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SPATIOTEMPORAL EVOLUTION OF CULTIVATED LAND PATTERN AND MULTIDIMENSIONAL DRIVING FORCE MECHANISM IN HEILONGJIANG PROVINCE

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Abstract: To deeply explore the dynamics of cultivated land use and its driving mechanism in Heilongjiang Province, a major grain-producing area in China, this study systematically reveals the spatiotemporal evolution characteristics of the cultivated land pattern in the study area over the past 20 years based on three phases of remote sensing of land use monitoring data (2000, 2010, and 2020) using methods such as land use transfer matrix and spatial analysis. On this basis, a driving force index system including natural factors (elevation, slope, precipitation, farmland production potential) and socioeconomic factors (population density, night-time light) was constructed. The Geographical Detector model was used to quantitatively examine explanatory capacity and interactive effects of each driving driver affecting the spatial heterogeneity of cultivated land changes in two time cross-sections (2000 and 2020). The research aims to clarify the evolution path of the cultivated land utilization pattern and its multidimensional driving force mechanism in Heilongjiang Province, providing a scientific basis for cultivated land protection, regional territorial space optimization, and the implementation of the national food security strategy.
Keywords: Cultivated land pattern; Land use transfer; Driving forces; Geographical detector; Heilongjiang province

1 INTRODUCTION

Land Use/Cover Change (LUCC) is a significant manifestation of human activities affecting the ecological environment and a key research agenda in global environmental change research [1,2]. Cultivated land is an important foundation for food production and a key resource for ensuring national food security and maintaining ecological balance. Against the backdrop of global climate change, continuous population growth, and increasingly severe resource and environmental constraints, how to achieve stable quantity and improved arable land quality has become one of the core issues of global sustainable development. For China, a country with a huge population, ensuring the stability and improvement of food production capacity is an important pillar of national security and social stability. Systematically identifying changes in cultivated land and their driving mechanisms not only helps optimize territorial spatial layout and improve land use efficiency but also has important strategic value for building a national food security guarantee system. As one among the world’s principal black soil zones, Heilongjiang Province possesses unique cultivated land resources and high soil fertility, making it China's most important major grain-producing area and commodity grain base. Its grain output has ranked first in the country for many consecutive years, accounting for more than a quarter of the national total output. The commodity grain and grain transfer volumes account for about one-third and 40% of the national total, respectively, serving as a core underpinning for protecting national food security and boosting sustainable agricultural progress. However, amid the rapid advancement of industrialization and urbanization, Tilled terrain use in Heilongjiang Province is facing increasingly severe pressures. On the one hand, the non-agricultural conversion of cultivated land caused by the expansion of construction land persists, leading to a reduction in high-quality cultivated land resources. On the other hand, the non-grain production trend brought about by agricultural structure adjustment and the problem of black soil degradation caused by long-term intensive use have become increasingly prominent, including thinning soil layers, decreasing organic matter content, and intensified soil erosion, which restrict regional sustainable agricultural development and comprehensive grain production capacity. In this context, systematically analyzing the spatiotemporal evolution characteristics of the Tilled soil pattern in Heilongjiang Province over the past 20 years and identifying its main driving mechanisms are of great practical significance for deepening the understanding of land use processes, promoting high-quality regional agricultural development, and implementing the national food security strategy.

Domestic and foreign research on the evolution of cultivated land patterns and their driving forces has formed a relatively systematic theoretical and methodological system. Early studies mainly focused on the quantitative analysis alterations in the quantum and composition of arable land, often using methods such as land use dynamic degree and land use transfer matrix to evaluate the rate of cultivated land change and the type conversion relationship. As Remote Sensing (RS) and Geographic Information System (GIS) technologies advance, research has gradually expanded to the spatial dimension. The gravity center migration model has been used to analyze the spatial movement direction and change trend of cultivated land, and landscape pattern indices such as patch density, edge density, and shape index have been widely applied to characterize the degree of fragmentation, aggregation characteristics, and morphological complexity of Tilled terrain, thereby revealing the dynamic evolution process of the cultivated land spatial pattern. The research paradigm of driving forces has undergone a transformation from qualitative analysis to quantitative modeling. Traditional statistical models, such as multiple linear regression and Logistic regression, have certain advantages in exploring the significance and direction of impact of driving factors, but they are difficult to effectively address the problems of multicollinearity and spatial autocorrelation among independent variables. To this end, researchers have introduced spatial dynamic simulation methods such as the CLUE-S model and cellular automata model to simulate the land use change process and predict future trends. In recent years, the Geographical Detector model has been widely used in the analysis of driving forces of land use change due to its advantages of no linear assumption, ability to handle type variables, and overcoming multicollinearity. By analyzing spatial stratified heterogeneity, this model quantitatively evaluates Each factor's capacity to elucidate the spatial disparities in geographical occurrences. and can identify the type and intensity of interactive effects among different driving factors, thus providing an effective means to reveal the multi-factor action mechanism of complex land systems.

Based on this, This investigation focuses on Heilongjiang Province. as the research area, aiming to systematically reveal the spatiotemporal evolution characteristics of the cultivated land pattern from 2000 to 2020 and quantitatively identify its dominant driving factors and interactive mechanisms. The main research contents include: (1) Using RS and GIS technologies to extract the spatial distribution information of cultivated land in 2000, 2010, and 2020, analyze the characteristics of Fluctuations in the extent of cultivated land, construct two phases of land use transfer matrices (2000-2010 and 2010-2020), and analyze the main transfer-in sources and transfer-out directions of cultivated land; (2) Using the factor detector of the Geographical Detector to quantitatively evaluate the explanatory power of natural and socioeconomic factors on the spatial differentiation of cultivated land; (3) Analyzing the type and intensity of interactive effects among different driving factors through the interaction detector, and revealing the comprehensive impact mechanism of multi-factor coupling on the evolution of the cultivated land pattern. This study aims to deepen the understanding of the spatiotemporal evolution laws and driving processes of cultivated land in Heilongjiang Province, providing a scientific basis and technical support for the optimal allocation of regional land resources, cultivated land protection, and the formulation of national food security policies.

2 COMPREHENSIVE OVERVIEW OF RESEARCH DOMAIN & INFO REPOSITORIES

2.1 Comprehensive Survey of the Research Region

Located in northeastern China, Heilongjiang Province has complex landforms, known as "five parts mountains, one part water, one part grass, and three parts farmland". The Sanjiang Plain and Songnen Plain are distributed in the northeastern and western parts, with fertile soil, abundant water resources, and synchronized rain and heat in summer, resulting in a high grain self-sufficiency rate and strong commodity grain output capacity. In 2023, The aggregate grain yield amounted to a substantial 155.76 billion kilograms., accounting for 11.2% of the national total grain output, ranking first in the country for 14 consecutive years, and achieving a bumper harvest for 20 consecutive years [3]. As the province with the largest cultivated land area in China, Heilongjiang Province serves as a pivotal commodity grain hub and stands out as a leading producer of rice., soybeans, and corn, with rich black soil resources and a solid agricultural foundation [4]. In 2018, grain production in Heilongjiang Province achieved a "15-year consecutive bumper harvest", with a total output reaching 7.5×10^11 kg. The total output, commodity volume, and transfer volume all ranked first in the country [5,6], making tremendous contributions to ensuring national food security. However, long-term intensive development has made the region face the dual pressures of black soil resource degradation and ecological environment protection.

2.2 Data Sources

The dataset employed in this research primarily encompasses land utilization resources., natural factor data, socio-economic factor data, and basic geographic data. Land utilization data is primarily sourced Derived from the China Land Cover Dataset (CLCD), which is based on Landsat series satellite imagery (TM/ETM+/OLI) and constructed using a random forest classification algorithm. The spatial resolution is 30 meters, with temporal coverage spanning 2000,2010, and 2020. The classification system includes categories such as arable land, forest land, grassland, water bodies, construction land, and bare land, demonstrating high classification accuracy.

Table 1 Data Source

Data Source	Data Name	Spatial Resolution	Data Description
Geospatial Data Cloud (SRTM)(http://www.gscloud.cn/)	China Land Cover Dataset (CLCD)	30m	-
Geospatial Data Cloud (SRTM)(http://www.gscloud.cn/)	elevation	90m	Extract topographic relief features
Calculated based on SRTMDEM	Slope	90m	Characterize topographic impact

Data Source	Data Name	Spatial Resolution	Data Description
NOAANCEI meteorological station data (https://www.ncei.nou.gov)	precipitation interpolation results	approximately 1km	Characterize climate humidity features
Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn/n)	Farmland production potential	1km	Characterize natural productivity level of cultivated land
WorkdPop dataset (https://www.worldpop.org)	Population	1km	Reflect population distribution density
2000: DMSP/OLS 2022: NPP/VHIRS	Nighttime lighting	approximately 1km	Characterize human activity intensity and urbanization level
TiantuMap (https://www.tianditu.gov.cn/)	administrative boundary	-	for the scope of the study area

Natural factor data include four categories: elevation, slope, precipitation, and farmland production potential. Among them, elevation data (DEM) are sourced from SRTM data provided by The Geospatial Data Cloud, boasting a spatial resolution of 90 meters,; slope data are calculated using ArcGIS spatial analysis tools based on DEM; precipitation data are sourced from meteorological station data of The National Oceanic and Atmospheric Administration (NOAA) of the United States of America, and spatially continuous precipitation distribution maps are generated using Kriging interpolation; The data on farmland production potential are sourced from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences. This data comprehensively considers the impact of natural Elements such as illumination, temperature, water, and soil on crop yield to reflect the natural productivity level of cultivated land. Socioeconomic factor data include population and night-time light. Population figures are derived from the WorldPop database, boasting a spatial resolution of one kilometer., selecting two phases (2000 and 2020) to characterize population distribution and density. For night-time light data, DMSP/OLS stable night-time light images are used for 2000, utilizing NPP/VIIRS night-time light imagery for the year 2020. To ensure the comparability of the two phases of data, correction, denoising, and saturation correction processes are performed to reflect the intensity of human activities and urbanization level. In addition, indicators such as county-level GDP, total agricultural mechanization power, and urbanization rate from statistical yearbooks are integrated and spatially processed. To meet the requirements of model operation, all continuous variables are resampled to a 1km grid and discretized into 5 levels using the natural breaks method.

3 RESEARCH METHODS

3.1 Analysis of the Evolution of Cultivated Land Use Pattern

The land use transfer matrix serves as an esteemed approach for methodically assessing shifts in the composition and flow of regional land utilization patterns. It meticulously and thoroughly illustrates the magnitude and trend of interconversion among diverse land categories over the course of the study period. By constructing transfer matrices for two periods (2000-2010 and 2010-2020), the transfer-in sources (i.e., which land types are converted to cultivated land) and transfer-out directions (i.e., which land types cultivated land is converted to) of cultivated land in Heilongjiang Province can be clearly revealed, thereby providing a quantitative basis for understanding the specific process of dynamic changes in cultivated land.

3.2 Geographical Detector

This research primarily employs the stratified differentiation factor analyzer and interaction analyzer to conduct a quantitative examination of the driving forces behind the spatiotemporal dynamics of cultivated land utilization in Heilongjiang Province, as well as the interplay between these influencing elements. [7]. The Geographical Detector serves as a robust statistical technique designed to discern the spatial disparities among geographical entities and unravel the underlying factors that drive these variations, which is extensively utilized in the exploration of ecological and environmental transformations, as well as in the study of socioeconomic progression[8-10]. The specific model is as follows:

$$q=1-\frac{\sum_{i=1}^{L} N_i \sigma_i^2}{N\sigma^2}=1-\frac{SSW}{SST} \tag{1}$$

$$SSW=\sum_{i=1}^{L} N_i \sigma_i^2, \quad SST=N\sigma^2 \tag{2}$$

In the given equations, SSW represents the aggregate of intralayer variances, while SST denotes the comprehensive variance across the entire domain. L signifies the categorization of variable Y or factor X.; Nh is the number of units in layer h, and N is the number of units in the entire region; σ is the variance of Y values in layer h, and σ^2 is the variance

of Y values in the entire region. The range of q is [0,1]. A higher q value signifies a more pronounced spatial differentiation in the transition of cultivated land Y. Should the categorization be attributed to factor X, an elevated q value points to a greater capacity of factor X to elucidate the characteristic Y of cultivated land change, and conversely.
This research employs the Geographical Detector model to quantitatively assess the impact of various driving factors on the spatial variability of the cultivated land pattern, as well as to explore their interplay. According to the model requirements, the dependent variable (Y) needs to be a numerical type, and the independent variables (X) need to be type or categorical variables. This study selects the spatial distribution of cultivated land in two years (2000 and 2020) as the dependent variable and processes it into a binary variable based on 1 km grid units: if the sampling point in the grid falls within the cultivated land patch, it is assigned a value of 1, otherwise 0. Based on data availability and relevance to the research theme, this study constructs a driving factor index system including 6 factors in two categories (natural and socioeconomic): natural factors include X1 (elevation), X2 (slope), X3 (annual average precipitation), and X4 (farmland production potential); socioeconomic factors include X5 (population density) and X6 (night-time light intensity). To meet the model requirements, continuous independent variable data such as elevation and slope need to be discretized into type variables. This study adopts the natural breaks method, which can minimize within-group differences and maximize between-group differences, thereby better reflecting the natural clustering characteristics of the data. Each continuous variable is divided into 5 levels.

4 RESULTS

4.1 Spatiotemporal Pattern Evolution of Cultivated Land in Heilongjiang Province

4.1.1 Spatiotemporal change characteristics

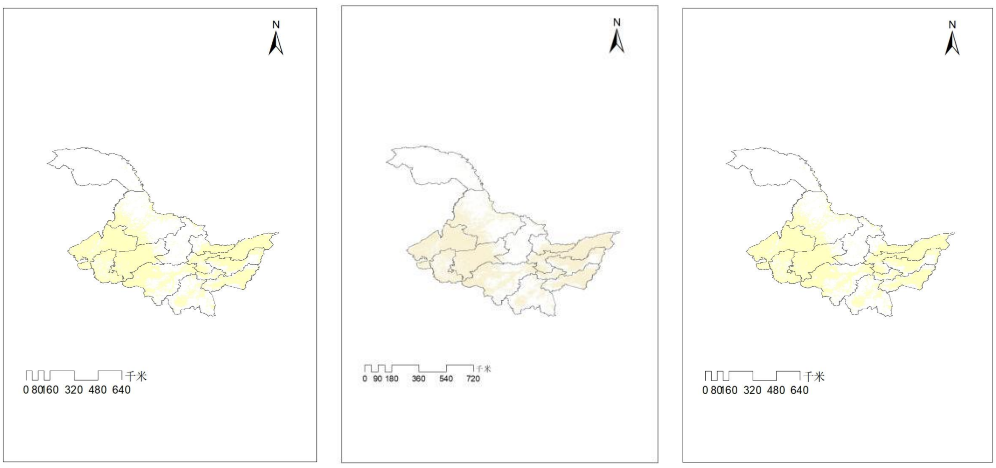

Figure 1 Spatiotemporal Change Characteristics of Cultivated Land in Heilongjiang Province from 2000 to 2020

As shown in Figure 1, drawn by ArcGIS, from the spatiotemporal change characteristics of the three phases of cultivated land spatial distribution maps in Heilongjiang Province (2000, 2010, and 2020), over the past 20 years, the spatial scope and distribution form of cultivated land in the province have shown obvious dynamic evolution. The spatial distribution of prime agricultural land within the central region has maintained a consistent pattern, whereas the boundaries of cultivated land at the periphery have experienced periodic expansions and contractions in their delineation, showing an overall spatiotemporal change law of "stable core and active edge".

4.1.2 Spatial distribution characteristics

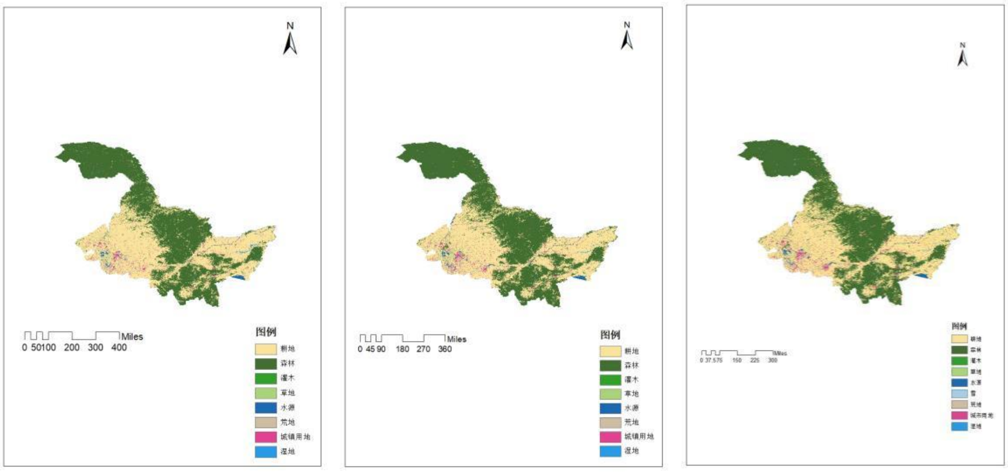

Figure 2 Changes in the Spatial Distribution Characteristics of Cultivated Land in Heilongjiang Province from 2000 to 2020

As shown in Figure 2, Rendered by ArcGIS, the spatial dispersion of cultivated land across Heilongjiang Province from 2000 to 2020 exhibits a pattern marked by "central concentration and peripheral oscillation." In the heartland of agriculture, such as the Songnen and Sanjiang Plains, the cultivated land has historically been densely packed, maintaining a consistent expanse. Conversely, at the province's periphery, particularly in mountainous regions and forest-grass transition zones, the cultivated land has undergone periodic fluctuations of expansion and retraction. This overarching spatial configuration not only sustains the agrarian edge of the central grain-growing regions but also manifests the adaptability in land utilization at the margins.

4.1.3 Analysis of cultivated land use transfer

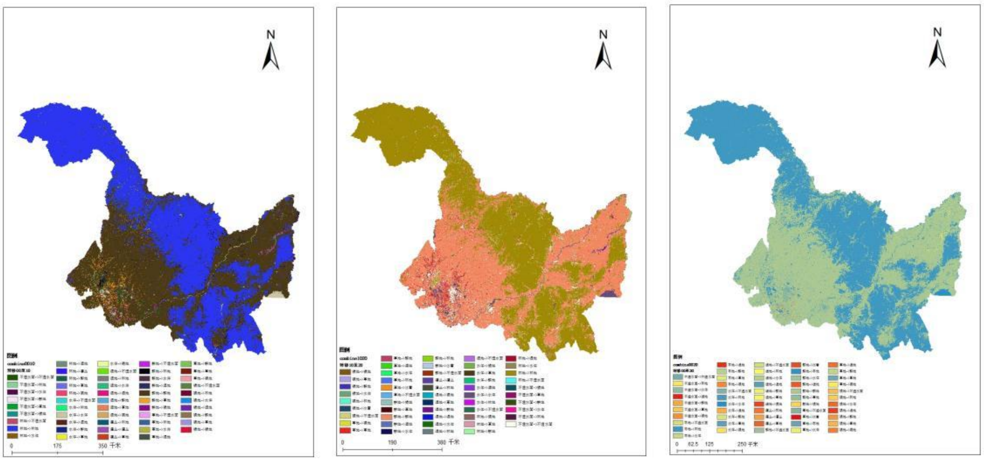

Figure 3 Analysis of Cultivated Land Use Transfer in Heilongjiang Province from 2000 to 2010, 2010 to 2020, and 2000 to 2020

As shown in Figure 3, Rendered by ArcGIS, the dynamics of cultivated land use in Heilongjiang Province between 2000 and 2020 are marked by a "bidirectional flux and categorical diversification." During the initial decade from 2000 to 2010, there was extensive interconversion among cultivated land, forestland, and grassland. This period witnessed, on one hand, the conversion of some forest and grassland into cultivated fields, indicative of the critical need for enhanced grain production at the time; conversely, the Grain for Green initiative led to the transformation of certain substandard cultivated areas into ecological lands. As the decade of 2010 to 2020 commenced, the pace of urbanization hastened, leading to a notable rise in the conversion of cultivated land into construction land. This trend was particularly pronounced in the vicinity of urban centers like Harbin and Daqing, where the encroachment upon prime cultivated land was especially evident. In sum, the trajectory of cultivated land distribution has shifted from a phase dominated by natural ecological interactions—primarily between agriculture, forestry, and grassland—to one characterized by construction encroachment and structural changes driven by socioeconomic factors.

4.2 Analysis of Driving Forces for the Evolution of Cultivated Land Pattern

4.2.1 Detection of spatial differentiation of driving factors and differences in their explanatory power

Drawing on the findings from the Geographical Detector, the degree of influence that geographical factors exert on the spatial variability of cultivated land in Heilongjiang Province has been quantitatively assessed. Analyzing the statistical outcomes, it is observed that there exists a pronounced hierarchy in the explanatory prowess (q-value) of each contributing factor regarding the distribution of cultivated land, with the influence ranking as follows: farmland production potential (0.1546) > slope (0.0901) > precipitation (0.0645) > elevation (0.0487). The farmland production potential stands out with the highest q-value, successfully passing the 1% significance level test ($p<0.01$), suggesting that the composite natural attributes represented by this indicator—encompassing light, temperature, water, and soil—are pivotal in dictating the spatial configuration of cultivated land in the region, fundamentally shaping its macro distribution. Following as the predominant contributory element, the slope exhibits exceptional statistical significance ($p<0.01$), aligning closely with Heilongjiang Province's characteristics as a vast plain dedicated to agricultural production, and highlighting the direct impact of topography on agricultural mechanization and soil and water conservation efforts. Conversely, the explanatory strength of precipitation and elevation factors is relatively subdued, failing to meet the 0.05 significance threshold in univariate statistical analysis. This indicates that, at the provincial macro scale, altitude or precipitation alone are not adequate to account for the intricate patterns of cultivated land distribution, with their influences typically realized through synergistic interactions with other environmental gradients.

4.2.2 Multi-factor interaction and synergistic driving mechanism

The analysis results of the interaction detector further confirm that the evolution of the cultivated land use pattern in Heilongjiang Province is driven by the complex coupling of multiple natural factors, rather than the linear superposition of a single factor. The explanatory power (q-value) after the interaction of any two driving factors is significantly better than that of a single factor, showing a significant "two-factor enhancement" or "nonlinear enhancement" effect, revealing the integrity and synergy of the natural geographical system. Specifically, the interaction explanatory power between farmland production potential and slope is the strongest ($q=0.2466$), which is close to the sum of the single powers of the two factors, indicating that the matching of high-production potential soil and suitable terrain is the core driving force for the aggregation of cultivated land. More importantly, although the single-factor explanatory power of the precipitation factor is weak ($q=0.0645$), its q-value after interaction with slope jumps to 0.2094, which is significantly greater than the sum of the q-values of the two factors, showing a strong nonlinear enhancement effect. This finding profoundly clarifies the coupling mechanism of water and soil elements: the effectiveness of precipitation resources is significantly regulated by terrain slope, and their synergistic effect greatly improves the explanatory power for the spatial distribution of cultivated land. In addition, the interaction results between farmland production potential and precipitation ($q=0.2199$) and between farmland production potential and elevation ($q=0.2191$) also show high explanatory levels, further confirming that the environmental combination of multi-factor synergy optimization is the key foundation for the formation of high-quality cultivated land in Heilongjiang Province.

4.2.3 Suitability intervals and risk detection of cultivated land distribution

By analyzing the average value of cultivated land distribution under different factor classifications, the risk detector accurately identified the optimal environmental suitability intervals conducive to the aggregation of Tilled terrain. The statistical findings indicate that the allocation of cultivated land exhibits distinct threshold impacts and selective preferences across diverse influencing factors, with variations between different categories being statistically significant as evidenced by the t-test. In terms of farmland production potential, the average value of cultivated land distribution in the 2nd partition is the highest, and the medium and high-grade production potential areas are the main bearing spaces for cultivated land, reflecting the dependence of agricultural development on the natural background. Among the precipitation factors, the 1st partition shows an extremely high degree of cultivated land aggregation, which is significantly different from other precipitation gradients, indicating the absolute leading role of specific humid climate zones in the distribution of cultivated land. In terms of topographic factors, the 5th partition of the slope factor and the 4th partition of the elevation factor are the dominant distribution intervals in their respective dimensions. This nonlinear distribution characteristic reflects the adaptive choice of human activities within a specific range of altitude and slope. Overall, the cultivated land in Heilongjiang Province is not randomly distributed but highly aggregated in specific environmental combination intervals with high farmland production potential, abundant hydrothermal conditions, and suitable terrain. This distinctive feature of spatial concentration is a consequence of the interplay between the inflexible confines of the natural setting and the strategic adaptions made throughout the extensive history of agricultural progress.

5 CONCLUSION AND DISCUSSION

While this investigation has yielded significant insights, it is not without its constraints, which warrant further exploration in subsequent studies. The 1km resolution data used in this study can effectively reveal the pattern and driving forces at the macro scale, but may not capture more detailed changes at the micro scale, such as rural residential land consolidation and the occupation of facility agriculture. In the future, higher-resolution remote sensing images can be used for more detailed analysis. At the same time, the index system selected in this study mainly covers natural and socioeconomic factors, but fails to effectively quantify important driving factors such as policies, technologies, and transportation accessibility. For example, policies such as the Grain for Green project and agricultural subsidy policies have a direct and profound impact on changes in cultivated land, but it is challenging to spatialize them and incorporate them into the Geographical Detector model. The Geographical Detector model has significant advantages in revealing spatial heterogeneity and driving mechanisms of ecosystem services.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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