

Spatiotemporal patterns and drivers of cultivated land conversion in Inner Mongolia Autonomous Region, northern China (Postprint)

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Abstract

Protection and optimization of cultivated land resources are of great significance to national food security. Cultivated land conversion in northern China has increased in recent years due to the industrialization and urbanization of society. However, the assessment of cultivated land conversion in this area is insufficient, posing a potential risk to cultivated land resources. This study evaluated the evolution and spatiotemporal patterns of cultivated land conversion in Inner Mongolia Autonomous Region, China, and the driving factors to improve rational utilization and to protect cultivated land resources. The spatiotemporal patterns of cultivated land conversion in Inner Mongolia were analyzed using the cultivated land conversion index, kernel density analysis, a standard deviation ellipse model, and a geographic detector. Results showed that from 2000 to 2020, the trends in cultivated land conversion area and rate in Inner Mongolia exhibited fluctuating growth, with the total area of cultivated land conversion reaching 7307.59 km² at a rate of 6.69%. Spatial distribution of cultivated land conversion was primarily concentrated in the Hetao Plain, Nengjiang Plain, Liaohe Plain, and the Hohhot-Baotou-Ordos urban agglomeration. Moreover, the standard deviational ellipse of cultivated land conversion in Inner Mongolia exhibited a directional southwest-northeast-southwest-northeast distribution, with the northeast-southwest direction identified as the main driving force of spatial change in cultivated land conversion. Meanwhile, cultivated land conversion exhibited an increase-decrease-increase change process, indicating that spatial distribution of cultivated land conversion in Inner Mongolia became gradually apparent within the study period. The geographic detector results further revealed that the main driving factors of cultivated land conversion in Inner Mongolia were the share of secondary and tertiary industries and per-unit area yield of grain, with explanatory rates of 57.00%, 55.00%, and 51.00%, respectively. Additionally, improved agricultural production efficiency and the coordinated development of population urbanization and industry resulted in

cultivated land conversion. Collectively, the findings of this study indicated that, from 2000 to 2020, the cultivated land conversion in Inner Mongolia was significant and fluctuated in time, and had strong spatial heterogeneity. The primary drivers of these events included the effects of agriculture, population, and social economy.

Full Text

Preamble

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Spatiotemporal Patterns and Drivers of Cultivated Land Conversion in Inner Mongolia Autonomous Region, Northern China

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Abstract

Protection and optimization of cultivated land resources are of great significance to national food security. Cultivated land conversion in northern China has increased in recent years due to industrialization and urbanization. However, assessment of cultivated land conversion in this area remains insufficient, posing potential risks to cultivated land resources. This study evaluated the evolution and spatiotemporal patterns of cultivated land conversion in Inner Mongolia Autonomous Region, China, and identified the driving factors to improve rational utilization and protect cultivated land resources. The spatiotemporal patterns were analyzed using the cultivated land conversion index, kernel density analysis, standard deviation ellipse model, and geographic detector. Results showed that from 2000 to 2020, both the area and rate of cultivated land conversion in Inner Mongolia exhibited fluctuating growth, with the total conversion area reaching 7307.59 km² at a rate of 6.69%. Spatially, conversion was primarily concentrated in the Hetao Plain, Nenjiang Plain, Liaohe Plain, and the Hohhot-Baotou-Ordos urban agglomeration. Moreover, the standard deviation ellipse exhibited a directional southwest-northeast-southwest-northeast distribution, with the northeast-southwest direction identified as the main driving force of spatial change in cultivated land conversion. Meanwhile, cultivated land conversion followed an increase-decrease-increase pattern, indicating that its spatial distribution became gradually more apparent during the study period. Geographic detector results further revealed that the main driving factors were the share of secondary and tertiary industries and per-unit area grain yield,

with explanatory rates of 57.00%, 55.00%, and 51.00%, respectively. Additionally, improved agricultural production efficiency and coordinated development of population urbanization and industry contributed to cultivated land conversion. Collectively, these findings indicate that from 2000 to 2020, cultivated land conversion in Inner Mongolia was significant and fluctuated temporally while showing strong spatial heterogeneity. The primary drivers included the effects of agriculture, population, and socioeconomic development.

Keywords: cultivated land conversion; spatiotemporal variation; standard deviation elliptical models; geographic detector; northern China

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1 Introduction

All human activities depend upon land resources to meet the needs of a growing population, among which farmland resources are the most valuable (Herzberger et al., 2019). Cultivated land serves as the carrier of grain production and the foundation of national economic development, bearing considerable responsibility for national food, ecological, and social security (Zhou et al., 2021). The basis for ensuring grain production capacity is maintaining a certain amount and quality of cultivated land while reducing the external diseconomies of cultivated land conversion (Li et al., 2022a; Sun et al., 2023).

China is responsible for feeding about 20.00% of the global population but possesses less than 7.00% of global farmland (Cui and Shoemaker, 2018; Qin et al., 2022). During the 21st century, China experienced rapid economic development, resulting in accelerated urbanization, industrialization, and expansion of non-agricultural land and construction. Agricultural land decreased correspondingly, with remarkable reductions in cultivated land severely threatening China's social, economic, and ecological security (Wu et al., 2017, 2022). In particular, the use of high-quality cultivated lands for non-agricultural construction has resulted in cultivated land conversion (Wang and Cheng, 2022). Therefore, research examining cultivated land conversion is critical for designing effective

strategies to protect farmland resources in China (Zhao and Pu, 2007; Wu et al., 2022).

Recent studies have focused on the relationship between cultivated land use change and economic growth (Xu, 2010; Song, 2017; Huo et al., 2022; Zhang et al., 2023), the impact of cultivated land use change on the agro-socio-ecological environment and its driving mechanisms (Wang, 2012; Yue et al., 2015; Huang et al., 2021), and optimal resource allocation during cultivated land use change (Ye, 2015; Zhou et al., 2020). Zhang et al. (2023) explored changing patterns of climatic factors and land suitability, revealing that croplands in high-latitude countries of the northern hemisphere are more likely to benefit from climate change, whereas mid- and low-latitude countries face higher risks of potential cropland loss. Meanwhile, Kiani (2016) quantified the effects of land management and cropland conversion on soil physical and biological properties, providing insights regarding best management practices to potentially reverse declining soil quality trends (Wu et al., 2022). Li et al. (2022a) evaluated cultivated land resources in Heilongjiang Province, northern China, observing that distribution characteristics of cultivated land conversion differed among cities of different grades and periods, with associated spatial diffusion paths varying over time. To verify the main driving factors of cultivated land conversion in Jilin Province and propose reasonable countermeasures, Xu et al. (2020) selected economic, societal, and policy mechanism indicators for empirical analysis, observing that total investment in fixed assets, comparative return on land, and urbanization level significantly impact changes in cultivated land area in Jilin Province. However, these studies focused primarily on conversion of cropland to other agricultural land types such as grassland, woodland, gardens, and other agricultural uses, as well as effects on soil cover and climate change. Considering that the economic value of development and construction land in China is markedly higher than that of farmers' cultivated land, the phenomenon of cultivated land conversion continues to be prevalent despite institutional restrictions to ensure food security. Accordingly, research on conversion of cultivated land to construction land remains a critical research focus.

Cultivated land conversion is the process of converting cropland into non-agricultural construction land. The transfer of cultivated land from the agricultural sector to the non-agricultural sector provides spatial support for urbanization and plays an increasingly vital role in economic growth. However, cultivated land conversion has caused considerable loss of farmland resources in China, ultimately resulting in human-land contradictions, including food security concerns and ecological environment degradation (Tan et al., 2004; Zhang et al., 2020).

Provincial and national-scale research related to cultivated land conversion is predominantly concentrated in South, Central, and Northeast China, as well as other economically developed areas. Consequently, systematic research investigating cultivated land conversion in economically underdeveloped areas is lacking. In particular, the northern dryland area constitutes a major portion

of Chinese agricultural land. This is a key area supported by the state for poverty alleviation and ecological security maintenance, playing a pivotal role in China's national economic development (Aodenggaowa, 2008). Hence, considering the severe ecological damage, natural disasters, and economic backwardness in northern China, clarifying the spatiotemporal characteristics of cultivated land conversion in northern China and its driving factors is of particular importance (Zhang et al., 2022).

To help address the contradiction between cultivated land conversion and socioeconomic development, this study seeks to provide a reference for effectively limiting the amount of cultivated land conversion and realizing the protection and sustainable development of cultivated land in northern China. Thus, taking Inner Mongolia Autonomous Region as the study subject, we constructed a cultivated land conversion index to analyze its spatiotemporal patterns and identify the driving factors of cultivated land conversion using kernel density analysis, standard deviation ellipse model, and geographic detector.

2.1 Study Area

The study area is located in Inner Mongolia ($37^{\circ}24' - 53^{\circ}23' \text{ N}$, $97^{\circ}12' - 126^{\circ}04' \text{ E}$), northern China, featuring the Yinshan Mountains extending east to west, the Da Hinggan Ling Mountains from northeast to southwest, and the Helan Mountains from north to south. The topography of Inner Mongolia is a high-plateau geomorphological area that includes the Inner Mongolia Plateau in the northwest, Nenjiang Plain in the southeast, Liaohe River Plain in the west, Hetao Plain in the middle, and prairie along the northwestern edge (Hao, 2014). Inner Mongolia is located in the interior of Eurasia and possesses a typical continental climate, spanning 4200 km from east to west. Basic conditions such as water and heat differ significantly, with land and cultivated land resources exhibiting apparent regional differences (Yang et al., 2022).

In 2020, Inner Mongolia had a resident population of 24.00×10^6 with an urbanization rate of 67.40%. Meanwhile, the GDP output value reached 173.60×10^9 CNY, with the primary industry contributing 202.51×10^9 CNY, the secondary industry contributing 686.80×10^9 CNY, and the tertiary industry contributing 846.67×10^9 CNY. Annual investment in fixed assets of the entire society decreased by 1.70% compared with the previous year, and the general public budget was 205.13×10^9 CNY. The general public budget expenditure was 526.82×10^9 CNY. Additionally, farmland accounted for 11.50×10^6 hm^2 , representing an increase of 1153.33 hm^2 from 2019. Paddy fields accounted for approximately 1.40%, irrigated land for 48.13%, and dry land for 50.47%. The total sown area of crops for 2019 and 2020 was 8.88×10^6 hm^2 , of which 6.83×10^6 hm^2 were sown with grain crops, yielding 36.64×10^6 t.

2.2 Data Sources

This study used land use data with a resolution of 30 m from the Resource and Environment Data Centre of the Chinese Academy of Sciences (<https://www.resdc.cn/>) for the years 2000, 2005, 2010, 2015, and 2020. Additionally, administrative boundary vector maps with leagues and cities were used as spatial units. The data were imported into ArcGIS v.10.3 software, and extraction and spatial overlay analysis provided data regarding the cultivated land of each league and city and the conversion of cultivated land in different periods in Inner Mongolia. Data pertaining to cultivated land area, total investment in fixed assets, local government revenue, and general public revenue were derived from the Natural Resources Bureau of Hohhot City and the Finance Bureau for each banner/county and district, whereas other statistical data were selected from the Inner Mongolia Statistical Yearbook and the Hohhot City Statistical Yearbook for 2000–2020.

3.1 Cultivated Land Conversion Index

The index of cultivated land conversion (Liu et al., 2020) was used to measure the level of cultivated land conversion in each banner/county using the relative values of cultivated land conversion area in actual farmland area. The formula for calculating the cultivated land conversion index is represented by Equation 1:

$$P_i = \frac{F_i}{S_i}$$

where P_i is the cultivated-land conversion index of league i ; F_i is the cultivated-land conversion area of league i (hm^2); and S_i is the cultivated land area of league i (hm^2). Based on calculation results for the cultivated land conversion index, the spatial distribution pattern for cultivated land conversion in Inner Mongolia was divided into six categories.

3.2 Kernel Density Estimation Method

Kernel density is a method widely used in empirical analysis of aggregation. It predominantly estimates the density of point or line patterns with the help of a moving cell, which can effectively capture the objective reality of data distribution to describe spatial distribution characteristics (Li et al., 2020). According to this principle, we analyzed the spatial aggregation characteristics of cultivated land conversion using ArcGIS v.10.3 to explore the distribution and change characteristics of hotspots in the spatial patterns of the study area. Kernel density ($P(x_i)$) is calculated by Equation 2:

$$P(x_i) = \frac{1}{nh} \sum_{j=1}^n K\left(\frac{x_i - x_j}{h}\right)$$

where n is the number of data points; h is the bandwidth; K is the kernel function; and $x_i - x_j$ is the distance from the measured point x_i to the sample point x_j .

3.3 Standard Deviation Ellipse

Standard deviation ellipse is a model used to accurately reveal the changing process and direction of spatial distribution of various geographic elements and to quantitatively explain the characteristics of centrality, spreading direction, and spatial pattern in the study area (Lin and Hui, 2022; Gai et al., 2023). The formulas that calculate the average center coordinates are represented by Equations 3 and 4:

$$SDE_x = \frac{\sum_{i=1}^n x_i}{n}$$

$$SDE_y = \frac{\sum_{i=1}^n y_i}{n}$$

where SDE_x and SDE_y are the centers of the standard deviation ellipse; x_i and y_i are the coordinates of sequence point i ; and \bar{X} and \bar{Y} are the average centers of all sequence points.

The direction of the ellipse was determined by Equation 5:

$$\tan \theta = \frac{\sum_{i=1}^n (x_i - \bar{X})^2 - \sum_{i=1}^n (y_i - \bar{Y})^2 + \sqrt{(\sum_{i=1}^n (x_i - \bar{X})^2 - \sum_{i=1}^n (y_i - \bar{Y})^2)^2 + 4(\sum_{i=1}^n (x_i - \bar{X})(y_i - \bar{Y}))^2}}{2 \sum_{i=1}^n (x_i - \bar{X})(y_i - \bar{Y})}$$

where θ is the azimuth angle of the standard deviation ellipse. The X-axis standard deviation and Y-axis standard deviation were calculated by Equations 6 and 7:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^n ((x_i - \bar{X}) \cos \theta - (y_i - \bar{Y}) \sin \theta)^2}{n}}$$

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^n ((x_i - \bar{X}) \sin \theta + (y_i - \bar{Y}) \cos \theta)^2}{n}}$$

where σ_x and σ_y are the standard deviations along the long and short axes, respectively.

3.4 Geographic Detector

Geographic detector encompasses a set of statistical methodologies employed to identify spatial differentiation and elucidate underlying causal factors. The fundamental premise is that if an independent variable exerts a significant impact on a dependent variable, their spatial distributions should exhibit similarity. Four types of detection exist: differentiation and factor detection, risk detection, interaction detection, and ecological detection. Differentiation, factor detection, and interaction detection were used to study the degree of influence of selected factors on cultivated land conversion and the interaction between factors (Cheng et al., 2007).

3.4.1 Differentiation and Factor Detection

Differentiation and factor detection were used to investigate the extent to which factor X explains the spatial differentiation of cultivated land conversion Y . When measured by the q -value, the expression is represented by Equation 8:

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

where L is the stratification of variable Y or factor X (classification or partitioning); N_h and N are the number of units in layer h and the entire area, respectively; and σ_h^2 and σ^2 are the variances of Y value of layer h and the entire area, respectively. The range of q -value is from 0.00 to 1.00. A larger q -value indicates that the independent variable X possesses stronger explanatory power for attribute Y , and vice versa. A q -value of 1.00 indicates that factor X completely controls the spatial distribution of Y , while a q -value of 0.00 indicates that factor X exhibits no relationship with factor Y .

3.4.2 Interaction Detector

An interaction detector was used to identify the interaction between different factors X_s and to evaluate whether two factors acting together increase or decrease the explanatory power of dependent variable Y or whether their effects on Y are independent. The method first calculates the q -values of two-factor pairs separately and the q -values when they interact. It then compares $q(X_1)$ and $q(X_2)$ to $q(X_1 \cap X_2)$. The relationships between these two factors can be divided into five categories: bifactor enhancement, independent enhancement, nonlinear enhancement, nonlinear attenuation, and single-factor nonlinear attenuation. The specific research framework is shown in Figure 1 [Figure 1: see original paper].

4.1 Area and Rate Changes in Cultivated Land Conversion

This research used raster data of arable land map spots based on the ArcGIS spatial superposition analysis module to calculate the area and rate of cultivated

land conversion for four periods: 2000–2005, 2005–2010, 2010–2015, and 2015–2020 (Fig. 2 [Figure 2: see original paper]). The cultivated land conversion area in Inner Mongolia from 2000 to 2020 was consistent with the overall trend of conversion rate and exhibited fluctuating growth, with the maximum conversion area (6341.84 km²) and conversion rate (5.51%) occurring from 2015 to 2020. The minimum conversion area (60.84 km²) and conversion rate (0.08%) occurred from 2005 to 2010. From 2000 to 2010, the conversion area and rate in Inner Mongolia slowed, then increased again in 2015, with a conversion area exceeding 500.00 km². From 2015, this trend accelerated and peaked in 2020.

4.2.1 Temporal Changes

With the socioeconomic development of Inner Mongolia, the role of cultivated land conversion is evident under the influence of environmental, policy, and regional strategy factors. Regions with more obvious non-agricultural cultivation of cultivated land often exhibited a high degree of spatial coincidence with urban development areas. Table 1 indicates the area of cultivated land converted from 2000 to 2020 for each league/city in Inner Mongolia. Among the 12 leagues/cities, the largest conversion area occurred in Tongliao City (1847.68 km²), followed by Bayannur (1169.36 km²), Chifeng (870.49 km²), and Hohhot (733.36 km²). The smallest conversion area occurred in Wuhai City (29.21 km²). Conversion areas were primarily concentrated in the eastern agricultural and plantation regions. Increased land for urban infrastructure and industrial, residential, and commercial construction accelerated cultivated land conversion. Although some arable land was converted to unused land due to changes in farming conditions, this exerted minimal effects on the overall extent of farmland conversion. From 2000 to 2005 and 2010 to 2015, conversion occurred primarily in the Hohhot-Baotou-Ordos urban agglomeration, while from 2005 to 2010 and 2015 to 2020, it occurred in the eastern region.

Hence, the pattern of spatiotemporal divergence in cultivated land conversion in Inner Mongolia from 2000 to 2020 was limited by topographical conditions and showed obvious geographical divergence. It was predominantly concentrated in the eastern region and the Hohhot-Baotou-Ordos urban agglomeration, primarily distributed along the Hetao, Nenjiang, and Liaohe plains.

4.2.2 Construction of Cultivated Land Conversion Index

We graded the index of cultivated land conversion in the 12 leagues/cities of Inner Mongolia from 2000 to 2020 based on calculation results (Fig. 3 [Figure 3: see original paper]). There were no heavy or extreme cultivated land conversion areas in any league/city during this period. From 2000 to 2005, 2005 to 2010, and 2010 to 2015, conversion levels in all cities were concentrated in areas with no or low conversion. From 2015 to 2020, Alagxa League and Bayannur City in the Hohhot-Baotou-Ordos urban agglomeration shifted from low to mild conversion areas. Overall, the change in conversion degree exhibited an initial slowing followed by subsequent increase, with an inflection point appearing in

2005. After 2005, the arable land area in Inner Mongolia increased. Due to natural conditions, arable land quality was generally poor, with few areas experiencing conversion. Quality was influenced by rapid economic development, and large-scale construction occupied high-quality farmland, ultimately resulting in cultivated land conversion.

4.2.3 Kernel Density Analysis

Kernel density analysis results reflect the spatial aggregation characteristics of cultivated land conversion (Fig. 4 [Figure 4: see original paper]). Higher kernel density values indicate more concentrated spatial distribution of conversion in the study area. From 2000 to 2005, high-density areas were concentrated near Tongliao City and the Hohhot-Baotou-Ordos urban agglomeration, with a maximum density of 28.30. From 2005 to 2010, fewer plots were converted, with a maximum density of 3.39. From 2010 to 2015, the spatial distribution density exhibited significant change, increasing to 94.86 and concentrating in the Hohhot-Baotou-Ordos urban agglomeration, further intensifying conversion in the region. From 2015 to 2020, cultivated land conversion exhibited a rapid trend, with overall density increasing to 1524.09 and showing spatial dispersion from the Hohhot-Baotou-Ordos urban agglomeration in the early stage to the eastern region. Conversion from 2000 to 2020 was primarily concentrated in the Hohhot-Baotou-Ordos urban agglomeration, the urban core of Inner Mongolia with concentrated population and rapid economic development, ultimately increasing demand for building land. Therefore, the phenomenon of non-agricultural land use has become increasingly prominent.

4.2.4 Standard Deviational Ellipse

The degree of concentration and trends in the spatial distribution of cultivated land conversion in Inner Mongolia were further analyzed using the ArcGIS standard deviational ellipse model. The standard deviational ellipse rotations in the study area were 68.89° , 62.71° , 64.81° , and 70.67° for 2000–2005, 2005–2010, 2010–2015, and 2015–2020, respectively (Fig. 5 [Figure 5: see original paper]; Table 2).

The spatial distribution exhibited an overall directional pattern of southwest-northeast-southwest-northeast, indicating that the main driving force for spatial change was the northeast-southwest direction. The changing pattern in the eastern region and Hohhot-Baotou-Ordos urban agglomeration exerted a strong pulling effect on spatial changes in conversion. During all four periods, there was no change in the center of gravity shift, with all located in Xilin Gol League.

The long and short axes of the standard deviational ellipse changed during the study period. The Y-axis and X-axis increased by 238.48 km and 409.24 km, respectively, from 2000–2005 to 2005–2010. The rotation direction was counterclockwise with a more pronounced angle, indicating expansion from southwest to northeast. Compared with 2005–2010, the Y-axis and

X-axis decreased by 349.83 km and 208.78 km, respectively, from 2010–2015, with clockwise rotation, indicating a spatial pattern shift from northeast to southwest. From 2015–2020, increases of 245.71 km and 145.05 km occurred on the Y-axis and X-axis compared with 2010–2015, with clockwise rotation and a clear angle. The conversion pattern expanded from southwest to northeast. The standard deviational ellipse areas for the four periods were 4.32×10^5 , 5.80×10^5 , 4.28×10^5 , and 6.07×10^5 km², respectively, following an increasing-decreasing-increasing pattern. The elliptical area was largest from 2015–2020, indicating that spatial aggregation of cultivated land conversion was strongest during this period.

4.3 Driving Factors

4.3.1 Factor Detector Analysis

Cultivated land conversion results from a combination of factors. This study focuses on three aspects: economic development factors, agricultural production factors, and social development factors. A total of 11 variables were selected as driving factors of cultivated land conversion. The variation in each driving factor was calculated, and the data were discretized into 5 layers using the natural breakpoint method, with corresponding q -values calculated. The most important drivers were the share of secondary and tertiary industries in GDP and per-unit area grain yield, with explanatory rates of 57.00%, 55.00%, and 51.00%, respectively (Table 3). This indicates a high correlation between cultivated land conversion, economic growth, and agricultural production conditions. From an economic perspective, when an economy reaches a certain development level, industrial structure transformation is reflected by changes in land structure. Increased shares of secondary and tertiary sectors indicated that Inner Mongolia's industrial structure had been effectively adjusted and that new industry development provided numerous employment opportunities. With secondary and tertiary industry development, employment opportunities increased, and the labor force shifted from agriculture to towns, increasing demand for construction land and indirectly affecting the degree of cultivated land conversion. Additionally, progress in agricultural technology, such as grain yield per-unit area and agricultural development, reflects improved intensive utilization of cultivated land. Moreover, improved agricultural technology can greatly enhance cultivated land production capacity and help lessen pressure from economic and social development on cultivated land, thereby reversing impacts on conversion levels. Taken together, grain yield was the endogenous driver of cultivated land conversion in Inner Mongolia from 2000 to 2020, while industry was the direct driver. The combined effects of economy, industry, and agriculture have formed the basic trend of cultivated land conversion in Inner Mongolia.

4.3.2 Interaction Detection

The explanatory power values obtained from interaction detection among the 11 driving factors were greater than those from single influencing factors (Fig.

6 [Figure 6: see original paper]), indicating that interaction between two factors can obtain stronger explanatory power and exert greater impact on conversion levels than any single factor. Two-factor enhancement was the interaction type between several factor pairs, while the interaction type between remaining factors was nonlinear enhancement.

The interactions between urbanization level and GDP per capita, or between urbanization and proportions of secondary and tertiary industries, exhibited the largest q -value ($q = 1.00$; Fig. 6). Therefore, urbanization and industrial proportions played primary roles in determining conversion degree after spatial superposition. Hence, population urbanization and industrial structure transformation have increased demand for housing, public infrastructure, and major industrial land. Moreover, consequent expansion of construction land has ultimately exacerbated cultivated land conversion. Additionally, the q -value for interaction of other factors was generally >0.70 , indicating strong interaction. Cultivated land conversion is the result of combined economic, social, and agricultural factors.

5.1 Spatiotemporal Patterns and Drivers of Cultivated Land Conversion

Previous studies have identified the current status of cultivated land conversion and its associated factors in different areas, such as eastern and central China (Yue et al., 2015; Song, 2017), central Vietnam (Nguyen et al., 2021), the agricultural area of Bangladesh (Quasem, 2011), and northern Argentina (Gasparri et al., 2015). Overall, research on spatiotemporal evolution characteristics and driving factors of cultivated land conversion is relatively comprehensive; however, it mostly focuses on economically developed areas in eastern and central China, while research on cultivated land conversion in northern areas remains lacking. Moreover, many urban districts and counties in northern China have great development potential. With continuous acceleration of urbanization, many cultivated land resources have been occupied by non-agricultural production, making cultivated land conversion increasingly prominent.

This study further analyzed the evolutionary characteristics of the spatial distribution of cultivated land conversion in Inner Mongolia from temporal and spatial perspectives and verified impacts of social, economic, and agricultural factors on local conversion in northern China. From 2000 to 2020, large amounts of cultivated land resources were occupied by construction land in Inner Mongolia, with total non-agricultural conversion reaching 7307.59 hm^2 (Table 1). Overall trends in conversion area and rate were consistent, exhibiting fluctuating growth (Fig. 2). The main reason for significant reduction in arable land area during 2000–2005 was the nationwide promotion of projects returning farmland to forest and grassland (Gegentana et al., 2024). In contrast, reduction in arable land from 2009–2021 is primarily due to socioeconomic development needs, occupation of industrial and mining land in towns and villages, and large-scale transport development (Zhao, 2017).

Research has shown that farmland conversion change in Inner Mongolia exhibited initial slowing followed by subsequent increase, with an inflection point in 2005 (Fig. 3). After 2005, arable land area in Inner Mongolia increased. Due to natural conditions, arable land quality is generally poor, with plowing retirement occurring in certain areas (Zhang et al., 2014). Quality is influenced by rapid economic development, and large-scale construction occupies high-quality farmland, ultimately converting cultivated land. Li et al. (2022a) reported apparent spatial distribution characteristics of cultivated land conversion grades in Heilongjiang Province, with higher-grade cities concentrated in western and economically developed areas. This indicates that demand for construction land for economic development has increased conversion area. These studies confirm that potential industrial development areas are economically developed and have high degrees of cultivated land conversion (Li et al., 2022a).

In the Hohhot-Baotou-Ordos urban agglomeration cluster in Inner Mongolia, with its energy advantages and rapid regional economic development, demand for construction of suburban development zones is high, resulting in considerable cultivated land conversion (Fig. 4).

This study selected quantifiable social, economic, and agricultural factors that, to a certain extent, reveal the interrelationship between urbanization, industrial development, and cultivated land conversion. Factor detector results indicated that the most important drivers were secondary and tertiary industries in GDP and per-unit area grain yield (Table 3), showing strong correlation between conversion, economic growth, and agricultural production conditions. Interaction detector findings revealed that urbanization and GDP per capita, and development of secondary and tertiary sectors in GDP exhibited the largest share (Fig. 6). This suggests that GDP, as a key socioeconomic factor, may propel transformation of farmland into urban land (Wang and Awadelkarim, 2024).

Nitsch et al. (2015) found that the main limiting factor for arable land expansion is not precipitation but land for infrastructure and services provided by towns. However, cultivated land conversion is affected by both quantifiable factors and difficult-to-quantify factors such as policies and regulatory efforts, which are independent of objective population, economy, and industry conditions. Off-farm arable land incidence is lower in areas with strong implementation of arable land protection policies. Xu et al. (2020) confirmed this, arguing that supervision by relevant land departments prevents governments and enterprises from blindly occupying farmland for economic interests. Bao et al. (2015) explored conversion trends over the past 30 years and concluded that natural factors are prerequisites for conversion, with elevation and slope determining vertical distribution trends of arable land conversion to built-up land. Due to limited data access, this study did not consider driving effects of natural factors on conversion in Inner Mongolia.

The interaction type of two driving factors influencing cultivated land conversion was predominantly characterized as nonlinear or bilinear enhancement during 2000–2020. This underscores that multifaceted consideration of various driving

factors and their interactions can elucidate driving mechanisms more effectively than any single factor. Wang et al. (2024) made a similar conclusion in their study on land use and land change in the Jinghe River Basin, indicating that conversion mechanisms respond to socioeconomic conditions. This highlights the importance of investigating conversion drivers in changing environments.

5.2 Strengthening Economic and Intensive Utilization of Land

Cultivated land conversion is an inevitable phenomenon during industrialization and urbanization in China (Li et al., 2022c). Conversion primarily occurs in economically developed areas and those with high urbanization coverage (Jiang et al., 2012; Li et al., 2015). Inner Mongolia's social economy is in a stage of rapid development, which affects cultivated land conversion. Social industrialization and urbanization require occupation of large amounts of construction land, and growing population has increased demand for nonproductive land use, particularly for commercial, residential, transportation, education, medical, real estate, and infrastructure construction. Cultivated land conversion is more prominent in peripheral areas of economically developed districts due to economic radiation effects from cities (Li et al., 2019). The most economically developed area, the Hohhot-Baotou-Ordos urban agglomeration, has the largest conversion area. Large-scale urban reconstruction occupies substantial surrounding farmland. Therefore, the economic radiation effect of these cities is relatively large, ultimately resulting in conversion of cultivated land in surrounding cities such as Ulanqab and Bayannur into urban construction. Loss of large amounts of arable land resources has markedly affected food security in China and threatened feeding of 1.4×10^9 people (Wu et al., 2017). It is necessary to control the scope of farmland occupied by urban construction areas, strengthen conservation and intensive utilization of land resources, and improve land resource utilization efficiency.

5.3 Increases in Secondary and Tertiary Industries and Regional Grain Yield

Agricultural production development partially drives cultivated land conversion trends, and advances in agricultural science and technology can increase the degree of intensive agricultural land use and food production. Additionally, pressure from food demand due to growing population diminishes with increased productivity per unit area of arable land (Liang, 2023). Cultivated land conversion causes changes in arable land quantity and quality, impacting sown grain area as well as grain yield per unit area and total grain output (Wu et al., 2015). The direct impact of conversion on food security is reduction in arable land amount, thus decreasing food production capacity (Song and Pijanowski, 2014). Zhao (2017) confirmed that economic development variables such as per capita GDP and proportion of fixed asset investment in GDP exert the greatest positive impact on non-agricultural farmland conversion levels. In contrast, we

observed that agricultural technology variables such as grain yield per unit area and total yield exert a positive impact on cultivated land conversion utilization levels in Inner Mongolia.

Agricultural technological progress and development, such as grain yield per unit area, reflect improvements in intensive utilization of cultivated land in Inner Mongolia. Moreover, agricultural technology can greatly improve cultivated land production capacity, which is conducive to weakening pressure from economic and social development on cultivated land to a certain extent and adversely affects conversion levels. Increased proportion of secondary and tertiary industries indicates that Inner Mongolia's industrial structure has been effectively adjusted and that new industry development has provided many employment opportunities. With secondary and tertiary industry development and increased employment opportunities, the labor force has shifted from agriculture to cities and towns, increasing demand for construction land and indirectly affecting conversion degree. Transfer from the agricultural sector to the non-agricultural sector increases changes in cultivated land nature, ultimately decreasing the proportion of primary industries and increasing the proportion of secondary and tertiary industries.

5.4 Suggestion and Implication

Urbanization in Inner Mongolia is continuously advancing, and the contradiction between economic development and arable land protection is becoming increasingly prominent (Wu, 2015). Therefore, we suggest that relevant management departments implement arable land protection work within a certain range, quantifying the work, clarifying arable land protection objectives (Furuseth and Pierce, 1982), and dynamically supervising actual implementation of protection tasks by local governments at all levels (Thompson and Prokopy, 2009). Arable land protection objectives can be reduced to specific townships, streets, and villages through breakdown of protection responsibilities and establishment of an efficient arable land protection responsibility system to achieve protection with clear objectives, feasible measures, and visible results (Newman et al., 2015).

6 Conclusions

Inner Mongolia is one of China's main grain-producing areas, making it significant to study the current status of cultivated land conversion. The area and rate of conversion in Inner Mongolia from 2000 to 2020 exhibited fluctuating trends with significant spatiotemporal differences. The spatial distribution of non-agricultural land growth was relatively clear. Restricted by terrain conditions, it is concentrated in the eastern area and the Hohhot-Baotou-Ordos urban agglomeration, primarily along the Hetao, Nenjiang, and Liaohe plains. Additionally, the proportion of secondary and tertiary industries and per-unit area grain yield caused by economic growth and agricultural production effi-

ciency were the main driving forces of conversion in Inner Mongolia. Hence, this study provides a reference for effectively limiting cultivated land conversion in northern China to facilitate protection and sustainable development of urban farmland. Nevertheless, this study had limitations. Although cultivated land conversion was an inevitable result of multiple factors, we primarily investigated driving factors from socioeconomic and agricultural production perspectives. Future research should investigate associated natural conditions and policy-driving factors.

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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