SPATIAL-TEMPORAL EVOLUTION OF URBAN LAND GREEN USE EFFICIENCY AND SPATIAL SPILLOVER EFFECT OF ITS INFLUENCING FACTORS IN THE YELLOW RIVER BASIN OF CHINA FROM 2005 TO 2019: THE PERSPECTIVE OF DUAL CONSTRAINTS OF CARBON EMISSION AND ENVIRONMENTAL POLLUTION

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Abstract. Given the dual constraints of carbon emissions and environmental pollution, the urban land green use efficiency (ULGUE) in the Yellow River Basin (YRB) of China is calculated using the slack-based measure (SBM) model on the basis of the panel data of 79 prefecture-level cities in the area of the YRB from 2005 to 2019. Moreover, various methods including coefficient of variation, exploratory spatial data analysis, and spatial econometric modeling are employed to examine the spatial-temporal pattern of the ULGUE and the spatial spillover effects of factors influencing ULGUE in the YRB. The results indicate that: ① The average value of ULGUE in the YRB was 0.63 from 2005 to 2019, exhibiting an overall trend of gradual initial increase, followed by fluctuating decline, and ultimately a gradual rise again. There are significant differences in the ULGUE in the region, and the overall spatial distribution tends to decrease from the lower reaches to the middle and upper reaches. ② The ULGUE in the YRB exhibits a significant spatial positive correlation. The “High-High” concentration areas are largely distributed in the Shandong Peninsula, and the spatial scope is progressively expanding to the western Shandong region and Hohhot, Inner Mongolia. The “Low-Low” cluster areas are mainly concentrated in the Shaanxi-Gansu-Ningxia region, which displays a cluster block distribution and has a significant locking effect. The “High-Low” heterogeneous areas are mainly provincial capitals and surrounding areas, while the “Low-High” heterogeneous areas are distributed in the middle and upper reaches, which undergo frequent changes. ③ There are multiple factors that influence ULGUE in the YRB, some of which display an obvious spatial spillover effect, such as economic development, population agglomeration, and land urbanization.
Keywords: *urban land use efficiency, spatial-temporal analysis, slack-based measure model, spatial Durbin model*

Introduction

Green development takes on a vital significance to the idea of ecological civilization, with an aim to establish a growth model that respects ecological and resource constraints (Adams, 2008; Ji et al., 2021). As socio-economic progress continues, alongside accelerating industrialization and urbanization, urban expansion encroaches upon agricultural and ecological lands, thereby threatening national food security and

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ecological stability. This expansion has resulted in disorganized urban land use, insufficiently intensive land utilization, and adverse environmental impacts. In the circumstance of high-quality development in the new era, urban land use must navigate the dual challenges of ecological constraints and economic support. Constrained by limited ecological capacity as well as land resources of the urban area, optimizing multi-input, multi-output benefits while minimizing environmental pollution is crucial for aligning economic, social, and environmental outcomes. Enhancing urban land green use efficiency (ULGUE) is therefore essential for achieving sustainable urban development. This study focuses on ULGUE, providing a comprehensive analysis and exploring the spatial spillover effects of its contributing factors, thereby offering significant theoretical and practical insights for promoting the ULGUE and informing policy formulation.

Beginning in the 1920s, theoretical studies on urban land use efficiency (ULUE) were conducted. Models like the fan, concentric circle, and multi-core urban land expansion were introduced by the ecological school. These models laid the foundation for understanding urban growth patterns. Subsequently, the development of economic location theory refined this framework by recognizing variables such as population size, geographic location, and labor market segmentation as influential in urban land use (Webber and Symanski, 1973). These advancements established a theoretical foundation for measuring ULUE. Contemporary research on evaluating ULUE generally adheres to three primary approaches. The first approach employs single economic indicators, such as the average GDP of secondary and tertiary industries (Liang et al., 2021) or land economic density (Liu et al., 2021), to characterize land use efficiency. The second approach constructs an indicator system around land input and output is built using the comprehensive evaluation method. On that basis, analytic hierarchy process, entropy method and other methods are adopted to obtain the weight and evaluate urban land use performance comprehensively (Chen et al., 2014; Ning et al., 2023; Wei et al., 2023). This method is capable of overcoming the deficiency of only considering single economic indicators, whereas it is subjective when building an indicator system and determining the weight, and different standardized methods will cause deviations in the results. The third approach employs more sophisticated techniques such as data envelopment analysis (DEA) and stochastic frontier analysis, which account for multiple inputs and outputs in evaluating ULUE (Liang et al., 2016; Herzig et al., 2018; Liu et al., 2020). In response to environmental pollution concerns, environmental factors have been integrated into the framework for assessing ULUE. This integration includes undesirable output indicators and the application of models such as the directional distance function and the slack-based measure (SBM) model to analyze efficiency (Lu et al., 2018; Luo et al., 2020; Xue et al., 2021; Yin et al., 2022). The connotation of ULGUE has been expanded bit by bit incorporating the concept of green development (Liang et al., 2019; Tang et al., 2021; Zhou and Lu, 2023; Ma et al., 2024). Various approaches, such as Tobit regression, threshold regression, ordinary least-squares (OLS) method, and panel models, have been employed to explore the influence of economic and social factors, as well as institutional policies, on ULUE (Dong et al., 2020; Kuang et al., 2020; Song et al., 2022; Zhang et al., 2024).

Scholars worldwide have made rich achievements on ULUE, whereas there are also visible defects. First, in terms of "Undesirable Output" indicators, existing research has paid more attention to environmental pollution, so it's rare to see studies that incorporate the carbon emission index into the framework of land use efficiency measurement. It is highly significant to put the double constraints of carbon emissions and environmental

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pollution into such a framework in the context of the "dual carbon" goal. This incorporation has two main benefits. To begin with, it aids in formulating urban land use policies that align with the "dual carbon" goal. In addition, it enables the accurate measurement of ULGUE. Accordingly, there is a need to expand and enrich the connotation of "Undesirable Output". While factor analysis has focused on the effect of relevant factors on ULGUE in the region, it has largely overlooked the spatial spillover effect. Therefore, further research in this area should urgently delve into the spatial spillover effect and deepen our understanding.

The Yellow River, as the second-longest river of China, traverses nine provinces and regions, encompassing an area exceeding 750,000 square kilometers. Based on data from the National Bureau of Statistics of China, by the end of 2023, these provinces and autonomous regions collectively housed a population of 421 million, representing 29.8% of China's total population, and generated a regional GDP of 3.164 trillion yuan, constituting 25.1% of the national economy. As a crucial grain production hub, ecological shield, and economic corridor, the Yellow River Basin (YRB) is of profound significance to the development of the Chinese economy and society as well as environmental security. To safeguard the long-term stability and security of the Yellow River, China has implemented a comprehensive strategy emphasizing ecological preservation and high-quality development in the region. However, the land use in the YRB is currently facing severe challenges, including low input-output efficiency, high resource and energy consumption, and significant pollution emissions (Fang et al., 2021). Increasing the ULGUE is imperative to support the national strategy of the YRB. This study investigates the ULGUE of cities within the YRB using the SBM model, analyzing spatial and temporal patterns, and exploring the spatial spillover effects of factors influencing ULGUE through a spatial econometric model. The findings aim to provide insights for boosting green development and regional coordination of cities in the YRB.

Materials and methods

Study area

This study centers on the YRB of China as the research object (*Fig. 1)*, encompassing nine provinces and regions. It evaluates the ULGUE of cities within the YRB from 2005 to 2019 and examines the spatiotemporal patterns as well as the spatial spillover effects of influencing factors. However, considering that Sichuan Province is part of the Yangtze River Economic Belt national strategy and the eastern part of the Inner Mongolia Autonomous Region falls under the "Rejuvenating the Northeast" strategy, these two regions are excluded from the analysis. Therefore, the research scope encompasses the prefecture-level cities in Qinghai, Gansu, Ningxia, Inner Mongolia (excluding eastern Inner Mongolia), Shanxi, Shaanxi, Henan, and Shandong provinces and regions. In total, 79 cities are included in the study, contingent on data availability.

Data source

The economic and social data required for the calculation primarily originate from the China Urban Statistical Yearbook, the China Urban Construction Statistical Yearbook, statistical yearbooks of provinces (districts), statistical bulletins of national economic and social development of local cities, environmental status bulletins, the China Coal Database from 2005 to 2019. For the carbon emission data of local cities, the IPCC

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calculation method should be adopted for estimation, and the carbon emission coefficient should refer to the IPCC Guidelines for National Greenhouse Gas Inventories. The individual missing data are predicted and tested using the Lasso BP neural network model (Sun et al., 2022; Zhu et al., 2023). It is noteworthy that Haidong City, Qinghai Province, is not included in the statistical area for the significant gap between the time range of this study and the land withdrawal in 2013. Furthermore, Laiwu City of Shandong Province will be included in Jinan in 2019, and Laiwu City will be retained. The relevant data for 2019 will be derived from Laiwu District in the Jinan Statistical Yearbook.

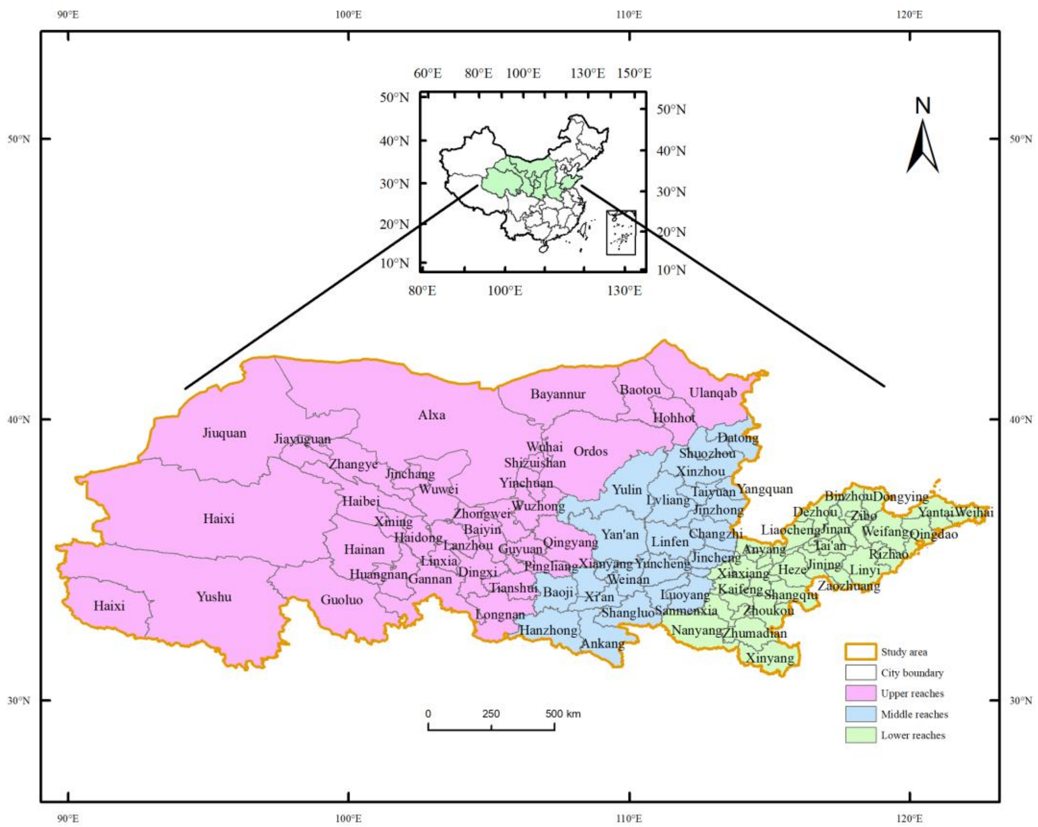

Figure 1. Study Area of YRB

Research methods

Measuring method of the ULGUE

The DEA model is applied to assess the technical efficiency of Decision-Making Units (DMUs) that comprise multiple inputs and outputs. This model does not require dimensionless processing of data. It optimally determines the index weight, thus avoiding the subjective effect of weight determination, and it has been extensively used to examine ULUE. However, it does not address the issue of unwanted outputs in efficiency measurement. With the recognition of the SBM model put forward by Tone (2003), in order to account for the shortcomings in input relaxation variables and output relaxation factors, the SBM model has been brought in to analyze ULUE (e.g., undesirable output). Thus, the ULGUE is calculated with Matlab software using the calculation method of SBM model, which is expressed as follows:

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$$\rho^{*}=min\frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^{-}}{x_{ik}}}{1+\frac{1}{p_1+p_2}\left(\sum_{r=1}^{p_1}\frac{s_h^{b-}}{b_{hk}}\right)}$$
$$s.t.\begin{cases}x_k=X\lambda+s^{-}\\ y_k=Y\lambda-s^{+}\\ b_k=B\lambda+s^{b-}\\ \lambda\geq 0,s^{-}\geq 0,s^{+}\geq 0,s^{b-}\geq 0\end{cases} \quad \text{(Eq.1)}$$

Eq. (1) suggests that every city in the area of YRB is regarded as a decision-making unit, which includes the following elements: m, p_1, p_2 in turn refers to inputs, output and types of undesirable outputs; s^-, s^+, s^{b-} represents relaxation variables of input, desirable output and undesirable output respectively; *X*, *Y*, *B* denotes input matrix, desirable output matrix and undesirable output matrix likewise; λ represents a weight vector and ρ^* the ULGUE.

The input-output indicator system for ULGUE is established, adhering to principles of scientific rigor, systematicness, and data availability (*Table 1*). The input indicators include the number of employed persons in the secondary and tertiary sectors, the built-up area, and investment in fixed assets, representing inputs of labor, land, and capital, respectively. The desired output indicators consist of municipal GDP and the green area within built-up areas, reflecting economic and environmental benefits. The undesirable output focuses on the dual constraints of carbon emissions and environmental pollution, with sulfur dioxide emissions serving as the primary indicator.

Table 1. *Indicator system for measuring ULGUE*

Standard	Feature layer	Indicator
Input	land labor force capital	Built up area /km^2 Number of employed population /10^4person Investment in fixed assets /10^4Yuan
Desirable output	economic performance ecological benefit	GDP/10^4Yuan Green area of the built-up area / hectare
Undesirable output	carbon emission environmental pollution	Carbon emissions /10^5t Sulfur dioxide emission /t

Coefficient of variation

The variation coefficient is adopted to reveal the difference degree of the ULGUE within the YRB. The specific calculation equation is:

$$CV=\sqrt{\frac{\sum_{i=1}^{N}(LUE_i-\mu)^2}{N}}\Big/\mu \quad \text{(Eq.2)}$$

where, CV is the coefficient of variation and N refers to the number of cities; LUE_i is the green land use efficiency value of *i* city; μ represents the average value of ULGUE in that year. The greater the CV value, the bigger the difference in ULGUE.

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Exploratory spatial data analysis (ESDA)

Exploratory Spatial Data Analysis (ESDA) is employed to investigate spatial autocorrelation calculated by ArcGIS software, encompassing both global and local dimensions. The specific calculation methods are detailed in Yang et al. (2016) research. In this study, global spatial autocorrelation is used to evaluate the overall spatial correlation of ULGUE in the YRB through the global Moran's I index. Local spatial autocorrelation is applied to identify patterns that may deviate from broader spatial trends. The local Moran's I index is employed to generate scatter plots and Local Indicators of Spatial Association (LISA) cluster maps. The value range is (-1,1): Moran's I > 0 denotes positive spatial correlation, while Moran's I < 0 denotes negative spatial correlation. Moran's I index. Local spatial auto-correlation is applied to identify local characteristic patterns that may deviate from the overall conclusion of broader spatial auto-correlation trends. The local Moran's I index is employed to generate scatter plots and LISA cluster maps. The spatial clustering features are classified into four types: High-High clustering area (H-H), Low-Low clustering area (L-L), Low-High heterogeneous area (L-H) and High-Low heterogeneous area (H-L).

Spatial econometric model

The spatial econometric model incorporates spatial interactions between variables to analyze the spatial dynamics among different geographical units (Elhorst, 2012). In this study, the model is employed to identify the direct factors influencing ULGUE in the YRB and to explore which factors exert spatial spillover effects on neighboring regions. Given the growing economic interconnections between regions, the economic distance matrix is particularly effective in avoiding the oversimplification of relationships between indirectly adjacent cities. Consequently, this study employs the economic distance spatial weight matrix. Moreover, by integrating a spatial lag term into a spatial econometric model, the influence of driving factors on ULGUE can be further broken down into direct, indirect (spillover), and total effects using the spatial partial differential decomposition method (Sun et al., 2014). The direct effect signifies the impact of these factors on the ULGUE within individual cities, while the indirect (spillover) effect indicates their influence on surrounding cities. The total effect encapsulates the overall average effect of these factors on ULGUE across the entire region under analysis. Additionally, the spatial econometric model employed in this study was implemented and analyzed using Stata software, ensuring robust and reliable computational results.

Results

Spatial-temporal characteristics of the ULGUE in the YRB

Temporal changes of the ULGUE in the YRB

Figure 2, created using Origin software, presents the box plot and coefficient of variation of the ULGUE in the YRB. The ULGUE of YRB area averaged 0.63 from 2005 to 2019, indicating a medium level with significant potential for improvement. From a temporal evolution perspective, the trajectory of changes within the research period can be divided into three stages. Firstly, from 2005 to 2008, there was a gradual upward trend. Influenced by rapid urbanization and industrialization, many cities in the YRB established development zones one after another, leading to a phase of high-speed economic and

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social growth. From 2005 to 2008, the ULGUE of the YRB also improved. Secondly, from 2009 to 2014, the ULGUE of the YRB exhibited a fluctuating downward trend. This may be attributed to the impact of the 2008 financial crisis, as local governments stimulated the economy through land finance and infrastructure development. Thirdly, from 2015 to 2019, although the ULGUE of the YRB showed some improvement compared to the previous stage, it remained relatively stable overall. This indicates that the improvement of the ULGUE in the YRB still faces significant pressure. Furthermore, the coefficient of variation of the ULGUE in the YRB exhibited significant fluctuations between 2009 and 2014, indicating pronounced changes in the ULGUE disparities among cities within the basin during this period. In other time intervals throughout the study period, the coefficient of variation showed minor fluctuations but remained relatively stable overall, with a slight downward trend. This suggests a gradual reduction of the ULGUE disparities in the YRB.

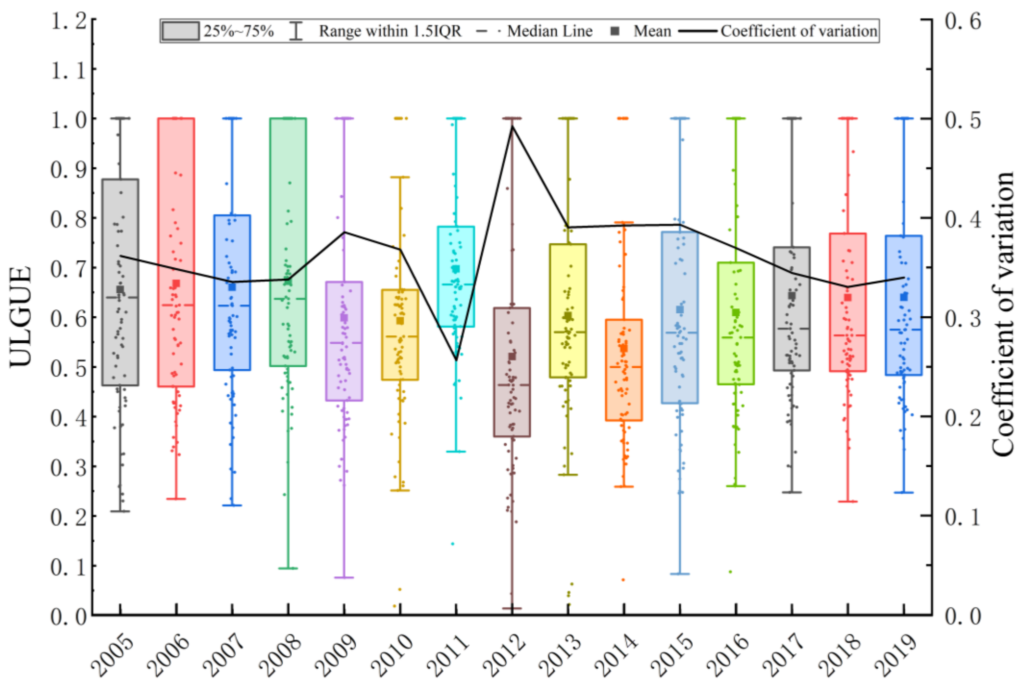

Figure 2. *Box plot and coefficient of variation of the ULGUE in the YRB from 2005 to 2019*

Spatial differentiation traits of the ULGUE in the YRB

Drawing on relevant research results and considering the distribution of efficiency values, the ULGUE of the YRB is set as five levels: $0.9<\rho^{*}\leq 1$ is high efficiency level, $0.7<\rho^{*}\leq 0.9$ is a higher efficiency level, $0.5<\rho^{*}\leq 0.7$ is medium efficiency level, $0.3<\rho^{*}\leq 0.5$ is a lower efficiency level, $\rho^{*}\leq 0.3$ is a low efficiency level. Additionally, changes in the ULGUE in the YRB from 2005 to 2019 were classified into five levels using the natural break method. The classification intervals were defined as follows: $-0.6<\Delta\rho^{*}\leq-0.4$, $-0.4<\Delta\rho^{*}\leq-0.1$, $-0.1<\Delta\rho^{*}\leq 0.1$, $0.1<\Delta\rho^{*}\leq 0.4$, $0.4<\Delta\rho^{*}\leq 0.6$. The spatial pattern of the ULGUE in the YRB in 2005, 2009, 2013, 2016, 2019 and changes from 2005 to 2019 are visualized by using ArcGIS software in *Fig. 3*.

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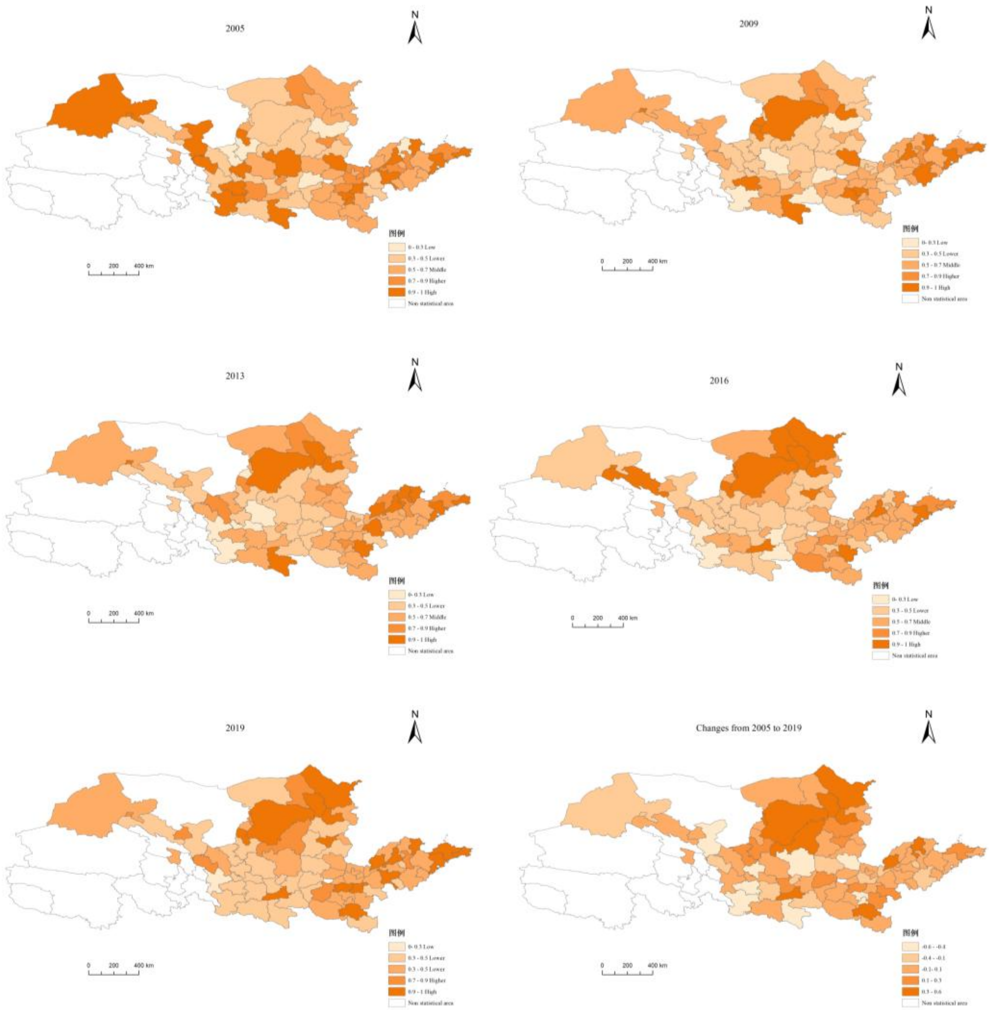

Figure 3. *Spatial difference characteristics of the ULGUE in the YRB*

The distribution of ULGUE levels in the YRB has undergone changes. In 2005, the proportions of cities with high efficiency, relatively-high efficiency, medium efficiency, low efficiency, and relatively-low efficiency were 24%, 14%, 34%, 22%, and 6% respectively. By 2019, these proportions changed to 22%, 10%, 33%, 34%, and 1% accordingly. The result suggests that cities with medium efficiency and low efficiency account for a large proportion. The high-value levels of ULGUE are primarily distributed in the downstream areas of the Yellow River. In the study period, there has been a visible trend of moving eastward, and the ULGUE of provincial capital cities has been significantly increased. From the change of grade and quantity, the proportion of efficiency above 0.7 (high efficiency and higher efficiency) is reduced, primarily distributed in Shandong Peninsula for the east, Hohhot and its surrounding areas for the north, Zhengzhou and its adjacent cities in Henan province for the middle. These cities were primarily concentrated in the middle and lower reaches of the Yellow River, as well as in the provincial capitals of the upper reaches. Cities concerned can be categorized into two types as follows. One is the area with a superior location, high economic development standards, and a noticeable radiation effect, of which the most significant is the provincial capital city and its surrounding areas. The other refers to cities with small scales, compact

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layouts, and apparent industrial characteristics. The proportion of cities with efficiency values between 0.5-0.7 (medium efficiency) has remained basically unchanged, mainly distributed in most regions of Henan and Shandong except for the cities with high efficiency. The proportion of cities with efficiency below 0.5 (low efficiency and lower efficiency) has increased, generally distributed in the middle and upper reaches of Shaanxi, Gansu, and western Shanxi. This shows that the number of cities that increase with low-value and lower-value and decrease with high-value and higher-value indicates the overall development of ULGUE in the YRB is not satisfactory. From the perspective of changes in the ULGUE from 2005 to 2019, approximately half of the cities experienced changes within the range of −0.1 to 0.1, while the number of cities with other levels of change was fairly consistent. Spatially, a significant improvement in the ULGUE from 2005 to 2019 was observed in cities located near the border regions of Shanxi, Shaanxi, and Inner Mongolia. In contrast, cities with other levels of change were evenly distributed, displaying no obvious spatial clustering characteristics. Significant regional disparities in ULGUE are evident within the YRB. The average ULGUE values in the upper, middle, and lower reaches of the basin are 0.61, 0.55, and 0.69, respectively. This demonstrates a distinct gradient, with the lower reaches exhibiting the highest overall efficiency, followed by the upper reaches, and the middle reaches having the lowest. ULGUE in these regions follows a similar pattern of decrease followed by increase (*Fig. 4*).

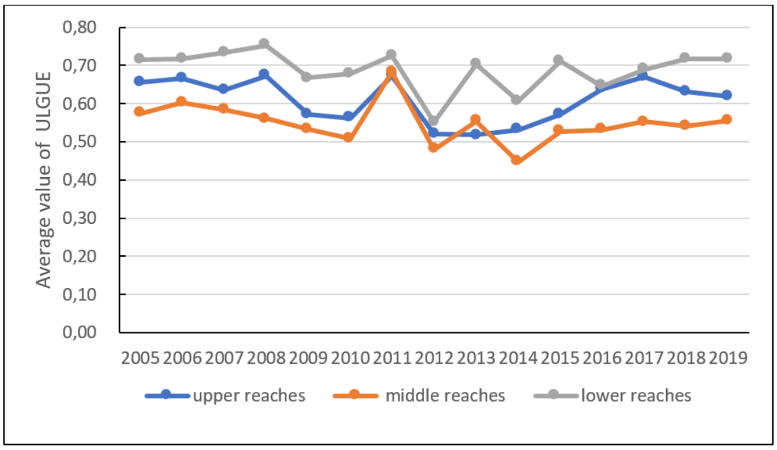

Figure 4. *ULGUE in the upper, middle and lower reaches of the YRB from 2005 to 2019*

Spatial auto-correlation analysis

(1) Global spatial auto-correlation analysis

The global Moran index calculated using ArcGIS software is used to determine and test the ULGUE of 79 local cities in the YRB from the year 2005 to 2019. The results, shown (*Table 2*) indicate that the Moran index was mostly significant during the study period, with values greater than 0. This suggests a positive spatial autocorrelation, with high-value areas embraced by other high-value areas, demonstrating significant spatial dependence and agglomeration. Notably, during the period of 2013-2019, the Moran index remained significant, with the degree of agglomeration initially increasing before declining.

Table 2. *Overall Moran index of the ULGUE in the YRB*

Year	Moran index	Z-statistic	P value	Year	Moran index	Z-statistic	P value

2005	-0.001664	0.190934	0.848577	2013	0.206928***	3.738512	0.000185
2006	-0.021272	-0.139550	0.889016	2014	0.214512***	3.871512	0.000108
2007	0.129772**	2.409973	0.015954	2015	0.184424***	3.338893	0.000841
2008	0.091128*	1.758281	0.078700	2016	0.152489***	2.799615	0.005116
2009	0.078234	1.543549	0.122698	2017	0.161715***	2.948866	0.003189
2010	0.103792**	1.985858	0.047049	2018	0.139433**	2.574897	0.010027
2011	0.146150***	2.707019	0.006789	2019	0.136958**	2.531324	0.011363
2012	0.066494	1.346638	0.178097				

Note: *, * *, * * * are significant at 10%, 5% and 1% levels respectively

(2) Local spatial auto-correlation analysis

The LISA cluster map of the ULGUE in the YRB in 2005, 2009, 2013, 2016 and 2019 was drawn with ArcGIS software to visually express the local spatial agglomeration characteristics, as shown in *Fig. 5*.

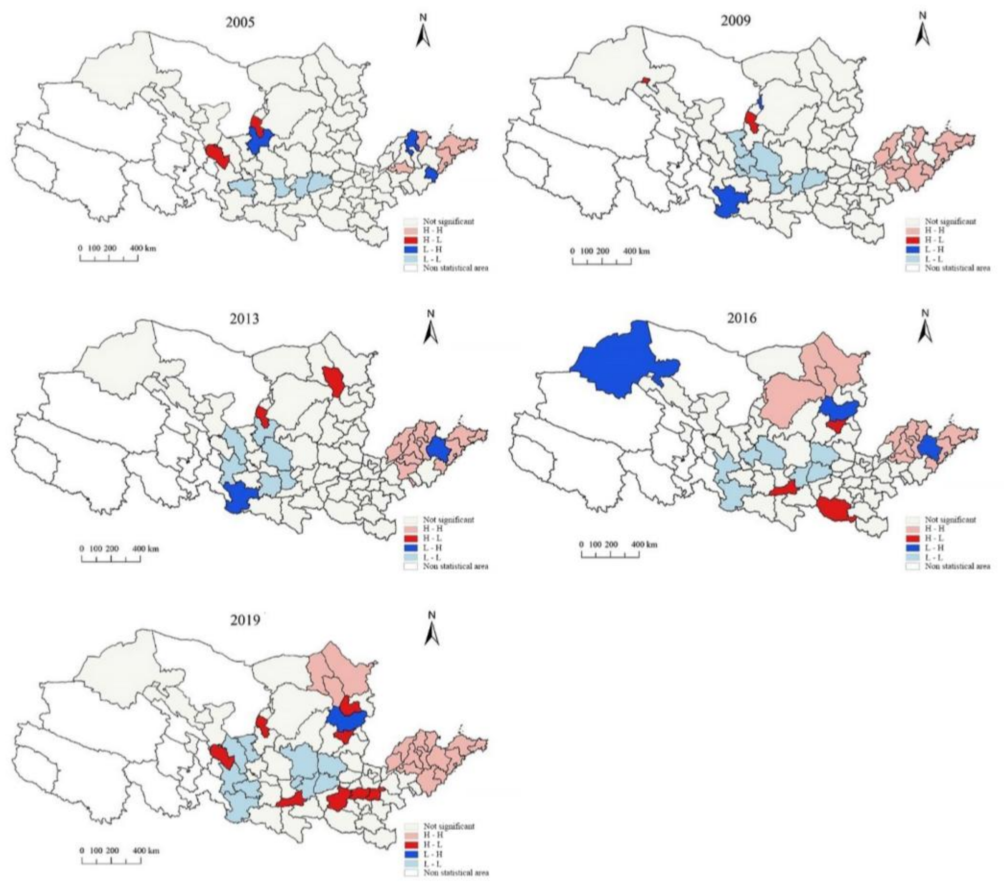

Figure 5. *Analysis of local spatial agglomeration characteristics of the ULGUE in the YRB*

The “High-High” cluster area is largely distributed in Shandong Province at the lower reaches of the YRB. The above type of area exhibits the gradual expansion from the coastal cities in the east of Shandong Peninsula to the western Shandong region and Hohhot, the capital of Inner Mongolia, as well as its surrounding areas. The result achieved is credible. To be specific, Shandong coastal areas has taken the lead in developing coastal economy by relying on superior geographical location and convenient

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traffic conditions and achieved effective results, such that high-value clusters have been progressively formed in this area. Within the framework of its big population, abundant resources and underdeveloped situation in the western part, Shandong Province has implemented a series of plans to boost regional coordinated development since 2013. As a result, the implementation of these plans has maximized the regional advantages of the coastal areas and their leading role, and a situation of coordinated development and complementary advantages between coastal cities and cities in western Shandong has been formed. In the above process, the industrial structure of western Shandong has tended to be satisfactory, and the pollution control has been enhanced. The “High-High” concentration area has gradually expanded to western Shandong. Moreover, cities in Inner Mongolia are mostly resource-based, and their economic development is dependent on heavy industry, such that the issue of environmental pollution in Inner Mongolia becomes more prominent. However, in recent years, resource transformation, the rise of new energy, and the enrichment of green energy (e.g., wind power and photovoltaic) have been vigorously promoted, which have a crowding out effect on highly polluting industries. The energy consumption per unit GDP and pollution emissions per unit of industrial added value have decreased on a year-to-year basis, which is particularly evident in Hohhot and surrounding areas. As a result, a “High-High” cluster has been gradually formed.

The “Low-Low” cluster areas are mostly distributed in Shaanxi-Gansu-Ningxia region, showing a clustered block distribution in geographical space, which is considered a collective depression state. Moreover, the spatial range changes slightly, with significant spatial locking effect. The above cities exhibit poor location conditions, neither good economic development foundation, nor significant location advantages and software and hardware development conditions. In the long run, urban land cannot be used orderly, so that a depression of ULGUE is caused.

The “High-Low” heterogeneous area is dominated by the provincial capital cities in the upper and middle reaches of the YRB and their surrounding areas. For spatial scope, the mode of isolated provincial capital cities (Yinchuan and Lanzhou) in 2005 has expanded to the combination mode of provincial capital surrounding clusters (Taiyuan and its surrounding areas, Zhengzhou-Kaifeng-Luoyang regions) plus isolated cities (Xi'an, Yinchuan and Lanzhou) in 2019, and cities in these regions show significant policy and resource preference advantages. They exhibit relatively strong competitiveness and resource advantages over surrounding cities. In addition, they are more likely to conform to the development expectation of high input and high output in land use while having more capital investment and governance capacity in environmental governance and ecological protection. As a result, provincial capital cities have already achieved a high value of ULGUE. It is noteworthy that the “high ULGUE” of these cities is more formed under the long-term policy support. The most significant defect of the city under this mode is that its radiation capacity is limited, while its driving effect on the surrounding cities is not significant. Lastly, the surrounding cities achieve low ULGUE, whereas the efficiency of the provincial capital cities is high.

The “Low-High” heterogeneous areas undergo frequent changes, they are mainly distributed in the middle and upper reaches of the Yellow River, while the overall trend is decreasing. These cities do not have significant advantages in geographical location. Besides, their own development level is low, thus making it difficult to form competitive industries and pillar industries. Furthermore, they have limited ability to receive radiation from surrounding “high-value” cities, and they may cause the loss of resources and human

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capital under the siphon effect of surrounding “high-value” cities, and finally form a low-value island of ULGUE.

Spatial spillover effects of factors influencing the ULGUE in the YRB

The results of the spatial autocorrelation analysis reveal that ULGUE in the YRB exhibits strong spatial correlation characteristics. Based on this, a spatial econometric model is constructed to investigate the spillover effects of the driving factors of the ULGUE.

Selection of factors

Referring to previous research (Bai et al., 2018; Xie et al., 2018; Yu et al., 2019), indicators like population concentration, degree of industrial structure optimization, economic development standard, level of science and technology, environmental regulation, land urbanization and degree of opening to the outside world are selected as the driving factors of the ULGUE in the YRB. The connotation of each indicator is listed in detail in *Table 3*.

Table 3. *Explanatory variables for driving factors of the ULGUE in the YRB*

Influence factor	Index connotation	Unit of measurement	Indicator code
Population agglomeration	Population density	10^4 person/km^2	density
Industrial structure	tertiary industry/ secondary industry	—	is
Economic development	GDP per capita	10^4Yuan	pgdp
Scientific and technological	technology expenditure/ financial expenditure	%	sci
Environmental regulation	Centralized treatment rate of sewage treatment plant	%	er
Land urbanization	Land urbanization rate	%	landurb
Opening up	Actual utilized foreign capital	USD100mn	fdi

(1) Population concentration. Higher population density reflects a greater concentration of labor and capital, fostering economies of scale and improving the efficiency of green land use. This study uses population density as a measure of population concentration. (2) Industrial structure optimization. Optimizing the industrial structure can reduce environmental pollution, improve land resource allocation, and promote efficient land use. In this study, the ratio of the gross output value of tertiary to secondary industries serves as the indicator. (3) Economic development. The level of economic development indicates the material inputs per unit of land. A more developed economy provides greater financial support for intensive land use, enhancing green land use efficiency. GDP per capita is used as a proxy for economic development in this study. (4) Scientific and technological level. The application of science and technology improves the absorption and transformation of urban resources, increasing the ratio of high-tech industrial output, optimizing the urban land use input-output structure, and thereby enhancing ULGUE. In this study, the level of science and technology is measured by the proportion of capital allocated to science and technology within total financial expenditures. (5) Environmental regulation. Environmental regulation refers to

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government measures aimed at controlling pollutant emissions from social and economic activities. By implementing pollution reduction policies, governments can directly increase green land use efficiency. The sewage treatment rate is used as the indicator of environmental regulation in this study. (6) Land urbanization level. Urban land is the foundation of development, and land urbanization reflects the degree of urban spatial expansion. Proper urbanization can improve land scale efficiency. This study characterizes the level of land urbanization using the urban land use rate. (7) Level of opening up. The degree of a city's external connectivity is captured by its level of opening up. This is measured by the actual amount of foreign capital utilized by the city. A higher inflow of foreign capital indicates a higher level of openness.

Measurement model inspection and selection

Spatial econometric models are tested and screened through OLS regression, LM test, LR test, Wald test and Hausman test (Anselin, 2013) to determine whether spatial Durbin model, spatial lag model or spatial error model should be selected. The inspection results are shown in *Table 4*.

Table 4. *Screening test results of spatial econometric model*

Inspection method	Inspection content	statistic	P value
LM test	Lagrange multiplier	107.27***	0.000
Spatial error	Robust Lagrange multiplier	18.89***	0.000
LM test	Lagrange multiplier	90.453***	0.000
Spatial lag	Robust Lagrange multiplier	2.073*	0.051
Wald test	Wald test	27.65***	0.0003
LR test	Slm nested in sdm	28.06***	0.0002
Hausman test	Hausman test	2.865	0.0000

Note: * * *, * * and * are significant at 1%, 5% and 10% respectively

The LM and Robust LM tests reveal significant spatial effects in the model. Specifically, the LM and Robust LM statistics for the spatial error effect are 107.27 and 18.89, respectively, both of which are significant at the 1% level. Similarly, the LM and Robust LM statistics for the spatial lag effect are 90.453 and 2.073, with significance at the 1% and 10% levels, respectively. These findings indicate the presence of both spatial lag and spatial error effects in the model, suggesting that the spatial Durbin model is more appropriate. The LR test further supports this choice, with the statistics for the spatial lag model and spatial error model being 27.97 and 28.06, respectively, both significant at the 1% level. This result rejects the null hypothesis that the spatial Durbin model can be simplified to either the spatial lag model or the spatial error model. Additionally, the Wald test validates the spatial Durbin model. Based on these results, the spatial Durbin model is chosen for the empirical analysis of the factors influencing ULGUE in the YRB and their spatial spillover effects.

Regression result analysis

Hausman test was implemented on variables in order to reassure whether random effects or fixed effects were more appropriate (Lee and Yu, 2012). The results indicate

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that the spatial Durbin model with fixed effects should be chosen. The LR test results suggest that the spatial Durbin model with individual and time fixed effects is appropriate. See *Table 5* for the parameters of regression results.

Table 5. *Regression results of spatial Durbin model of factors of the ULGUE in the YRB*

Variable name	Regression coefficient	Standard error	T statistic	P value
density	-0.0000508**	0.0000206	-2.47	0.014
is	0.0262039**	0.0149205	1.76	0.079
lnpgdp	-0.8643363***	0.2528023	-3.42	0.001
$lnpgdp^2$	0.0456518***	0.0117257	3.89	0.000
sci	-0.0097506*	0.0050274	-1.94	0.052
er	0.0003092	0.000363	0.85	0.394
landurb	0.0031184**	0.0012621	2.47	0.013
fdi	0.00216*	0.0013	1.66	0.096
ρ	0.2636181***	0.508532	5.18	0.000
sigma2_e	0.020705***	0.0008532	24.27	0.000
Individual effect	yes		time effect	yes
loglikelihood	611.1580		R^2	0.0997
N	1185			

Note: * * *, * * and * are significant at 1%, 5% and 10%, respectively

Coefficient of spatial lag term ρ the value is apparently not 0, indicating that the presence of spatial spillover effects from the independent variable and the impact on the ULGUE cannot be simply explained by regression coefficient (LeSage and Pace, 2009). The influence of driving factors on ULGUE can be divided into direct effects, indirect effects (spillover effects), and total effects. To disentangle these effects, the partial differential decomposition method is employed to decompose the influence of explanatory variables on the dependent variable (Bai et al., 2017). See *Table 6* for details.

(1) Population concentration: The population concentration level’s overall effect coefficient, direct effect coefficient, and spillover effect coefficient all pass the 1% significance test with scores of -0.0003931, -0.0000686, and -0.0003245 respectively. The above result suggests that the urban population concentration in the YRB will inhibit the ULGUE of local cities and neighboring cities (spillover effect). The possible explanation for this finding is that the improvement of population concentration level has two major effects on the ULGUE as follows. First, population concentration may increase the concentration of resources and bring more human resources to the region, thus producing economies of scale, which facilitates the increase of the ULGUE. Second, excessive population concentration may increase the negative effect of “urban disease”, produce congestion effect, lead to land supply and demand imbalance, environmental pollution and other problems, thus hindering the improvement of the ULGUE. These are two completely different aspects. The reality of the YRB at present is that the negative effect of population agglomeration is greater than the economic agglomeration effect triggered by the increase of population agglomeration. In addition, the regional integration in some parts of the YRB has achieved remarkable results, such as the Central Plains Urban Agglomeration, Guanzhong Urban Agglomeration, Shandong Peninsula

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Urban Agglomeration, etc. There has been a more common phenomenon of population flowing to regional central cities or cities with higher levels of economic development, corresponding with the reduction of urban population concentration in other regions, which has also been confirmed by the results of the sixth demographic census. On that basis, the spillover effect of population agglomeration will inevitably occur, thus causing the decline of ULGUE of cities in other regions where the degree of population agglomeration decreases.

Table 6. *Partial differential regression results*

variable	Total effect	Direct effect	overflow effect
Density	-0.0003931***	-0.0000686***	-0.0003245***
	（0.000977）	（0.0000218）	（0.0000893）
is	0.0630341*	0.0292107**	0.0338234
	（0.03354）	（0.0143405）	（0.0339753）
lnpgdp	-0.1047403**	0.0889267***	-0.1936669***
	（0.0463463）	（0.0219409）	（0.0491916）
sci	0.0190599	-0.0052599	0.0243198*
	（0.015181）	（0.0048679）	（0.0147441）
er	-0.0013401	0.0001318	-0.0014719
	（0.0013307）	（0.0003501）	（0.001232）
landurb	0.0191304***	0.0043492***	0.0147812***
	（0.0058642）	（0.0012705）	（0.0053944）
Fdi	0.00906	0.00374***	0.00532
	（0.00647）	（0.00137）	（0.0051）

Note: * * *, * * and * indicate that they are significant at 1%, 5% and 10%, respectively, and the brackets are standard errors

(2) Industrial structure optimization (is): the analysis shows a total effect coefficient of 0.0630341 on ULGUE, significant at the 10% level. The direct effect coefficient is 0.0292107, significant at the 5% level, while the spillover effect coefficient is 0.0338234 but does not reach statistical significance. These results suggest a positive correlation between ULGUE and industrial structure optimization in the YRB. Although industrial structure optimization may generate positive spillover effects in peripheral areas, these effects do not reach statistical significance. The benefits of industrial structure optimization are mainly observed in the shift from low-value to high-value industries, increased product value, and improved economic outcomes. This process promotes the optimization and upgrading of land use structures. Moreover, industrial transformation and upgrading help reduce environmental pollution and lower energy consumption per unit of output, thereby enhancing ULGUE in local cities. However, industrial structure development across the YRB remains uneven, with many cities still dependent on low-level industrial structures. Additionally, some cities encounter significant challenges in transforming their industrial bases due to poor initial conditions. Consequently, these cities struggle to drive regional development through industrial chain extensions, resulting in an insignificant spillover effect.

(3) Economic development (lnpgdp and lnpgdp2): The possible explanation for results is that when a city is less developed in economy, it would present a relatively extensive development mode and a rather low efficiency in resource use. As a result, the urban land expands rapidly, thus hindering the increase of the ULGUE. As economic development progresses, the development mode has shifted from extensive to intensive. The combination of capital, labor, science and technology, environment and other elements has tended to be optimized. Moreover, the expansion of land scale has been effectively restricted. The gradually increased attention has been placed to environmental pollution control and ecological protection investment, thus facilitating the improvement of the ULGUE. The total effect coefficient of the economic development reaches -0.1047403, passing the 5% level of significance test. To be specific, the direct effect coefficient is 0.0889267, passing the 1% significance level, and the spillover effect coefficient is -0.1936669, passing the 1% significance level. The above result reveals that the improvement of urban economic level only positively affects the ULGUE due to the large differences between regions in economic development. The main reason for the negative spillover effect on the surrounding cities is that the cities with higher economic development levels do not significantly promote the surrounding cities, whereas they may exert a siphon effect, thus causing uneven resource allocation among regions; uneven development will exert a negative spatial spillover effect. Furthermore, the malicious competition between local governments to up-regulate the level of economic development around investment promotion results in more negative spatial spillover effect.

(4) Science and technology level (sci): the total effect coefficient on ULGUE is 0.0190599, but this does not reach statistical significance, indicating that the positive impact of science and technology in the YRB on ULGUE has not yet materialized. The direct effect coefficient is -0.0052599, which also fails to reach significance, while the spillover effect coefficient is 0.0243198, significant at the 10% level. These findings suggest that while there may be potential spillover effects of scientific and technological advancements on neighboring regions, this impact is currently minimal and not reflected in significant improvements in ULGUE. Several factors contribute to this outcome: the overall level of science and technology in the YRB is relatively low compared to more economically developed regions along the southeast coast. The distribution of technological resources is uneven, with significant disparities in science and technology investment across different cities, resulting in a generally low level of development that requires substantial improvement. Moreover, most urban land use models in the YRB have yet to be transformed into technology-driven models, limiting the impact of scientific and technological advancements on significantly enhancing ULGUE. As a result, the positive spillover effects of technological diffusion on other regions are challenging to realize under current conditions.

(5) Environmental regulation (er): total effect coefficient on ULGUE is -0.0013401, with a direct effect coefficient of 0.0001318 and a spillover effect coefficient of -0.0014719. None of these coefficients are statistically significant, indicating that environmental regulation currently exerts no discernible impact on ULGUE in the YRB. This lack of significant influence may stem from the entrenched belief in the YRB that economic development often occurs at the expense of ecological preservation. In practice, enterprises in the region may find it more profitable to bypass environmental regulations, thereby enabling the pursuit of low-cost, high-pollution industries. This approach not only complicates pollution control efforts but also hinders improvements in ULGUE.

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Moreover, the absence of significant effects suggests that the "Porter hypothesis"—which posits that stringent environmental regulations can drive innovation and efficiency, benefiting both the environment and the economy—does not apply in the YRB. This finding aligns with the research conclusions of Hao et al. (2018), reinforcing the notion that environmental regulation in the region has not yet reached a level where it can positively influence ULGUE.

(6) Land urbanization: the total effect coefficient, direct effect coefficient, and spillover effect coefficient are 0.0191304, 0.0043492, and 0.0147812, respectively, all of which pass the 1% level of significance. This indicates that land urbanization in the YRB has begun to exert a positive influence on ULGUE, both locally and in surrounding areas. The observed positive impact can be attributed to increased state emphasis on cultivated land protection and the implementation of a novel urbanization strategy. These policies have mitigated the issues associated with uncontrolled land urbanization and rapid urban expansion. As a result, the level of land conservation and intensive use has improved, enhancing the alignment of land urbanization with population size and industrial development within cities. These findings suggest that the YRB's approach to land urbanization is beginning to enhance ULGUE. Moreover, the imitation and diffusion effects are contributing to increased ULGUE in adjacent regions, reflecting a growing regional synergy in sustainable land management practices.

(7) Opening up level (FDI): The total effect coefficient of the opening up level reaches 0.00906, failing the significance level test. The direct effect coefficient reaches 0.00374, passing the 1% significance level. The spillover effect coefficient is 0.00532, failing the significance level test. The possible explanation is that for an area like the YRB where the overall level of economic development is not high, the introduction and utilization of foreign capital can effectively supplement the local production factors and enhance the intensity of land use. The above results reveal that the improvement of the level of opening up can stimulate the increase of the ULGUE to a certain extent (Zhu and Fu, 2017). At this stage, however, the opening up level of the YRB is not high, and the regional gap is significant. The diffusion effect of foreign capital economic development is not significant, and the spillover effect on the surrounding areas cannot be indicated.

Robustness test

This study primarily presents regression results using the spatial economic distance matrix. However, recognizing that spatial econometric models are particularly sensitive to the choice of spatial weight matrix, robustness tests were conducted using alternative matrices, including the spatial adjacency matrix, geographic distance matrix, and gravity model matrix. The robustness of the results was assessed using the LM test, LR test, and Wald test across these alternative matrices. These tests consistently indicated a preference for the spatial Durbin model across all three spatial weight matrices. The summarized regression results in *Table 7* confirm the robustness of the findings. Despite the inclusion of multiple variables, the regression outcomes using the three different spatial weight matrices closely align with the initial results based on the spatial economic distance matrix. Consequently, the conclusions of this study can be considered robust, as the alternative spatial weight matrices yield similar results, reinforcing the validity of the findings.

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Table 7. *Robustness test based on different spatial weight matrices*

-	Spatial adjacency matrix model	Geographic distance matrix model	Space gravity model
density	-0.000035*	-0.0000505**	-0.0000349*
	(-1.77)	(-2.51)	(-1.77)
is	0.0160705	0.0220246	0.0164771
	(1.08)	(1.47)	(1.11)
lnpgdp	-1.021341***	-0.9653914***	-0.9702836***
	(-6.36)	(-3.80)	(-5.86)
$lnpgdp^2$	0.0535913***	0.0509876***	0.0511538***
	(6.90)	(4.31)	(6.38)
sci	-0.0117864**	-0.0115144**	-0.0114762**
	(-2.38)	(-2.32)	(-2.32)
er	0.0004515	0.00002932	0.0004546
	(1.26)	(0.82)	(1.27)
landurb	0.0025669**	0.0028998**	0.0024624**
	(2.10)	(2.35)	(2.51)
fdi	0.00266**	0.0024*	0.0034**
	(1.99)	(1.87)	(2.51)
ρ	0.1627828***	0.2636181***	0.1679829***
sigma2_e	0.019246***	0.020705***	0.0191365***
loglikelihood	657.2507	628.3631	660.8389
R2	0.0145	0.0145	0.0279
N	1185	1185	1185

Note: * * *, * *, * are significant at 1%, 5%, and 10% respectively, and t statistics are presented in brackets

Conclusion and discussion

In this study, the panel data of 79 cities in the YRB from 2005 to 2019 are selected based on the “Undesirable Output” of environmental pollution and carbon emission. Moreover, the ULGUE is examined using the SBM model, and its spatial differentiation characteristics are analyzed by exploratory spatial data analysis. Furthermore, the spatial spillover effects of its factors are analyzed using a spatial econometric model built in this study. The main conclusions are drawn as follows:

(1) The ULGUE in the YRB had an average value of 0.624 between 2005 and 2019, which was at the medium level. It showed an initial gradual increase, followed by periods of fluctuation and decline, and ultimately ended with a steady rise. The development turned to the good aspect, but there was still space for improvement. The ULGUE in the YRB exhibits a decreasing spatial difference from the lower reaches to the middle and upper reaches. The regional difference of the YRB is significant, and the overall performance is lower reaches>middle reaches>lower reaches. Thus, in the process of promoting the national strategy of YRB, emphasis should be placed on the organic integration of green development principles with urban land use processes. It is essential to adhere to the principles of intrinsic development and ecological civilization

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construction, establish networks and mechanisms for local government cooperation, and prioritize the reduction of regional dis-parities in policy formulation.

(2) In the study period, the ULGUE has indicated a more significant spatial positive auto-correlation, with the degree of autocorrelation showing an initial increase followed by a decrease. The local spatial correlation is at a state of “small aggregation and large dispersion”. The high-value aggregation areas in the YRB are predominantly located in the Shandong Peninsula, and the spatial scope is gradually expanding to western Shandong and around Hohhot, Inner Mongolia. The “Low-Low” cluster areas are mainly distributed in Shaanxi-Gansu-Ningxia region, which are clustered and blocky, forming a significant locking effect in these areas. High-value heterogeneous regions and low-value heterogeneous regions are relatively distributed, of which high-value heterogeneous regions are distributed in Shaanxi, Ningxia, Gansu and Inner Mongolia, mainly in provincial capital cities and surrounding areas while low-value heterogeneous regions are distributed in the upper and middle reaches of the region, with frequent changes, and the number gradually decreases. This provides a theoretical basis for different regions to implement differentiated policy measures and regional coordinated development. For high-value cluster areas, they are required to continuously maintain their advantages in land resource allocation, guide the rational layout of industrial land through high-quality land spatial planning, enhance land-use structures, and harness the potential of existing land resources. Accelerate the layout of modern industries and high-tech industries with significant added value, high and new technology intensity, low energy consumption and low pollution discharge intensity, giving priority to ensuring the land use of such industries. Use the capital advantage accumulated in the economic development pilot area to increase investment in environmental governance infrastructure and ecological environment remediation. For low-value cluster areas, it is imperative to face up to the development gap between regions, fully utilizing the advantages of backwardness. Close attention should be given to optimizing the spatial layout of urban construction land so as to identify Low-utility land and high pollution industrial land for stock land accurately, thus establish a market-guided paid exit mechanism, and set thresholds undertaking external industrial transfer with investment intensity and pollution indicators as the core. Moreover, strengthen cooperation and coordinated development with surrounding cities to avoid the trap of the regional “lock-in effect”. The common feature of high-value heterogeneous regions and low-value heterogeneous regions is that efficient high-value cities are adjacent to inefficient low-value cities. The reason for their spatial heterogeneity is that the efficient high-value cities have limited ability to radiate and drive surrounding cities, or the inefficient low-value cities have incomplete software and hardware infrastructure to accept the radiation and diffusion of surrounding cities. On that basis, the key to eliminate the spatial heterogeneity in efficiency lies in enhancing the influence of high-efficiency cities while strengthening the capacity of low-efficiency cities to absorb spillover effects.

(3) The spatial econometric model’s findings provide several crucial insights into ULGUE in the YRB. Notably, increased population concentration exerts a negative direct impact on local cities, while also generating a similar negative spillover effect on surrounding areas. This highlights the necessity of future urbanization strategies that mitigate excessive population concentration in prefecture-level cities. Instead, efforts should focus on developing small towns and implementing localized urbanization strategies in areas with more advanced economic development. The correlation between industrial structure optimization and ULGUE is positive; however, the absence of a

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significant spillover effect indicates uneven growth and generally low levels of industrial structure across YRB cities. Conversely, economic development demonstrates a "Kuznets" curve relationship with ULGUE, with economic development exerting a negative spillover effect on adjacent cities. This is likely attributable to the siphon effect and intense competition among local governments. The study further reveals that the overall scientific and technological level in the YRB is low, coupled with uneven resource distribution, resulting in a minimal impact on ULGUE. Similarly, no direct or spatial spillover effects of environmental regulation on ULGUE were detected. Nonetheless, land urbanization positively impacts ULGUE, accompanied by a significant spatial spillover effect. Increasing openness to external factors can also enhance ULGUE, although the spatial spillover effect remains constrained. Unbalanced development in the YRB has impeded the full realization of both positive direct and spillover effects on ULGUE, especially in areas such as science and technology, environmental regulation, industrial structure, and openness. To address these issues, it is essential to improve and equilibrate development across these areas through targeted measures. Furthermore, the positive spillover effect of core cities should be fully utilized to prevent surrounding low-efficiency cities from becoming environmental pollution hotspots. Strengthening intergovernmental exchanges and cooperation between neighboring cities regarding land resource utilization and ecological protection is crucial for fostering regional integrated development and achieving sustainable urbanization in the YRB.

(4) Overall, compared to eastern China, the YRB exhibits significant shortcomings and imbalances in areas such as technological advancement, environmental regulation, industrial structure, and openness to the global market. These disparities are particularly pronounced when compared to regions like the Yangtze River Delta and the Guangdong-Hong Kong-Macao Greater Bay Area. However, as a vital producer of grain, energy, raw materials, and a key base for fundamental industries in China, the YRB is characterized by resource-intensive and labor-intensive industries, closely linking it to these developed regions. To address these challenges, customized industrial transformation strategies should be developed based on the unique industrial development characteristics of provinces and cities within the basin. Innovative models of inter-regional industrial transfer cooperation should be explored, alongside policies that encourage and support the growth of high-tech industries in the YRB. These measures could facilitate the integration of upstream and downstream segments of the industrial chain and promote the relocation of industries from developed regions to the YRB. From an international perspective, research on the ULGUE in the YRB provides valuable case studies and practical insights for other river basins or regions undergoing similar urbanization processes worldwide.

REFERENCES

[1] Adams, B. (2008): Green development: Environment and sustainability in a developing world. – Published by Routledge.
[2] Anselin, L. (2013): Spatial econometrics: methods and models. – Springer Science & Business Media.
[3] Bai, J., Wang, Y., Jiang, F. (2017): R&D Element Flow, Spatial Knowledge Spillovers and Economic Growth. – Economic Research 52(07): 109-123.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_31253146

[4] Bai, Y., Deng, X., Jiang, S., Zhang, Q., Wang, Z. (2018): Exploring the relationship between urbanization and urban eco-efficiency: Evidence from prefecture-level cities in China. – Journal of Cleaner Production 195: 1487-1496.
[5] Chen, L., Yang, X., Chen, L., Potter, R., Li, Y. (2014): A state-impact-state methodology for assessing environmental impact in land use planning. – Environmental Impact Assessment Review 46: 1-12.
[6] Dong, Y., Jin, G., Deng, X. (2020): Dynamic interactive effects of urban land-use efficiency, industrial transformation, and carbon emissions. – Journal of Cleaner Production 270: 122547.
[7] Elhorst, J. P. (2012): Dynamic spatial panels: models, methods, and inferences. – Journal of Geographical Systems 14: 5-28.
[8] Fang, L., Wang, L., Chen, W., Sun, J., Wang, L. (2021): Identifying the impacts of natural and human factors on ecosystem service in the Yangtze and Yellow River Basins. – Journal of Cleaner Production 314: 127995.
[9] Hao, Y., Deng, Y., Lu, Z.-N., Chen, H. (2018): Is environmental regulation effective in China? Evidence from city-level panel data. – Journal of Cleaner Production 188: 966-976.
[10] Herzig, A., Nguyen, T. T., Ausseil, A.-G. E., Maharjan, G. R., Dymond, J. R., Arnhold, S., Koellner, T., Rutledge, D., Tenhunen, J. (2018): Assessing resource-use efficiency of land use. – Environmental Modelling & Software 107: 34-49.
[11] Ji, Y., Lei, Y., Li, L., Zhang, A., Wu, S., Li, Q. (2021): Evaluation of the implementation effects and the influencing factors of resource tax in China. – Resources Policy 72: 102126.
[12] Kuang, B., Lu, X., Zhou, M., Chen, D. (2020): Provincial cultivated land use efficiency in China: Empirical analysis based on the SBM-DEA model with carbon emissions considered. – Technological Forecasting and Social Change 151: 119874.
[13] Lee, L. F., Yu, J. (2012): Spatial panels: Random components versus fixed effects. – International Economic Review 53: 1369-1412.
[14] LeSage, J., Pace, R. K. (2009): Introduction to spatial econometrics. – Chapman and Hall/CRC.
[15] Liang, L., Zhang, B., Fan, P. (2016): Analysis of farmers' land use efficiency and influencing factors based on environmental constraints: Taking the grain production core area of Henan Province as an example. – Geographic Science 36(10): 1522-1530.
[16] Liang, L., Yang, Y., Yuan, C. (2019): Measurement of urban land green use efficiency and its spatial differentiation characteristics - an empirical study based on 284 cities above prefecture level. – China Land Science 33(06): 80-87.
[17] Liang, L., Qu, Z., Wang, S., Shi, Y., Chen, X., Sun, Y. (2021): Analysis of multi–scale spatial pattern and influencing factors of urban land economic density in the Yellow River basin. – Geographic Science 41(08): 1336-1344.
[18] Liu, S., Xiao, W., Li, L., Ye, Y., Song, X. (2020): Urban land use efficiency and improvement potential in China: A stochastic frontier analysis. – Land Use Policy 99: 105046.
[19] Liu, L., Fan, C., Zheng, B. (2021): Evaluation of green land use and its spatial and temporal pattern in cities above prefecture level in China. – Journal of Henan University (Natural Science Edition) 51(04).
[20] Lu, X., Kuang, B., Li, J. (2018): Regional difference decomposition and policy implications of China's urban land use efficiency under the environmental restriction. – Habitat International 77: 32-39.
[21] Luo, X., Ao, X., Zhang, Z., Wan, Q., Liu, X. (2020): Spatiotemporal variations of cultivated land use efficiency in the Yangtze River Economic Belt based on carbon emission constraints. – Journal of Geographical Sciences 30: 535-552.
[22] Ma, D., Zhang, J., An, B., Guo, Z., Zhang, F., Yan, Y., Peng, G. (2024): Research on urban land green use efficiency and influencing factors based on DEA and ESTDA models: Taking 284 cities in China as an example. – Ecological Indicators 160: 111824.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_31253146

[23] Ning, X., Zhang, H., Shao, Z., Huang, X., Wang, H., Zhang, R., Hao, M. (2023): Sustainability Evaluation of Chinese Capital Cities Based on Urban Geographic Environment Index. – Remote Sensing 15: 1966.
[24] Song, Y., Yeung, G., Zhu, D., Xu, Y., Zhang, L. (2022): Efficiency of urban land use in China's resource-based cities, 2000–2018. – Land Use Policy 115: 106009.
[25] Sun, C., Zhao, L., Zou, W., Zheng, D. (2014): Water resource utilization efficiency and spatial spillover effects in China. – Journal of Geographical Sciences 24: 771-788.
[26] Sun, Y., Jia, Z., Chen, Q., Na, H. (2022): Spatial pattern and spillover effects of the urban land green use efficiency for the Lanzhou-Xining urban agglomeration of the Yellow River Basin. – Land 12: 59.
[27] Tang, Y., Wang, K., Ji, X., Xu, H., Xiao, Y. (2021): Assessment and spatial-temporal evolution analysis of urban land use efficiency under green development orientation: Case of the Yangtze River Delta urban agglomerations. – Land 10: 715.
[28] Tone, K. (2003): Dealing with undesirable outputs in DEA: A slacks-based measure (SBM) approach. – GRIPS Research Report Series I-2003-0005.
[29] Webber, M. J., Symanski, R. (1973): Periodic markets: an economic location analysis. – Economic Geography 49: 213-227.
[30] Wei, C., Meng, J., Zhu, L., Han, Z. (2023): Assessing progress towards sustainable development goals for Chinese urban land use: A new cloud model approach. – Journal of Environmental Management 326: 116826.
[31] Xie, H., Chen, Q., Lu, F., Wu, Q., Wang, W. (2018): Spatial-temporal disparities, saving potential and influential factors of industrial land use efficiency: A case study in urban agglomeration in the middle reaches of the Yangtze River. – Land Use Policy 75: 518-529.
[32] Xue, D., Yue, L., Ahmad, F., Draz, M. U., Chandio, A. A. (2021): Urban eco-efficiency and its influencing factors in Western China: Fresh evidence from Chinese cities based on the US-SBM. – Ecological Indicators 127: 107784.
[33] Yang, W., Du, D., Liu, C., Ma, Y. (2016): The space–time evolution characteristics and internal mechanism of China's geo economic relations. – Journal of Geography 71(06): 956-969.
[34] Yin, Y., Hou, X., Liu, J., Zhou, X., Zhang, D. (2022): Detection and attribution of changes in cultivated land use ecological efficiency: A case study on Yangtze River Economic Belt, China. – Ecological Indicators 137: 108753.
[35] Yu, J., Zhou, K., Yang, S. (2019): Land use efficiency and influencing factors of urban agglomerations in China. – Land Use Policy 88: 104143.
[36] Zhang, H., Zheng, J., Hunjra, A. I., Zhao, S., Bouri, E. (2024): How does urban land use efficiency improve resource and environment carrying capacity? – Socio-Economic Planning Sciences 91: 101760.
[37] Zhou, Y., Lu, Y. (2023): Spatiotemporal evolution and determinants of urban land use efficiency under green development orientation: Insights from 284 cities and eight economic zones in China, 2005–2019. – Applied Geography 161: 103117.
[38] Zhu, M., Fu, X. (2017): Temporal and spatial characteristics of land use efficiency in Guangdong Hong Kong Macao Greater Bay Area and its impact mechanism. – Tropical Geography 37(06): 814-823.
[39] Zhu, Y., Xu, Y., Luo, Y. (2023): The green GDP accounting system based on the BP neural network: an environmental pollution perspective. – Frontiers in Environmental Science 11: 1277717.

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