \frac{H_{\min}}{H_a} = \frac{\beta \cdot G_r / C \cdot Q \cdot A}{H_a} \tag{1}$$

$$K = \frac{K_a}{\alpha} = \frac{K_a}{C_i \cdot A_i / C_n \cdot A_n} \tag{2}$$

where, K is the modified cultivated land pressure index; K_a is the cultivated land pressure index; $H_{\min}$ is the minimum per capita cultivated land area capable of guaranteeing grain security; H_a is the actual per capita cultivated land area; β is the self-sufficiency rate of grain (%); G_r is the per capita grain demand (kg/person); C is the grain yield per unit sown area (kg/hm^2); Q is the ratio of the sown area of grain crops to the total sown area of crops (%); A is the multiple cropping index (%); α is the correction coefficient of cultivated land quality; C_i is the grain yield per unit sown area of city i (kg/hm^2); A_i is the multiple cropping index of a city (%); C_n is the grain yield per unit sown area of a province (kg/hm^2); A_n is the multiple cropping index of a province (%). According to related studies and the *China's Grain Security Program for Medium and Long-Term (2008–2020)*, (National Development and Reform Commission, 2008), it is proposed that the self-sufficiency rate of grain should have been kept above 95% by 2020, so β was set as 95% in this study. The State Food and Nutrition Consultant Committee (https://sfncc.caas.cn/) proposed that the objective per capita grain demand for a well-off society in an all-round way should be 437 kg/person, therefore, G_r was set as 437 kg/person.

With reference to the evaluation criteria on the cultivated land pressure index and the findings of related studies, the cultivated land pressure index can be graded at five levels (Yang and Yang, 2015): grain security zone ($K \leq 0.9$), alarm pressure zone ($0.9 < K \leq 1$), low pressure zone ($1 < K \leq 1.5$), medium pressure zone ($1.5 < K \leq 2$) and high pressure zone ($K > 2$).

2.4.2 Correlation analysis of spatial distribution of cultivated land pressure

Performing correlation analysis on the spatial distribution of cultivated land pressure deepens existing research on the spatiotemporal pattern of cultivated land pressure and reveals the spatial clustering and evolution mechanism of cultivated land pressure more profoundly. In this study, spatial correlation models were implemented to quantify the clustering and dispersion modes of the cultivated land pressure index. The aim was to discuss the clustering features of cultivated land pressure distribution in the HEZ from a global perspective in different periods and identify the hot spots (high-value clusters) and cold spots (low-value clusters) of cultivated land pressure distribution from the local perspective, therefore offering scientific references for preparing a cultivated land resources optimization scheme adaptive to local circumstances.

Moran's I index is used to test the overall trend of the attribute values of spatially adjacent or neighboring regional units in the study area in terms of spatial correlation (Gimona and van der Horst, 2007; Li et al., 2019). It can be expressed by the following equation:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{s^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \tag{3}$$

$$S^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \tag{4}$$

where, S^2 is the variance of the observed value; $\bar{x}$ is the mean observed value; n is the number of regions; x_i and x_j are the observed values of regions i and j, respectively; and w_{ij} is the spatial weight matrix. Moran's I statistics has a value range of [–1, 1]. When $I > 0$, there will be a positive correlation, meaning that the units under investigation will have a significant spatial correlation (or clustering level). When $I < 0$, there will be a negative correlation, meaning that the units under investigation will be spatially dispersed. When $I = 0$, it means that the units under investigation will have no spatial correlation. The significance of I values can be measured by the z-statistics test.

Getis-Ord G_i^* is used to identify the high-value and low-value clusters of cultivated land pressure, i.e., the spatial distribution of hot spots and cold spots (Li et al., 2019). It can be expressed by the following equation:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij}x_i x_j}{\sum_{j=1}^{n} x_j} \tag{5}$$

$$Z(G_i^*) = \frac{G_i^* - E(G_i^*)}{\sqrt{V(G_i^*)}} \tag{6}$$

where, $E(G_i^*)$ and $V(G_i^*)$ are the mathematical expectation and variance of G_i^*, respectively; w_{ij} is the spatial weight; and $Z(G_i^*)$ is the statistical test value for the normalization of G_i^*. When $Z(G_i^*)$ is positive and significant, it means that the values around region i are greater than the mean value and constitute high-value clusters (hot spots). On the contrary, when $Z(G_i^*)$ is negative and significant, it means that the values around the region i are smaller than the mean value and constitute low-value clusters (cold spots). This process is completed using the Optimized Hot Spot Analysis module of the ArcGIS spatial statistics tool. The Optimized Hot Spot Analysis module adopts the Getis-Ord G_i^* statistical model, it takes pixels as the scale, and automatically aggregates event data. By identifying a suitable scope of analysis, it creates the map of statistically significant hot and cold spots.

2.4.3 Selection of the influencing factors of the spatial differentiation of cultivated land pressure

The evolution of cultivated land pressure in a region is not generated by the independent action of any single geographical factor, rather to the combined action of multiple geographical factors. Depending on the grain production demand of humans for survival and development and the support of grain supply by the 'human, land, and industry' interactions of agricultural-territorial system, the geographical factors having an influence on the evolution of cultivated land pressure can be classified into two types: physiographical factors and socioeconomic factors (Song and Ouyang, 2012). The natural environmental background is one of the essential factors of grain production, and a possible condition influencing the magnitude of cultivated land pressure. Socioeconomic factors, according to the type of action, can be divided into urbanization and agricultural production conditions. Urbanization acts on cultivated land pressure either directly or indirectly through encroaching on cultivated land resources, stimulating the transfer of agricultural population, *etc.* In contrast, agricultural production conditions directly influence cultivated land pressure by changing the production performance of cultivated land. In view of this, this study gave comprehensive contemplation to the circumstances and index availability of the study area, and constructed an integrated influencing factor system from the dimensions of the natural environmental background, urbanization, and agricultural production conditions. See the explanations of specific indices in Table 1.

(1) Natural environmental background. Natural environmental factors drive grain production mainly by affecting the production potential and suitability of the land (Wang et al., 2010). In this study, annual precipitation and annual mean temperature were chosen because suitable water-heat conditions provide favorable growth conditions for crops. Average slope was selected as a terrain factor, since the HEZ has diversified geomorphological types (e.g., mountains, hills, terraces, and plains).

(2) Urbanization. Population urbanization rate, the proportion of built-up area, and the proportion of the output value of the secondary and tertiary industries in regional GDP were selected to analyze the power of the influence of urbanization on cultivated land pressure from three dimensions: population, space, and economy. Specifically, population urbanization rate denotes population urbanization level. The proportion of built-up area depicts the spatial development of a city. The proportion of the output value of the secondary and tertiary industries in regional GDP characterizes the non-agricultural economic level.

(3) Agricultural production conditions. Agricultural mechanization level, fertilizer application per unit area, multiple cropping index, grain yield per unit area and the proportion of non-grain crops were taken as the influencing factors of agricultural production conditions. Namely, agricultural mechanization level denotes the input of agricultural machinery, alters the labor-saving investment in agricultural production, and improves the productivity of cultivated land. Fertilizer application per unit area affects the cultivated land pressure by affecting the production performance of cultivated land. Multiple cropping index reflects the use efficiency of cultivated land resources. Grain yield per unit area reflects the grain yield level per unit sown area. The proportion of non-grain crops indicates the structure of crops cultivation.

2.4.4 Quantitative analysis of influencing factors of cultivated land pressure

For the purpose of quantifying the inner mechanism of the spatial differentiation of cultivated land pressure in the HEZ in 2018, a geographical detector model was employed to identify the dominant factors affecting the spatial differentiation of cultivated land pressure. The multi-scale geographically weighted regression (MGWR) model was used to explore in-depth the action mechanism of the prevalent factors on the spatial differentiation of cultivated land pressure. The results provide references for establishing cultivated land protection strategies in a scientific manner, with a consideration of local circumstances.

(1) Geographical detector. Geographical detector can be employed to detect the spatial differentiation of geographical phenomena, and reveal the driving forces be-

Table 1 Index system of the influencing factors of cultivated land pressure in the Huaihai Economic Zone of China

Criterion layer	Index layer	Index description
Natural environmental background	Annual precipitation (X_1)	Annual precipitation from 2000 to 2018 / mm
	Annual mean temperature (X_2)	Annual mean temperature from 2000 to 2018 / °C
	Average slope (X_3)	Calculated in ArcGIS using DEM / °
Urbanization	Population urbanization rate (X_4)	Urban population/total population / %
	Proportion of the output value of the secondary and tertiary industries in regional GDP (X_5)	Output value of the secondary and tertiary industries/regional GDP / %
	Proportion of built-up area (X_6)	Built-up area/total land area / %
Agricultural production conditions	Agricultural mechanization level (X_7)	Total power of agricultural machinery (including cultivation, harvesting, irrigation and drainage, and agricultural transport machinery/total cultivated land area / (10 000 W/ha)
	Fertilizer application per unit area (X_8)	Converted pure fertilizer application/total sown area of crops / (kg/ha)
	Multiple cropping index (X_9)	Total sown area of crops/cultivated land area / %
	Grain yield per unit area (X_{10})	Total grain yield/sown area of grain crops / (kg/ha)
	Proportion of non-grain crops (X_{11})	Sown area of non-grain crops/total sown area of crops / %

hind them. They obey four principles of detection, namely: factor, ecological, interactive, and risk detections (Wang and Xu, 2017). Existing studies mainly use the multiple linear regression model to investigate influencing mechanisms, nonetheless, this approach neglects the spatial heterogeneity of research objects and only explains the relationship between the alteration of Y and the independent variable X. Geographical detector is adept at analyzing type variables. By converting the numerical magnitude of X into a type variable, the principle of factor detection can be utilized for the purpose of detecting the degree to which the factor X can explain the spatial differentiation of the attribute Y. Individual factors can also be contrasted in terms of the magnitudes of explanatory power to identify the dominant factors influencing the spatial differentiation of cultivated land pressure (Wang et al., 2010). Additionally, while traditional multiple regression models are normally based on a series of assumptions, the geographical detector model does not formulate too many assumptions, hence, it can overcome the limits of statistical methods in variable processing (Wen et al., 2018). In consideration of this, the study followed the principle of factor detection for geographical detector in identifying the dominant factors influencing the spatial differentiation pattern of cultivated land pressure. The magnitude of explanatory power can be measured using the q statistics. q indicates that the independent variable explains $100 \times q\%$ of the dependent variable, as expressed by the equation below:

$$q = 1 - \frac{1}{N\delta^2}\sum_{h=1}^{L} N_h {\delta_h}^2 \tag{7}$$

where, L is the stratification (i.e., classification or zoning) of the variable Y or the factor X; N_h and δ_h represents the unit number and variance of layer h, respectively; N and δ represent the unit number and variance of the entire study area, respectively. The q value has a range of [0, 1], where a greater value signifies a stronger influence imposed by the independent variable on the dependent variable.

(2) MGWR analysis. In the HEZ, diverse cities have different natural environments, urbanization development levels, and agricultural production conditions in terms of spatial scales, which cause further differences in the spatial scales of cultivated land pressure. In other words, a single influencing factor has similar effects on cultivated land pressure within a certain scope. After exceeding this spatial scope, it begins exerting different effects on cultivated land pressure. The heterogeneity of the spatial scales of driving factors falls within the basic category of geographical research as well. Classical geographically weighted regression (GWR) has been used extensively for the purpose of detecting the heterogeneity of the spatial scales of driving factors, with the assumption that their spatial scales are constant (that is to say, each variable has the same bandwidth). However, in numerous cases, a research object involves spatial processes of different spatial scales, hence, the assumption of constant spatial scales produces substantial estimation biases (Fotheringham et al., 2017; Lao and Gu, 2020; Mansour et al., 2021). By differentiating the bandwidth of each variable, MGWR optimizes classical GWR, so that the specific bandwidth of each variable can be used to measure the spatial scales of every spatial process. In this way, the multi-bandwidth method produces more valid estimation results (Shen et al., 2020). For this reason, this study chose the MGWR model to analyze several dominant influencing factors at different spatial scales. The calculation process was completed using MGWR2.2 software released in March 2020. The equation of the MGWR model is as follows:

$$y_i = \sum_{\mathrm{j}=1}^{k} \beta_{bwj}(u_i, v_i)x_{ij} + \varepsilon_i \tag{8}$$

where y_i is the response variable; β_{bwj} is the jth parameter estimate; bwj is the bandwidth used by the regression coefficient of the jth explanatory variable; (μ_i, v_i) is the projected coordinates of the sample point i; x_{ij} is the jth explanatory variable of the sample point i; and ε_i is a random error term.

3 Results and Analysis

3.1 Spatiotemporal evolution of cultivated land pressure

By analyzing the cultivated land pressure index of the HEZ since 2000, it can be seen that mean index has shown a trend of declining beforehand and rising afterwards, with the mean values of 0.9131, 0.7899, 0.7458, and 0.7695 in 2000, 2006, 2012, and 2018, respectively. Overall, it declined abruptly and also underwent a transition from alarm pressure state to pressure-free state. As a core grain-producing area in China, the study area has a generally positive situation. In 2000, there were 12 grain security zones, mainly scattered in clusters in the north, west, and southeast. The zones with grain security problems were mostly distributed at the intersection of Anhui, Jiangsu, and Shandong provinces, and centered around Xuzhou in a T-shaped pattern. There were two alarm pressure zones (Suzhou and Heze), and six low-pressure zones (Fuyang, Huaibei, Xuzhou, Lianyungang, Laiwu, and Linyi). In 2006, the number of grain security zones increased to 16. The zones with grain security problems were mostly distributed in Xuzhou and central and southern Shandong Province. There were two alarm pressure zones (Xuzhou and Rizhao), one low-pressure zone (Linyi), and a single newly-added high-pressure zone (Laiwu). In 2012, the number of grain security zones increased to 17. The three zones with grain security problems were concentrated in central and southern Shandong Province. There were: alarm pressure zone (Linyi), low-pressure zone (Rizhao), and high-pressure zone (Laiwu). In 2018, the number of grain security zones stabilized at 17. The zones with grain security problems remained concentrated in central and southern Shandong Province. Linyi upgraded to a low-pressure zone, Rizhao upgraded to a high-pressure zone, while Laiwu remained a high-pressure zone (Fig. 3).

At the level of individual prefecture-level cities, 11 cities consistently remained in grain security zones, and scattered in the north, south, and west of the HEZ. A total of 15 zones experienced relieved cultivated land pressure. In particular, Huaibei saw the most significant relief of cultivated land pressure (with a pressure index drop of 0.8725), followed by Lianyungang and Xuzhou (with a decrease in the pressure index of 0.6563 and 0.5636, respectively). All three cities transformed from low-pressure zones into grain security zones. Huaibei is a major land consolidation zone in Anhui Province, and the relief of cultivated land pressure in Huaibei is mainly attributable to the effective implementation of land consolidation projects, which greatly expanded cultivated land area. Xuzhou and Lianyungang are major industrial cities in the northern Jiangsu, where a great deal of cultivated land has been occupied as a result of urbanization and industrialization. However, the local governments of the two cities have invested considerably in agricultural production, improved their irrigation and other agricultural infrastructure effectively, and significantly raised their agricultural mechanization level. Combined with the extension of improved varieties and the substantial increase in grain sowing area and productivity, the two cities have evidently relieved their

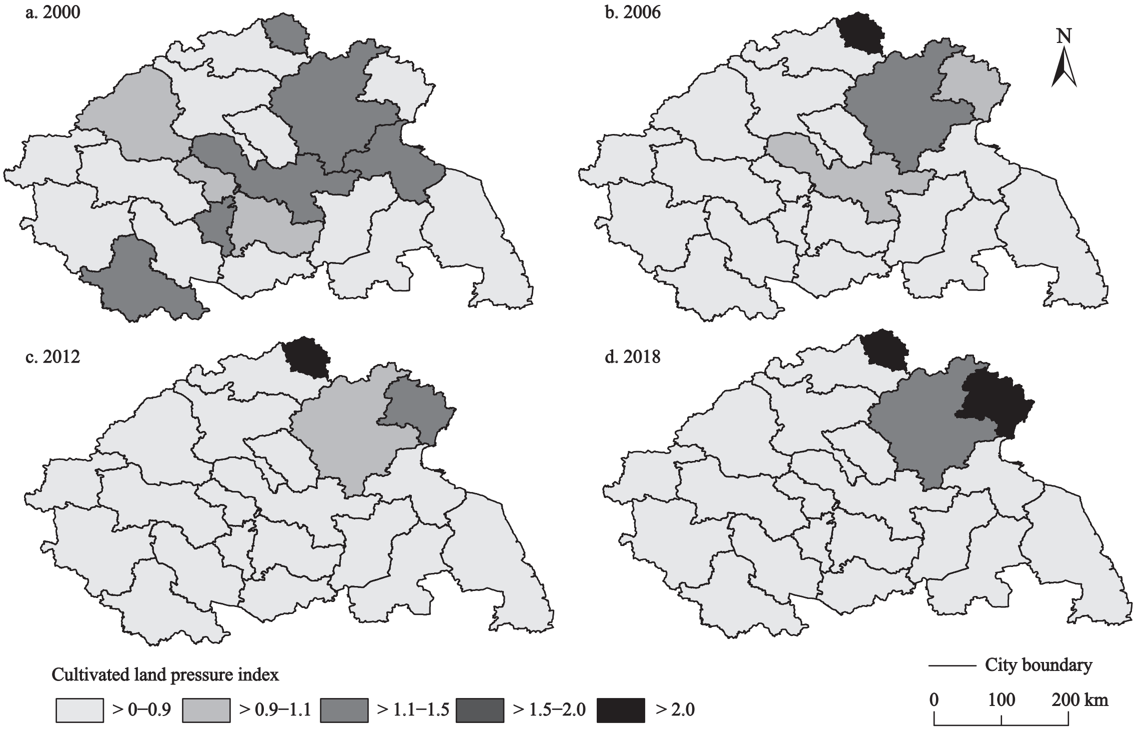

Fig. 3 Spatiotemporal change of cultivated land pressure index in the Huaihai Economic Zone of China

high cultivated land pressure. In contrast, five cities (Laiwu, Rizhao, Linyi, Tai'an, and Jining) experienced increased cultivated land pressure. They were mainly distributed in the central and southern Shandong Province. The largest expansion of cultivated land pressure occurred in Laiwu and Rizhao, where the pressure indices increased by 1.4853 and 1.3805, respectively. As a result, Laiwu and Rizhao turned from a low-pressure zone and a grain security zone into a high-pressure zone, respectively. Shandong Province is known for its vigorous implementation of land consolidation, and Laiwu and Rizhao have both witnessed a notable increase in cultivated land area, but the role of agriculture in the economy of resident households progressively weakened in the two cities as a result of rapid urbanization. Therefore, grain sowing area and grain yield continuously decreased, and grain security problems aggravated daily. Linyi faced a high cultivated land pressure that was under frequent changes. It first transformed from a low-pressure zone in 2000 into an alarm pressure zone in 2012, and then into a low-pressure zone again in 2018. Overall, since 2000, most parts of the HEZ have experienced a gradual relief of cultivated land pressure, and the general grain security status has ameliorated. Nonetheless, some zones still face the increase in the cultivated land pressure.

3.2 Spatiotemporal pattern of cultivated land pressure

3.2.1 Global features

Based on the adjacency relationships between cities, the global Moran's I of the cultivated land pressure index in the study period was calculated by the Inverse Distance Weighted method. The ArcGIS 10.2 software was used to calculate the Moran's I of the cultivated land pressure index in 2000, 2006, 2012, and 2018. The calculated values were 0.8227, 0.8357, 0.8507, and 0.9013, respectively, and all passed the 1% significance level. The result suggests that the spatial distribution of cultivated land pressure in the study area demonstrates a positive spatial correlation, with increasingly significant global spatial clustering features. In addition, the result also explains that it is possible to detect the influencing factors of the spatial differentiation pattern of cultivated land pressure using Geo Detector and MGWR.

3.2.2 Spatial hot and cold spots

By analyzing hot and cold spots, we can thoroughly explore the clustering features of the high-value and low-value zones throughout years. In this study, the grid cell of 5 km × 5 km was adopted as the object to calculate the local G_i^* statistics of the cultivated land pressure intensity of each grid in every year and obtain the Z values. Jenks's Natural Break method was implemented to classify the values from high to low into four types: hot spots, secondary hot spots, secondary cold spots, and cold spots; and to create the hot and cold spots distribution map of cultivated land pressure in the HEZ (Fig. 4).

The clustering features of the cultivated land pressure index of the study area showed apparent spatial differences across different years. The hot spots and secondary hot spots of cultivated land pressure presented a narrowing and clustering trend, and gradually advanced towards central and southern Shandong Province in the northeast. The number of main hot spot cities reduced from six in 2000 to two in 2018. The number of main secondary hot spot cities decreased from five in 2000 to one in 2018. The cold spots and secondary cold spots of cultivated land pressure manifested a spreading and clustering trend. Cold spots gradually advanced to the west, south, and southeast. The number of main cold spot cities increased from four in 2000 to nine in 2018. Secondary cold spots gradually advanced toward the central and northern parts. The number of main secondary cold spot cities increased from five in 2000 to nine in 2018. Alterations in hot and cold spots indicated that the high-value zones of cultivated land pressure decreased to some extent, while its low-value zones progressively increased. In other words, zones with a high grain security level enlarged within the pressure-free scope. Moreover, the clustering features of the spatial distribution of hot and cold spots were enhanced.

Locally, southwestern Shandong Province underwent frequent changes. It has always remained within the pressure-free scope after 2006, but it also changed considerably within this scope. Some cities in the south also changed significantly within the pressure-free scope. The central part experienced frequent changes as well, and transformed from a hot spot into a secondary hot spot, and subsequently into a secondary cold spot. Currently, the central part is within the pressure-free scope, but it also has a higher index. Zhoukou and Shangqiu in the west and Yancheng in the northeast have always been cold spots, meaning that they have always had high grain security levels. Laiwu was consistently a hot

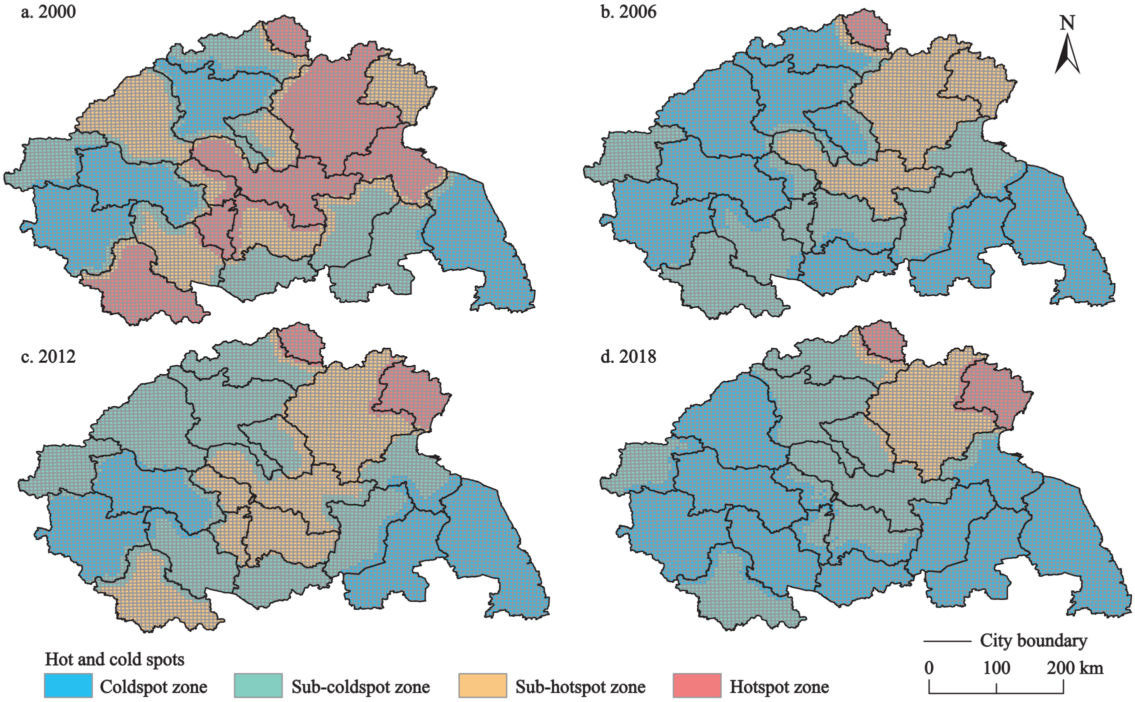

Fig. 4 Hot and cold spots distribution map of cultivated land pressure in the Huaihai Economic Zone of China

spot, with the largest potential grain security hazard.

3.3 Influencing factors of spatial differentiation of cultivated land pressure

In this study, the cultivated land pressure of every city in 2018 was adopted as the dependent variable, and the 11 influencing factors were taken as the independent ones (Table 1). For geographical detector, a numerical magnitude serves as the dependent variable, while the independent variables are ought to be type variables. Therefore, the numerical magnitudes of the independent variables were discretized using the Jenks's Natural Break method. Variables related to the cultivated land pressure served as the input into the model based on the Geo Detector user interface of Excel. Table 2 provides an illustration of factor detection. Multiple cropping index, average slope, the proportion of non-grain crops, and population urbanization rate had higher q-values (0.815, 0.788, 0.714, and 0.619, respectively), which passed the significance test. This implies that the spatial differentiation of cultivated land pressure in the HEZ is mainly affected by these four factors. Moreover, the proportion of the output value of the secondary and tertiary industries in regional GDP, the proportion of built-up area, fertilizer application per unit area, grain yield per unit area and agricultural mechanization level were closely related to the spatial differentiation of cultivated land pressure, however, their driving forces were relatively minor. Annual precipitation and annual mean temperature had small q-values, which failed to pass the significance test. This suggested that climate conditions exerted a weak driving effect on the spatial differentiation of cultivated land pressure, perhaps due to the relatively balanced distribution of water-heat conditions in the HEZ.

3.4 Spatial differentiation of dominant influencing factors

3.4.1 Model selection

The MGWR and GWR models of the MGWR2.2 software were used to measure the spatial differentiation of four dominant factors, hence further demonstrating the plausibility of MGWR. It can be seen from Table 3 that the multiple coefficient of determination (R^2) of MGWR is greater in comparison with the classical GWR, and its goodness-of-fit (AICc) is apparently lower than that of GWR. Thus, the measurement outcome of MGWR is superior to that of GWR. Furthermore, MGWR has a smaller residual sum of squares, implying that MGWR obtains more valid regression results closer to true values with fewer parameters. Therefore, the MGWR model was chosen in this study. As it can be con-

Table 2 Factor detection results of regional differentiation of cultivated land pressure in the Huaihai Economic Zone of China

Influencing factors	q-values	Influencing factors	q-values
Annual precipitation (X_1)	0.178	Agricultural mechanization level (X_7)	0.546**
Annual mean temperature (X_2)	0.241	Fertilizer application per unit area (X_8)	0.340**
Average slope (X_3)	0.788**	Multiple cropping index (X_9)	0.815**
Population urbanization rate (X_4)	0.619**	Grain yield per unit area (X_{10})	0.487**
Proportion of the output value of the secondary and tertiary industries in regional GDP (X_5)	0.493**	Proportion of non-grain crops (X_{11})	0.714**
Proportion of built-up area (X_6)	0.314**		

Note: **means that q-values passed the 5% significance level

Table 3 Indicators comparison of classical geographically weighted regression (GWR) with multi-scale geographically weighted regression (MGWR)

Model Indexes	MGWR	GWR
The multiple coefficient of determination (R^2)	0.936	0.841
Goodness-of-fit (AICc)	29.243	32.571
Sum of squares of residuals	1.288	2.339

cluded from the analysis, average slope, the proportion of non-grain crops and population urbanization rate exerted positive effects on the spatial distribution of cultivated land pressure. On the other hand, multiple cropping index exerted negative effects on the spatial distribution of cultivated land pressure (Fig. 5).

3.4.2 Multiple cropping index

Multiple cropping index was negatively correlated with cultivated land pressure, with a correlation coefficient from –0.2090 to –0.4824 (–0.3520 on average). The effect of multiple cropping index was considerable, showed an apparent spatial differentiation, and declined from east to west gradually. Multiple cropping index exerted a remarkable influence on Laiwu, Rizhao and Linyi. The reason for this is that, on the one hand, central and southern parts of the Shandong Province are covered by Shandong Hills and characterized by fragmented, scattered cultivated land and demanding cultivation. On the other hand, the massive transfer of rural labor leads to the extensive operation of cultivated land as well as the low efficiency of cultivated land use. Furthermore, the low efficiency of cultivated land use causes a low multiple cropping index, thus remarkably influencing the grain security of this part. Additionally, multiple cropping index exerted a significant influence on Lianyungang and Yancheng in the southeast. This is because Lianyungang is an eastern coastal city greatly affected by export-oriented economy and it has advanced tourism and industry. The large-scale transfer of its labor into the secondary and tertiary industries has brought about a low multiple cropping index. As a result, multiple cropping index exerts a stronger restraining effect on grain production in Lianyungang in comparison to other cities. Compared to nearby cities in the east, Yancheng has a higher multiple cropping index, which makes a great contribution to grain security. However, the cities moderately influenced by multiple cropping index were largely concentrated in the west with a high multiple cropping index. This is probably due to the fact that these cities generally have high multiple cropping indices, which have almost reached their limit in terms of relieving cultivated land pressure. Consequently, multiple cropping index exerts the minimum influence on these cities in comparison with central and eastern ones.

3.4.3 Average slope

Average slope was positively correlated with cultivated land pressure, with a correlation coefficient from 0.2829 to 0.3697 (0.3280 on average). The influence of slope was significant, yet it did not produce evident interregional differences. The spatial distribution of the coefficient values showed that the effect of the average slope continuously decreased from east to west, and that the most impacted cities were mostly concentrated in the east. This is because the eastern part is distributed from north to south with the Shandong Hills and the Huang-Huai Plain, and the terrain relief significantly affects cultivated land pressure. The central and southern Shandong Province in the northeast is dotted with many mountains, and is characterized by steep terrain. Therefore, the terrain slope has a strong restraining effect on grain production in this area. On the contrary, Yancheng and Lianyungang in the southeast are coastal cities characterized by low elevation and flat terrain that promote crop cultivation. Grain production in Yancheng and Lianyungang, compared to other cities nearby, benefited greatly from their flat terrain. The central and western

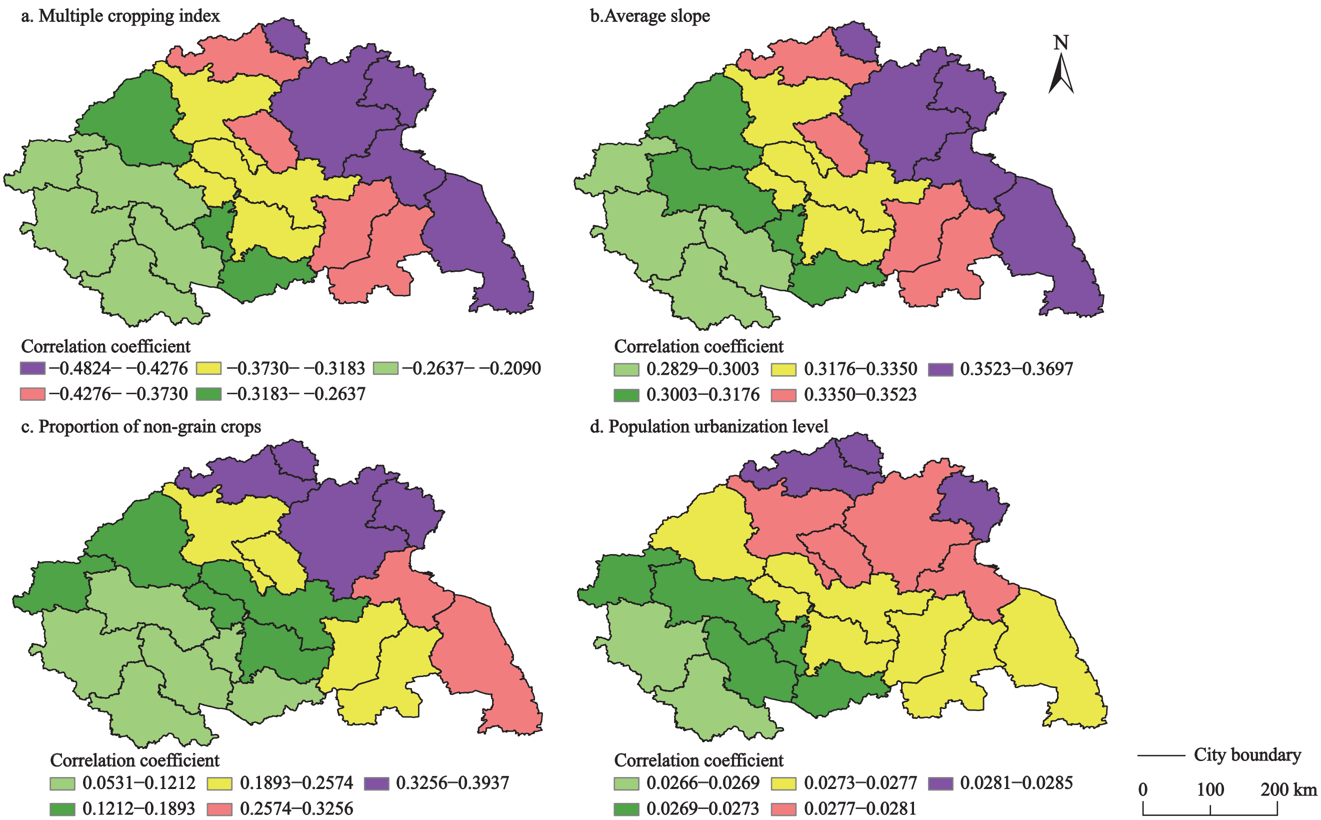

Fig. 5 Spatial coefficient distribution of driving factors based on the multi-scale geographically weighted regression (MGWR) model in the Huaihai Economic Zone of China in 2008

parts of the study area generally have a low elevation and a similar terrain slope, so the influence of the terrain slope on the cultivated land pressure is insignificant.

3.4.4 *Proportion of non-grain crops*

The proportion of non-grain crops was positively correlated with cultivated land pressure, with correlation coefficients from 0.0531 to 0.3937 (0.2050 on average). Although the effect of non-grain cultivation was relatively small, it produced significant spatial differentiation, with the effect progressively weakening from northeast to southwest. It can be seen that the apparent interregional differences in non-grain cultivation dominated the spatial variation in cultivated land pressure. The proportion of non-grain crops was highest in central and southern Shandong Province, and where its impact on cultivated land pressure was the strongest. A possible explanation for this is that hilly areas are more prone to non-grain cultivation due to the similar labor requirements of different crops and higher benefits from cash crops. Secondly, the proportion of non-grain crops had a more significant impact on Lianyungang and Yancheng, mainly because the lower proportion of non-grain crops obviously eased the cultivated land pressure compared to neighboring central and southern Shandong Province. Notably, Xuzhou had a higher proportion of non-grain crops and significantly lower cultivated land pressure, which may be related to the high grain productivity. Meanwhile, the proportion of non-grain crops had a weak effect on cultivated land pressure in eastern Henan and northern Anhui. This is because the proportion of non-grain crops in these cities was low and their differences were small, thus it did not have a significant negative impact on grain production.

3.4.5 *Population urbanization rate*

Population urbanization rate was positively correlated with cultivated land pressure, with a correlation coefficient from 0.0266 to 0.0285 (0.0276 on average). The influence of population urbanization rate was the weakest compared to the other three driving factors. which indicated that the increase in population urbanization level would cause the increase in cultivated land pressure to some extent. Spatially, the influence of population urbanization rate progressively declined from northeast to southwest. The most affected cities were mainly concentrated in central and southern Shandong Province, especially Laiwu, Rizhao, and Tai'an. Laiwu had the highest population urbanization rate (68%) in the HEZ, and the population urbanization rates of Rizhao and Tai'an exceeded 60% as well. The possible reason is that rapid urbanization leads to the massive transfer of rural labor and the shortage of agricultural labor in these regions, which further cause the extensive operation of cultivated land and exert a significant negative influence on grain production. The least influenced cities were mainly concentrated in northern Anhui. These cities have low levels of population urbanization and sufficient labor to engage in agricultural production, therefore, population urbanization rate has a rather slight influence on them. However, northern Jiangsu has a relatively higher level of population urbanization that has not exceptionally influenced its cultivated land pressure. This may be explained by regional economic development level. That is to say, Jiangsu Province is an economically strong province where residents have generally high-income levels, as a consequence, farmers have stronger capabilities to invest in grain production. Moreover, grain yield has been expanded by the increased governmental input in agricultural production, for example: the construction of high-standard farmland, the use of perfect water-saving irrigation facilities, the extension of enhanced varieties, and other agriculture-supporting and farmer-benefiting policies. For these reasons, the relatively higher population urbanization rate has not had any significant negative influence on grain production.

4 Discussion

Notably, existing studies mostly focus on spatial changes of cultivated land pressure at the macroscopic scale, but rarely probe into the internal spatial structural features of cultivated land pressure. While, they generally take a global perspective to explore the driving factors of changes in cultivated land pressure. Comparatively, the merit of this study lie in that not only does it probe into the pattern of the spatial distribution of cultivated land pressure using the spatial correlation models, but it also investigates the influencing factors of the spatial differentiation of cultivated land pressure through geographical detector and MGWR model, from the perspective of the heterogeneity of the spatial scales of driving factors. This study enriches the research methods in the field of grain security to some extent. Its findings provide scientific foundation for formulating regional grain security guarantee policies in accordance with local circumstances, and contribute to the promotion of regional sustainable development. We will inquire the important policy implications of this study.

4.1 Steadily advancing cultivated land consolidation and balancing the quality and quantity of cultivated land

For the purpose of preventing the large-scale occupation of cultivated land by urban expansion and industrial construction, the Chinese government introduced Farmland Requisition-Compensation Balance in the late 1990s, and later continued to introduce a series of cultivated land protection policies. As a result of benefiting from these policies, the quantity of cultivated land was significantly increased. According to official statistics, the quantity of newly-reclaimed cultivated land reached 2.47 million ha between 2000 and 2013 (Ministry of Land and Resources of People's Republic of China, 2016). Nonetheless, the grain security problems that some regions underwent could not be solved by the increased quantity of cultivated land. Some scholars argue that this is because newly-reclaimed cultivated land is permitted to be sold in China to other cities of the province for the purpose of achieving a farmland requisition-compensation balance within the province. In this context, local governments pay more attention to the fiscal revenue formed by the sales of newly-reclaimed cultivated land, instead of the position, quality, or efficiency of use of such land. In general, there are plentiful backup cultivated land resources in mountainous and hilly areas, so newly-reclaimed cultivated land is largely located in these areas. Nonetheless, cultivated land in these areas is usually of poor quality and distant from rural residential areas, therefore, farmers lack the enthusiasm to manage such land. Consequently, newly-reclaimed cultivated land fails to make contribution to grain production (Xin and Li, 2018).

Similar phenomena existed in the study area. Central and southern Shandong Province has witnessed an increase in cultivated land area, but it is located in the Shandong Hills, where cultivated land is scattered, difficult to take care of, and far away from residential areas. Therefore, the increase in cultivated land has failed to arouse the enthusiasm of farmers. For example, Linyi witnessed the largest increase in cultivated land area

(190.29 ha), yet it was ranked fourth from the bottom (just above Laiwu, Rizhao, and Tai'an) in regard with the increase of total grain yield. It can be seen that the newly-reclaimed cultivated land may not be fully and rationally used, and the low multiple cropping index confirms this. In view of this, local governments should conduct a rigorous assessment of ecological and economic feasibility before reclaiming newly cultivated land, instead of pursuing the fiscal revenue blindly, and avoid reclaiming cultivated land in places where farmers have no interest in cultivating. It is important to guarantee the levelling and fertility of newly-reclaimed cultivated land. In addition, local government can actively try to introduce social capital into cultivated land consolidation in the future, which will enrich the source of funds and strengthen public supervision through improved public participation.

4.2 Guiding zoning regulation and ensuring region-wide grain security

China's grain yield growth is lagging behind its demand growth, and the gap between grain supply and demand is steadily widening. It is predicted that the grain demand and supply in China will be 609 and 585 million t respectively in 2030 (Zhang et al., 2012; Lv, 2013). Accordingly, grain imports have become an effective measure to ensure grain security in China. Currently, the international grain trade situation facing China is complex. On the one hand, with the spread of COVID-19 around the world, several countries have begun to restrict grain exports; on the other hand, trade frictions between China and the United States are wavering, and grain trade is significantly hampered (Huang and Zhou, 2020). In response to these difficulties, China will have to ensure that grain security in areas suitable for grain cultivation is completely reliable. In this study, not all cities in the HEZ achieved grain security, and there was an increasing risk of cultivated land pressure in some grain-secure cities. Therefore, it is necessary to conduct zoning regulation in order to ensure region-wide grain security based on regional differences.

From the spatial pattern of cultivated land pressure, hot and secondary-hot spots of cultivated land pressure, that is, high-pressure and low-pressure zones, are located in Laiwu, Rizhao and Linyi, which are characterized by extensive hills, and excessive non-grain crops and marginalization of farmland. Given that, gully leveling cultivated land and high-quality terraces, located in the mountainous and hilly areas of central and southern Shandong Province, should be firmly controlled for non-grain crops. In addition, targeted production incentive policies should be formulated to foster the enthusiasm of agricultural production entities and exploit the full potential of idle cultivated land. Moreover, the low agricultural mechanization of these regions can be attributed to the relief of the mountainous terrain, which limited the efficiency of grain production. In the future, local government is ought to increase support for agricultural mechanization service and promote small-micro agricultural machines in these regions.

Secondary cold spots of cultivated land pressure belonged to the grain security zones. The risk of its deterioration is relatively high, especially in the cities of the central region, where the urbanization speed is relatively high. The local government should strengthen the planning and management of construction land on the one hand, and increase subsidies for grain cultivation in order to guide the planting of grain crops at an appropriate scale and stabilize the grain production space, on the other hand. Furthermore, the local government can encourage labor return to the countryside, develop a new management mode of grain production, and improve the comparative benefit of grain cultivation.

For cold spots zones of cultivated land pressure, grain production needs to be transformed from increasing quantity to improving quality. Particularly, the ultra-intensive fertilizer application in eastern Henan will inevitably cause agricultural non-point source pollution, and threaten the healthy and sustainable development of local agriculture. These regions should increase science and technology input, guide soil testing for formulated fertilization, encourage the combined application of chemical fertilizers (at reduced rate) with organic fertilizers, and actively promote straw mulching, biological pesticides, and degradable films.

5 Conclusions

Taking 20 prefecture-level cities in the HEZ of China as the research objects, this study analyzed the changes and spatial pattern of cultivated land pressure from 2000 to 2018, and noted the influencing factors of the spatial differentiation of cultivated land pressure in 2018. According to the results of this study: 1) The HEZ changed from an alarm pressure zone into a pressure-free zone.

The general grain security status was sound, but cultivated land pressure increased locally, principally in central and southern Shandong Province. 2) The hot and secondary hot spots of cultivated land pressure gradually narrowed. In contrast, the cold and secondary cold spots gradually spread into continuous regions. 3) Multiple cropping index, average slope, the proportion of non-grain crops, and population urbanization rate were the main factors driving the spatial differentiation of cultivated land pressure. To be specific, the influences of the first two factors gradually decreased from east to west, and the influences of the other two factors gradually decreased from northeast to southwest.

This study proposes that the government should strengthen pre-planning of cultivated land consolidation in order to avoid the blind pursuit of the fiscal revenue from newly-reclaimed cultivated land. Additionally, for areas with excessive non-grain cultivation, the government is ought to reasonably increase farmers' willingness to plant grain by formulating targeted incentive policies for grain production, especially in mountainous and hilly areas. Furthermore, support for the agricultural mechanization input should also be reinforced in mountainous and hilly areas. Moreover, the intensive application of fertilizers should be controlled by testing soil for formulated fertilization and applying together chemical and organic fertilizers. The research findings and policy implications of this study apply to most major grain-producing areas in China.

This is a preliminary study on cultivated land pressure in the HEZ, China, and in-depth research will be conducted in the future. This study mainly investigated the cultivated land pressure of overall grain production, therefore, future research should pay attention to the cultivated land pressure of various grain crops. In addition, agricultural policy adjustments and global grain trade have a profound effect on grain production by affecting farmers' planting decisions, which have been weakly focused in this paper. Henceforth, these factors should be further investigated to deepen our comprehension of the close connections between cultivated land pressure and various influencing factors.

References

Bratley K, Ghoneim E, 2018. Modeling urban encroachment on the agricultural land of the eastern Nile delta using remote sensing and a GIS-based Markov chain model. *Land*, 7(4): 114. doi: 10.3390/land7040114

Bren D'Amour C, Reitsma F, Baiocchi G et al., 2016. Future urban land expansion and implications for global croplands. *Proceedings of the National Academy of Sciences of the United States of America*, 114(34): 8939–8944. doi: 10.1073/pnas.1606036114

Cai Yunlong, Fu Zeqiang, Dai Erfu, 2002. The minimum area per capita of cultivated land and its implication for the optimization of land resource allocation. *Acta Geographica Sinica*, 57(2): 127–134. (in Chinese)

Cheng L, Jiang P H, Chen W et al., 2015. Farmland protection policies and rapid urbanization in China: a case study for Changzhou City. *Land Use Policy*, 48: 552–566. doi: 10.1016/j.landusepol.2015.06.014

Clark M, Tilman D, 2017. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environmental Research Letters*, 12(6): 064016. doi: 10.1088/1748-9326/aa6cd5

Deng Z Q, Zhao Q Y, Bao H X H, 2020. The impact of urbanization on farmland productivity: Implications for China's requisition-Compensation balance of farmland policy. *Land*, 9(9): 311. doi: 10.3390/land9090311

Fotheringham A S, Yang W B, Kang W, 2017. Multiscale geographically weighted regression (MGWR). *Annals of the American Association of Geographers*, 107(6): 1247–1265. doi: 10.1080/24694452.2017.1352480

Fu Zeqiang, Cai Yunlong, Yang Youxiao et al., 2001. Research on the relationship of cultivated land change and food security in China. *Journal of Natural Resources*, 16(4): 313–319. (in Chinese)

Gimona A, van der Horst D, 2007. Mapping hotspots of multiple landscape functions: a case study on farmland afforestation in Scotland. *Landscape Ecology*, 22(8): 1255–1264. doi: 10.1007/s10980-007-9105-7

Huang Hanquan, Zhou Zhen, 2020. New sistuation of global food security and China's response. *Theroy Guide*, (9): 55–56. (in Chinese)

Jayne T S, Chamberlin J, Headey D D, 2014. Land pressures, the evolution of farming systems, and development strategies in Africa: a synthesis. *Food Policy*, 48: 1–17. doi: 10.1016/j.foodpol.2014.05.014

Kastner T, Rivas M J I, Koch W et al., 2012. Global changes in diets and the consequences for land requirements for food. *Proceedings of the National Academy of Sciences of the United States of America*, 109(18): 6868–6872. doi: 10.1073/pnas.1117054109

Lao X, Gu H Y, 2020. Unveiling various spatial patterns of determinants of *hukou* transfer intentions in China: a multi-scale geographically weighted regression approach. *Growth and Change*, 51(4): 1860–1876. doi: 10.1111/grow.12429

Li Z G, Sun Z S, Tian Y J et al., 2019. Impact of land use/cover change on Yangtze River delta urban agglomeration ecosystem services value: temporal-spatial patterns and cold/hot spots ecosystem services value change brought by urbanization. *International Journal of Environmental Research and Public Health*, 16(1): 123. doi: 10.3390/ijerph16010123

Liao L W, Long H L, Gao X L et al., 2019. Effects of land use transitions and rural aging on agricultural production in China's farming area: a perspective from changing labor employing quantity in the planting industry. *Land Use Policy*, 88: 104152. doi: 10.1016/j.landusepol.2019.104152

Lichtenberg E, Ding C R, 2008. Assessing farmland protection policy in China. *Land Use Policy*, 25(1): 59–68. doi: 10.1016/j.landusepol.2006.01.005

Lu C, 2020. Does household laborer migration promote farmland abandonment in China? *Growth and Change*, 51(4): 1804–1836. doi: 10.1111/grow.12431

Lu Shasha, Liu Yansui, Qin Fan, 2019a. Spatio-temporal differentiation of agricultural regional function and its impact factors in the Bohai Rim region of China. *Acta Geographica Sinica*, 74(10): 2011–2026. (in Chinese)

Lu Xinhai, Liu Ruihong, Kuang Bing, 2019b. Regional differences and dynamic evolution of cultivated land pressure in Hubei Province. *Transactions of the Chinese Society of Agricultural Engineering*, 35(23): 266–272. (in Chinese)

Luo Xiang, Luo Jing, Zhang Lu, 2015. Farmland pressure and China's urbanisation: an empirical study with the view of geographical differences. *Chinese Journal of Population Science*, (4): 47–59,127. (in Chinese)

Lv Xinye, 2013. Review of mid- and long-term predictions of China's grain security. *China Agricultural Economic Review*, 5(4): 567–582. doi: 10.1108/caer-05-2013-0086

Ma Xin, Zheng Xiaoxiao, Wang Yun et al., 2021. Study on the spatial-temporal evolution of cultivated land pressure and its driving factors in central plains economic region. *Chinese Journal of Agricultural Resources and Regional Planning*, 42(3): 58–66. (in Chinese)

Mansour S, Al Kindi A, Al-Said A et al., 2021. Sociodemographic determinants of COVID-19 incidence rates in Oman: geospatial modelling using multiscale geographically weighted regression (MGWR). *Sustainable Cities and Society*, 65: 102627. doi: 10.1016/j.scs.2020.102627

Meng Hao, Huang Xianjin, Yang Jun et al., 2019. Network structure and development concept in Huaihai Economic Zone. *Economic Geography*, 39(12): 1–10. (in Chinese)

Ministry of Land and Resources of the People's Republic of China, 2016. *China Land and Resources Statistical Yearbook 2016*. Beijing: Geology Press. (in Chinese)

Moseley W G, Watson N H, 2016. Agriculture, food production, and rural land use in advanced placement® human geography. *Journal of Geography*, 115(3): 118–124. doi: 10.1080/00221341.2015.1108354

Niu Shandong, Fang Bin, Cui Cui, Huang Shihui, 2020. The spatial-temporal pattern and path of cultivated land use transition from the perspective of rural revitalization: Taking Huaihai Economic Zone as an example. *Journal of Natural Resources*, 35(8): 1908–1925. (in Chinese). doi: 10.31497/zrzyxb.20200812

National Development and Reform Commission, 2008. China's Grain Security Program for Medium and Long-Term (2008–2020).

Peters C J, Picardy J, Darrouzet-Nardi A F et al., 2016. Carrying capacity of U. S. agricultural land: ten diet scenarios. *Elementa:Science of the Anthropocene*, 4: 000116. doi: 10.12952/journal.elementa.000116

Pretty J, Bharucha Z P, 2014. Sustainable intensification in agricultural systems. *Annals of Botany*, 114(8): 1571–1596. doi: 10.1093/aob/mcu205

Pretty J, Benton T G, Bharucha Z P et al., 2018. Global assessment of agricultural system redesign for sustainable intensification. *Nature Sustainability*, 1(8): 441–446. doi: 10.1038/s41893-018-0114-0

Shen Tiyan, Yu Hanchen, Zhou Lin et al., 2020. On hedonic price of second-hand houses in Beijing based on multi-scale geographically weighted regression: scale law of spatial heterogeneity. *Economic Geography*, 40(3): 75–83. (in Chinese)

Skinner M W, Kuhn R G, Joseph A E, 2001. Agricultural land protection in China: a case study of local governance in Zhejiang Province. *Land Use Policy*, 18(4): 329–340. doi: 10.1016/S0264-8377(01)00026-6

Song Xiaoqing, Ouyang Zhu, 2012. Key influencing factors of food security guarantee in China during 1999–2007. *Acta Geographica Sinica*, 67(6): 793–803. (in Chinese)

Uddin G, Oserei K, 2019. Positioning Nigeria's manufacturing and agricultural sectors for global competitiveness. *Growth and Change*, 50(3): 1218–1237. doi: 10.1111/grow.12308

Wang Jinfeng, Xu Chengdong, 2017. Geodetector: principle and prospective. *Acta Geographica Sinica*, 72(1): 116–134. (in Chinese)

Wang J F, Li X H, Christakos G et al., 2010. Geographical detectors-based health risk assessment and its application in the neural tube defects study of the Heshun region, China. *International Journal of Geographical Information Science*, 24(1): 107–127. doi: 10.1080/13658810802443457

Wen Qi, Shi Linna, Ma Caihong et al., 2018. Spatial heterogeneity of multidimensional poverty at the village level: Loess Plateau. *Acta Geographica Sinica*, 73(10): 1850–1864. (in Chinese)

Wu Chuanjun, 1991. The core of study of geography: man-land relationship areal system. *Economic Geography*, 11(3): 1–6. (in Chinese)

Xin L J, Li X B, 2018. China should not massively reclaim new farmland. *Land Use Policy*, 72: 12–15. doi: 10.1016/j.landusepol.2017.12.023

Yang Qing, Yang Zisheng, 2015. The measurement and grading of pressure on cultivated land in city-level in Yunnan province. *Agricultural Science & Technology*, 16(7): 1562–1564. doi: 10.3969/j.issn.1009-4229.2015.07.056

Yang Xiaohuan, Cheng Chuanzhou, Li Yuejiao, 2010. Effect of cropland occupation and supplement on light-temperature potential productivity in China from 2000 to 2008. *Chinese Geographical Science*, 20(6): 536–544. doi: 10.1007/s11769-010-0429-x

Yu D, Hu S G, Tong L Y et al., 2020. Spatiotemporal dynamics of cultivated Land and its influences on grain production potential in Hunan Province, China. *Land*, 9(12): 510. doi: 10.3390/land9120510

Zhang Hui, Wang Yang, 2017. Spatial differentiation of cropland pressure and its socio-economic factors in China based on panel data of 342 prefectural-level units. *Geographical Research*, 36(4): 731–742. (in Chinese)

Zhang K F, Thé J, Xie G Y et al., 2020. Multi-step ahead forecasting of regional air quality using spatial-temporal deep neural networks: a case study of Huaihai Economic Zone. *Journal of Cleaner Production*, 277: 123231. doi: 10.1016/j.jclepro.2020.123231

Zhang Y, Li X B, Song W et al., 2016. Land abandonment under rural restructuring in China explained from a cost-benefit perspective. *Journal of Rural Studies*, 47: 524–532. doi: 10.1016/j.jrurstud.2016.06.019

Zhang Yumei, Li Zhiqiang, Li Zhemin et al., 2012. China grains demand forecast analysis based on China economy-wide multi-market model. *Food and Nutrition in China*, 18(2): 40–45. (in Chinese)