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Research article

Synergy level of urban resilience and urban land use efficiency in the Yellow River Basin: Spatial-temporal evolution characteristics and driving factors

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ABSTRACT

The complex global context, including globalization, rapid urbanization, and climate change, poses significant challenges to urban stability and development. Balancing urban land use efficiency and resilience is crucial for sustainable progress. Focusing on the vulnerable Yellow River Basin (YRB), this study examines the interplay between urban resilience and land use efficiency. Panel data from 2013 to 2020 for 54 cities in the YRB were used, it quantifies the Coupling Coordination Degree of Urban Resilience and Urban Land Use Efficiency (CCDUU), explores its spatiotemporal evolution and influencing factors. Key findings include: The CCDUU exhibits a sustained and discernible growth trend. Notably, CCDUU is higher in downstream areas in comparison to the middle reaches, reaching its lowest point in the upstream areas; however, the increase in CCDUU in the upstream areas surpasses that observed in other regions. Concurrently, regional disparities in CCDUU are diminishing. Despite the presence of a notable positive spatial correlation in CCDUU within the YRB, the strength of this spatial association is not sufficiently robust. Of paramount importance factor is the role of regional innovation, which significantly influences the enhancement of CCDUU. Following closely is the degree of openness, whereas the positive effects of government support and population density are concentrated predominantly in the upper YRB region. In contrast, urban-rural disparity exerts an adverse impact on CCDUU in most regions. Policy recommendations for enhancing CCDUU in YRB cities include strengthening government support and planning control, particularly in upstream regions, to achieve efficient resource utilization and environmental protection. Implementing population density management policies, encouraging rational movement, and promoting population migration to upstream areas can alleviate pressure in downstream cities. Enhancing openness, attracting foreign investment, and promoting innovation and industrial upgrading will drive economic structural upgrades and improve CCDUU.

1. Introduction

With the continuous acceleration of urbanization, urban areas are rapidly expanding in size; however, this uncontrolled expansion

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often comes at the cost of low efficiency and high pollution [1,2]. This development model not only hinders the high-quality sustainable development of cities but also poses a serious threat to urban security, social progress, and public health [3]. In order to achieve high-quality sustainable development in cities, it is imperative to transform the development mode, strengthen urban planning and management, and realize both high-quality sustainable development and urban security.

Improving urban land use efficiency (ULUE) and urban resilience (UR) is crucial for ensuring high-quality development and urban safety. Improving ULUE not only allows limited land to accommodate more people, provide more services and facilities to meet the growing demands of the city [4], but also contributes to achieving sustainable coordinated development of the economy, society, and environment [5], reducing pressure on the natural environment, mitigating ecosystem destruction, and achieving harmonious coexistence between cities and nature. Enhancing UR can enhance the city’s capacity to respond to such unforeseen events, leading to the development of more effective planning and management strategies for the rapid recovery and reconstruction of impacted urban systems [6].

Many experts and scholars have also recognized the importance of UR and ULUE, and extensive research has been conducted on how to enhance UR and ULUE. However, existing research still faces the following issues: (1) Scholars mostly discuss urban resilience or urban land use efficiency from an independent perspective [2,4,7–12], without studying the interactive relationship between the two. However, the sustainable and high-quality development of cities is a complex system that should not be confined to just one aspect [13]. Overemphasis on efficient land use may have a negative impact on urban security, while excessive focus on urban security may reduce the efficiency of land resource utilization. Therefore, this paper argues that synergistically enhancing efficient land resource utilization and the secure development of cities will better serve urban development. (2) There are few studies analyzing influencing factors about UR and ULUE, and most of them used linear regression models such as Grey Relational Analysis, Spatial Durbin Model, Tobit Regression Model, etc., to analyze these factors [14–19]. However, different regions may exhibit different responses to influencing factors due to varying levels of economic development and geographical features. Traditional linear analysis methods may not comprehensively capture these complex spatial interactions. Therefore, considering spatial factors in the analysis will provide a more comprehensive and accurate understanding of influencing factors in different regions. This offers more precise data support, aiding in the formulation of more targeted policies and strategies.

The YRB (Fig. 1) holds a significant position in China, functioning both as a vital economic region and a natural geographic barrier [20]. However, due to the prevalence of resource-based cities and the delicate ecological backdrop, the YRB has emerged as a focal point and a challenging aspect concerning China’s ecological security and the socio-economic development trajectory [21]. Regional heterogeneity is serious in the YRB, with unbalanced development in the upper, middle and lower reaches [2]. Thus, this study focuses on the YRB as the research domain, leveraging panel data spanning from 2013 to 2020. The study computes the Coupling Coordination Degree of UR and ULUE (CCDUU) within the YRB, analyzing their spatiotemporal evolution patterns. Furthermore, it employs the GWR model to spatially analyze influencing factors across different cities. The objective is to provide a scientific foundation and decision-making support for guiding the YRB toward high-quality, sustainable development. Additionally, this research aims to provide insights that can serve as reference points for other regions.

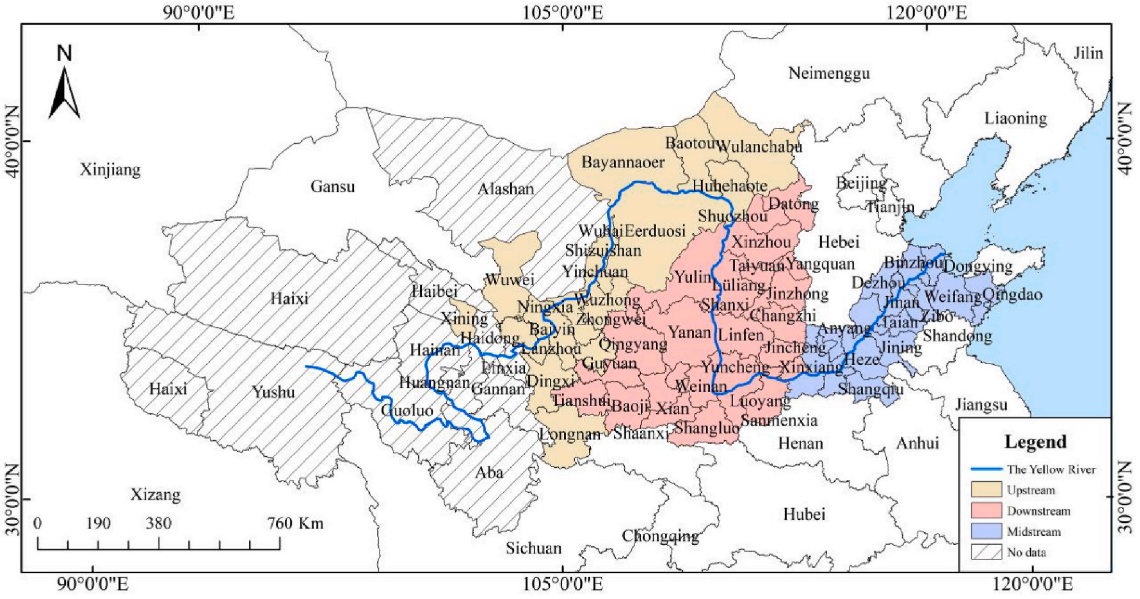


Fig. 1. Overview of study area.

2. Mechanisms of coupling coordination

Coupling coordination refers to a mutually interactive and constraining relationship, achieved through interaction or mutual influence between two or more systems or within a system, resulting in a mutually beneficial and coordinated development [22]. There exists a crucial coupling coordination relationship between UR and ULUE. They interact with each other, impose constraints, and ultimately jointly propel cities towards a direction of positive interaction in the context of sustainable urban development (Fig. 2). Optimizing land use efficiency not only enhances resource utilization but also positively impacts UR. By rational allocation and maximizing the use of land resources, cities can better adapt to external pressures and challenges, enhance urban environmental quality [23], thereby reinforcing UR to withstand natural disasters and environmental changes effectively. Conversely, the enhancement of UR also safeguards and promotes the optimization of ULUE. Cities with high resilience can flexibly respond to various pressures and changes, including improving land use to adapt to different needs, thus ensuring the efficient utilization of land resources [24].

ULUE is a critical indicator for evaluating the economic structure, ecological balance, and infrastructure development status of a city [25]. High ULUE signifies a healthy economic structure, a well-maintained ecological balance, and a rational utilization of infrastructure, all of which are crucial for the sustainable development of a city. Firstly, high ULUE implies a more effective utilization of limited land resources, reducing resource wastage, including land, water, energy, and more [26]. This frugality promotes the sustainable utilization of resources, extends their lifespan, is beneficial for the sustainable development of the city, alleviates excessive pressure on natural resources, thereby enhancing the city's resilience. Secondly, high ULUE usually can reduce traffic problems, reduce personal and urban energy consumption, minimize carbon emissions, help improve urban air quality, and reduce the carbon footprint [27,28]. This is significant for reducing environmental pressure and addressing climate change. Furthermore, high ULUE typically accompanies compact urban planning, making the city more compact and intensive, forming a close-knit community network, enhancing communication, collaboration, and support between communities [29,30]. This compactness of communities can strengthen the social cohesion of the city, reinforce social relationships, and is advantageous for the city's collective resilience and adaptability when facing various challenges and disasters [31,32]. Moreover, high ULUE also contributes to reducing the risk of natural disasters. Through more effective land use, construction can be avoided in disaster-prone areas, reducing the impact of natural disasters on the city, including floods, landslides, mudslides, etc. Finally, high ULUE can enhance the value and utility of land, promoting the city's economic development [12]. By efficiently utilizing land resources, cities can gain more economic benefits, strengthening the city's resistance and resilience in the face of economic fluctuations. Conversely, low ULUE may exacerbate the vulnerability of the city. Firstly, low ULUE leads to resource wastage and increased pressure; the city's land, water, energy, and other resources are inefficiently utilized [33] With the growth of the city's population and economy, demand for these resources also increases, intensifying resource scarcity and pressure. Secondly, low ULUE often accompanies excessive land development and coverage, causing ecosystem damage, increasing environmental burdens, posing threats to the surrounding ecological environment of the city, and augmenting the risk of natural disasters and environmental issues faced by the city, such as floods, soil erosion, and ecological imbalances [2]. Additionally, low ULUE leads to traffic congestion and increased energy consumption, resulting in aggravated traffic congestion. Moreover, it also amplifies energy consumption, causing adverse effects on the environment [34]. Lastly, low ULUE may result in uneven urban development; some regions witness resource wastage while others experience resource scarcity, exacerbating social and economic imbalances, augmenting social instability and vulnerability [35].

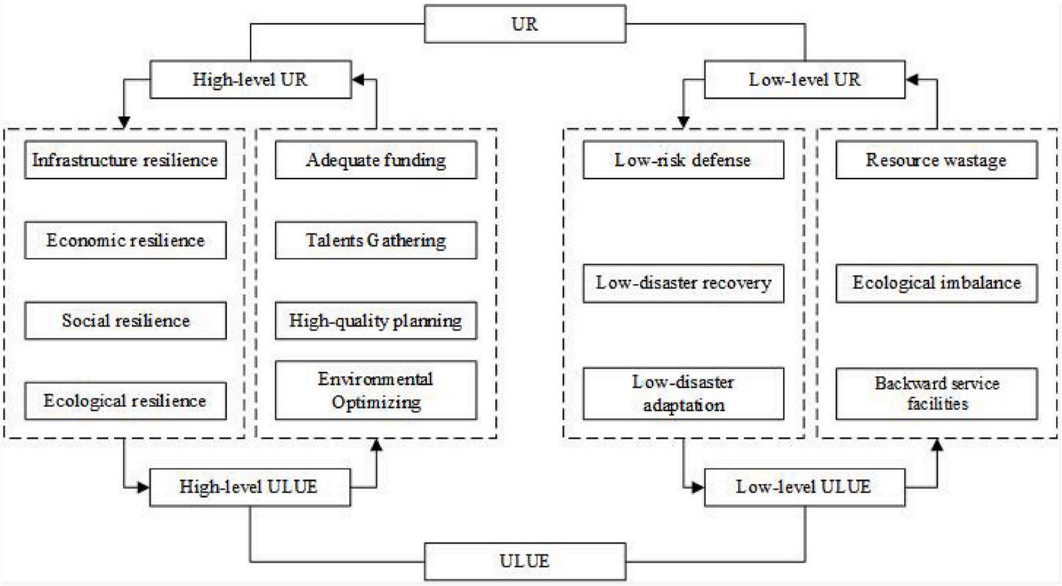


Fig. 2. Coupling coordination mechanism.

UR has a profound and critical impact on land use. High UR demonstrates rapid adaptability and recovery capabilities when facing various shocks and challenges [36]. This resilience is crucial for ensuring efficient land use in a city. High UR can adapt to constantly changing social, economic, and environmental needs by flexibly adjusting land use planning. This flexible land use planning allows cities to quickly adjust land allocation and functions to accommodate population growth, the development of emerging industries, or the occurrence of unforeseen circumstances. Additionally, cities with high UR tend to adopt multifunctional land use strategies, enabling land to meet a variety of different needs, including residential, commercial, green spaces, cultural, and educational purposes, thus maximizing ULUE [37]. In contrast, cities with low UR often face difficulties when dealing with shocks. This not only severely impacts the functioning of the city but also has negative effects on land use [38]. When a city is in a state of paralysis, ULUE sharply decreases, making it challenging to adjust land planning effectively and in a timely manner to meet new demands. The reconstruction process can lead to significant land wastage, as the demolition of existing structures and infrastructure, as well as new construction, require a large amount of land. This severely affects the rational utilization of land resources. Temporary land use may also arise in disaster response, often lacking planning and coordination, further exacerbating issues of irrational and inefficient land use.

3. Materials and methods

3.1. Methods

3.1.1. Coupling coordination degree

The coupled coordination degree model was usually used to express the overall efficiency and coordination effect, so this model was chosen to calculate the CCDUU in the YRB, and the formula were as follows [39,40]:

$$D = \sqrt{CT} \tag{1}$$

$$T = \alpha u_1 + \beta u_2 \tag{2}$$

$$C = \left\{ u_1 u_2 \Big/ \left((u_1 + u_2)/2 \right)^2 \right\}^{\frac{1}{2}} \tag{3}$$

where T is the comprehensive level of UR and ULUE; C is the coupling degree between UR and ULUE; u_1 and u_2 are the UR and ULUE index, respectively; α and β are the contribution degrees of UR and ULUE, respectively, where they are considered to be equally important.

In order to be able to intuitively reflect the CCDUU, this paper divides it into severe dissonance, moderate dissonance, mild dissonance, primary coordination, intermediate coordination, and advanced coordination, and the specific division standard and the corresponding types are shown in Table 1.

3.1.2. Kernel density estimation

The kernel density function can visualize the dynamic evolution of the overall difference of CCDUU in different study periods by exploring the convergence of the function curve and the change of convergence range, so this model was used to investigate the distribution and evolution [41], and the formula were as follows:

$$f(x_0) = \frac{1}{Nh} \sum_{i=1}^{N} K\left(\frac{X_i\text{-}x_0}{h} \right) \tag{4}$$

where, N is the number of sample observations and h is the bandwidth; K(*) denotes a kernel function.

3.1.3. Spatial autocorrelation model

(1) Global spatial autocorrelation

The global Moran's I was used to test whether the spatial phenomenon has a clustering effect on the YRB [42].

Table 1
CCDUU type division.

Degree of CCDUU	Type of CCDUU
$0 < D \leq 0.2$	Severe dissonance
$0.2 < D \leq 0.3$	Moderate dissonance
$0.3 < D \leq 0.4$	Mild dissonance
$0.4 < D \leq 0.6$	Primary coordination
$0.6 < D \leq 0.8$	Intermediate coordination
$0.8 < D \leq 1$	Advanced coordination

$$Moran's\ I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})(x_j - \overline{x})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \tag{5}$$

$$S^2 = \frac{1}{n}\sum_{j=1}^{n}(x_i - \overline{x})^2 \tag{6}$$

where: n is the number of cities; x_i and x_j is the CCDUU between cities i and cities j; W_{ij} is the spatial weight value between cities i and cities j; $\overline{x}$ and S^2 is the mean and standard deviation.

(2) Local spatial autocorrelation

The local Moran index was used to judge which specific cities have agglomeration in their CCDUU [43], with the following formula:

$$I_i = \frac{\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})(x_j - \overline{x})}{S^2} \tag{7}$$

3.1.4. GWR

The GWR model was used to explore factors that take into account geographical location [44], the model has the form:

$$Y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{p} \beta_k(u_i, v_i)X_{ij} + \varepsilon_i \tag{8}$$

where (u_i, v_i) is the spatial location of i; X and Y are the explanatory and explained variables; p is the number of explanatory variables; $\beta_0(u_i, v_i)$ is the regression constant; $\beta_k(u_i, v_i)$ is the regression parameter; and ε_i represents the residuals.

3.2. Selection of indicators

3.2.1. UR

By deeply understanding the core concepts of UR, leverages insights from established indicators used in previous studies [40,45], and adhering to sound principles for constructing an indicator system, then takes Entropy weight-topsis model to measure the UR. A total of 23 indicators are thoughtfully chosen, representing the four key urban subsystems: infrastructure, economy, society, and ecology. These indicators not only encompass the foundational elements of urban areas but also effectively mirror the core features and stages of resilience, resulting in a well-coordinated indicator system. For a detailed list of specific indicators, please refer to Table 2.

Table 2

Comprehensive evaluation index system for UR in the YRB.

Target layer	The standard layer	Index layer	attribute
Urban resilience	Infrastructure resilience	Internet penetration rate	+
		Mobile Phone Penetration Rate	+
		Road area per capita	+
		Number of buses per 10,000 people	+
		Drainage Pipe Density	+
		Gas penetration rate	+
	Economy resilience	General budgetary income of local finances	+
		Gross Domestic Product	+
		Proportion of tertiary industry in GDP	+
		Per capita retail sales of consumer goods	+
		Science and Education Expenditures as a Percentage of Fiscal Expenditures	+
	Society resilience	Number of hospital beds per 10,000 people	+
		Number of doctors per 10,000 people	+
		Share of employees in public administration and social organizations	+
		Number of university students per 10,000 people	+
		Urban registered unemployment rate	+
	Ecological resilience	Industrial sulfur dioxide emissions	−
		Industrial wastewater emission	−
		Industrial soot (dust) emission	−
		Greening coverage rate of built-up areas	+
		Green space per capita	+
		Harmless treatment rate of domestic garbage	+
		Comprehensive utilization rate of general industrial solid waste	+

3.2.2. ULUE

When measuring ULUE, it is imperative to take into account the holistic economic, social, and ecological advantages, aiming to steer clear of repetitive "coarse development models" [2,46], In this study, environmental pollution has been integrated as an unfavorable output within the assessment criteria. For a detailed list of specific indicators, please refer to Table 3.

3.2.3. Selection of impact factors

The CCDUU in the YRB is influenced by various factors such as economic, demographic, and governmental factors, making its underlying dynamics quite complex. Drawing on the achievements of previous research [12,19,47], and taking full account of the reality of the YRB, considering data availability, this study ultimately selects indicators from 5 major aspects that impact the two systems (Table 4).

3.3. Data sources

The data needed for this study mainly include vector data of the YRB, vector data of provincial and municipal administrative divisions in the YRB, and socio-economic data of 54 prefecture-level cities in the YRB.

The vector data of the YRB and the vector data of provincial and municipal administrative divisions in the YRB are obtained from the Geospatial Data Cloud Platform; the statistical data came from EPS database and the national economic and social development statistical bulletin of the cities in the YRB.

4. Results and analysis

4.1. Overview of CCDUU

The CCDUU were measured using coupling coordination degree model for various cities from 2013 to 2020. Time trend charts and spatial distribution maps were created to illustrate the regional differences (Fig. 3, Fig. 4). Overall, CCDUU was relatively good, with high-value areas mainly distributed in provincial capitals or economically developed cities in the middle and lower reaches. CCDUU showed an increasing trend year by year, with CCDUU in the lower reaches higher than in the middle reaches. The lowest CCDUU was in the upper reaches. During the study period, the overall mean for the entire research area was 0.5869. It increased from 0.5382 in 2013 to 0.6429 in 2020, representing a growth rate of 19.45 %. Looking at the different basins, the efficiency mean in the upper reaches was 0.5595, increasing from 0.4989 at the base year to 0.6196 at the end of the study period, indicating a growth rate of 24.19 %. The efficiency mean in the middle reaches was 0.5947, increasing from 0.5462 to 0.6553, resulting in a growth rate of 19.97 %. In the lower reaches, the efficiency mean was 0.6120, increasing from 0.5820 to 0.6521, reflecting a growth rate of 12.04 %.

4.2. Temporal and spatial characteristics analysis of CCDUU

4.2.1. Temporal characteristics analysis of CCDUU

The kernel density estimation method is used to study the dynamic evolution trends of CCDUU in the entire region, upstream, middle reaches, and downstream areas.

At the overall domain leve. Fig. 5(a) illustrates the spatiotemporal dynamic evolution characteristics of CCDUU in the Yangtze River Basin (YRB) from 2013 to 2020. In general, the kernel density center of CCDUU in the YRB gradually shifted to the right, and the function extended to the right on the horizontal axis projection, indicating a progressive increase in CCDUU levels across cities during the study period. Moreover, the regional disparity of CCDUU was gradually widening. Specifically, the main peak center of the kernel density curve shifted to the right with accumulating years, signifying a continuous increase in CCDUU in the YRB from 2013 to 2020. Additionally, the width of the peaks fluctuated and narrowed in the later stages of the study, suggesting a diminishing multi-peak phenomenon and a pronounced "catch-up effect" of CCDUU in lower regions to higher regions. The kurtosis change indicated an accelerated growth of CCDUU with coexisting homogeneity and heterogeneity. Notably, major cities witnessed a slight increase in CCDUU during the study period. he shape analysis revealed a transformation from a "sharp peak-multiple peaks" form to a "sharp

Table 3
Comprehensive evaluation index system for ULUE in the YRB.

Index type	Category	Specific index
Input index	Land input	Built-up area
	Labor input	People employed in secondary and tertiary industries
	Capital input	Total investment in fixed assets
Expected output indicator	Economic output	Gross domestic product of secondary and tertiary industries
	Economic output	Total retail sales of consumer goods
	Social output	Per capita disposable income
	Environmental output	Park green area
Unexpected outputs	Environmental pollution	Industrial sulfur dioxide emissions
		Industrial wastewater emission
		Industrial soot (dust) emission

Table 4
Impact factors of CCDUU.

Variable name	Variable description	unit
Government support	Regional fiscal expenditure as a proportion of GDP	%
Population density	Population density	Person/km2
Urban regional innovation	Number of patent applications	Number
The degree of openness	Actual amount of foreign capital used	Ten thousand dollars
The degree of urban-rural disparities	Urban-rural income ratio	%

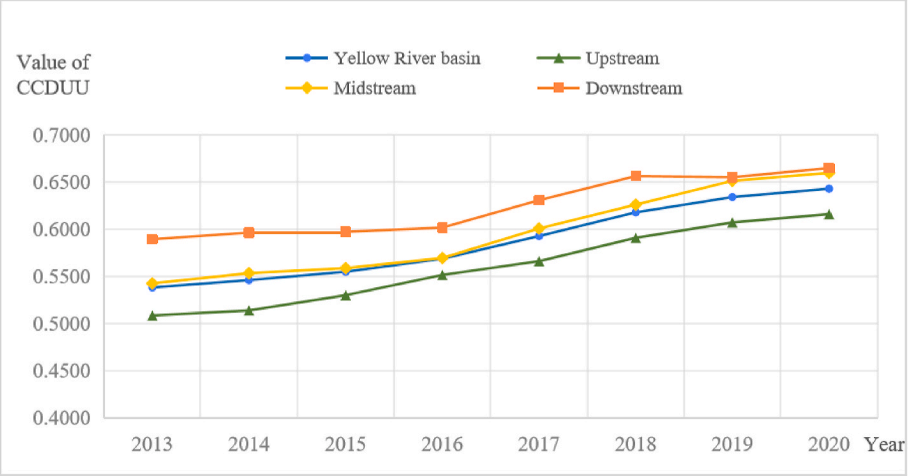


Fig. 3. Trends of CCDUU in the YRB from 2013 to 2020.

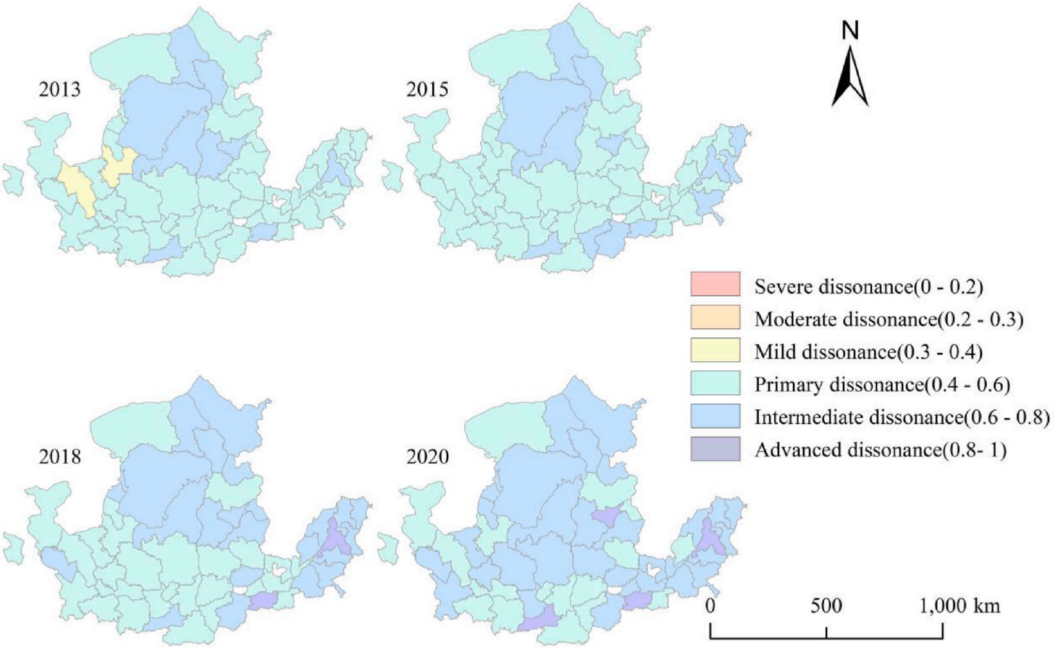


Fig. 4. Spatial distribution of CCDUU.

peak" form in CCDUU across various cities, with the main peak's projection between 0.5 and 0.6 on the x-axis. This transformation signified a convergence of CCDUU within their respective peak value intervals. Furthermore, the disappearance of the main peak and the second side peak over the study period indicated the gradual fading of extreme values in CCDUU across cities.

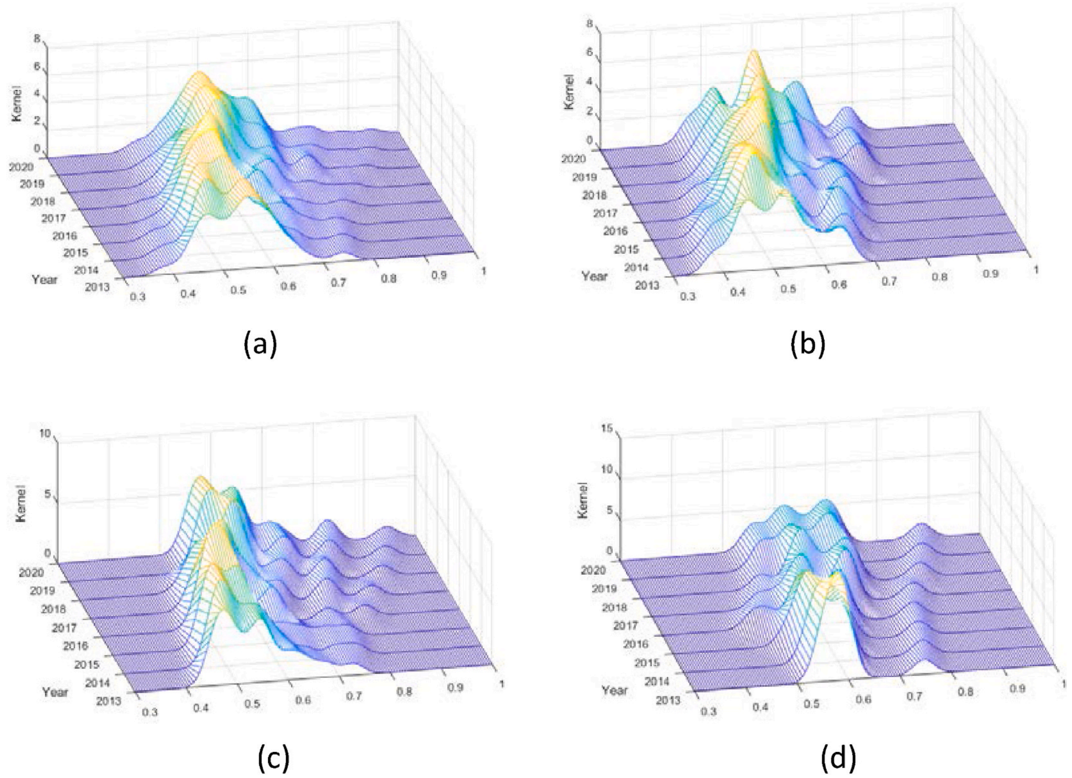


Fig. 5. Dynamic evolution of CCDUU in the YRB.

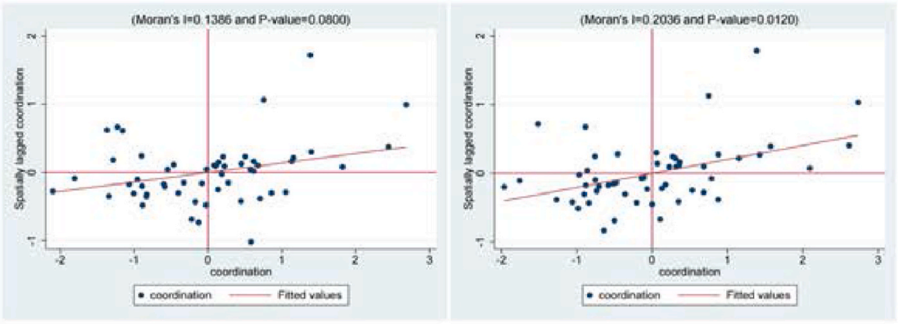
Different Regional Levels. This section focuses on analyzing the evolving patterns of CCDUU differences in the upper reaches, middle reaches, and lower reaches of the YRB. Fig. 5(b), (c), and (d) respectively illustrate the dynamic evolution process of CCDUU in the upper, middle, and lower reaches. Firstly, from the movement of the kernel density curve, the centers of the density functions in the upper, middle, and lower reaches generally exhibit a trend of moving to the right, indicating a continuous increase in CCDUU in these regions. Secondly, the widths of the main peaks in the upper, middle, and lower reaches continuously expand and change from relatively narrow peaks to relatively broad peaks as the research period progresses. However, the widths of the side peaks continually narrow, becoming sharp peaks. This indicates that the development of CCDUU in the upper, middle, and lower reaches tends to be imbalanced within each region. Cities are distributed at different levels of development, but a few areas show concentrated distribution. It is apparent that the widths of the peaks in the upper, middle, and lower reaches generally tend to increase, albeit at a slow pace. This suggests that the overall dispersion of CCDUU in the upper, middle, and lower reaches is continuously expanding. In terms of the number of peaks, the curves in the upper, middle, and lower reaches display significant multi-peak features and exhibit a right-skewed expansion characteristic, which becomes more pronounced with the accumulation of years. This demonstrates a serious polarization phenomenon in the ecological CCDUU between the upper, middle, and lower reaches.

4.2.2. Spatial characteristics analysis of CCDUU

(1) Global autocorrelation

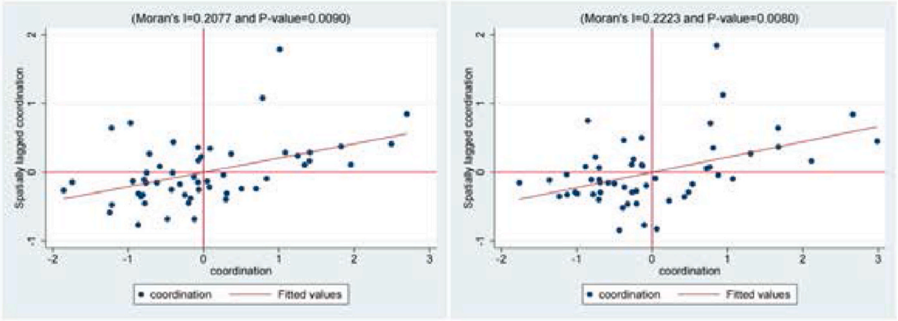
Table 5
Global Moran's I value of CCDUU from 2013 to 2020.

Year	Global Moran's I	Z value	P value
2013	0.139	2.107	0.035
2014	0.204	2.987	0.003
2015	0.208	3.035	0.002
2015	0.222	3.249	0.001
2017	0.216	3.157	0.002
2018	0.244	3.538	0
2019	0.21	3.09	0.002
2020	0.206	3.031	0.002



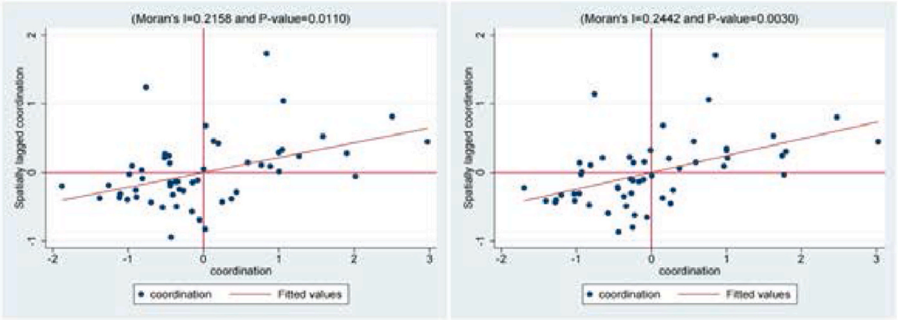
A. 2013

B. 2014



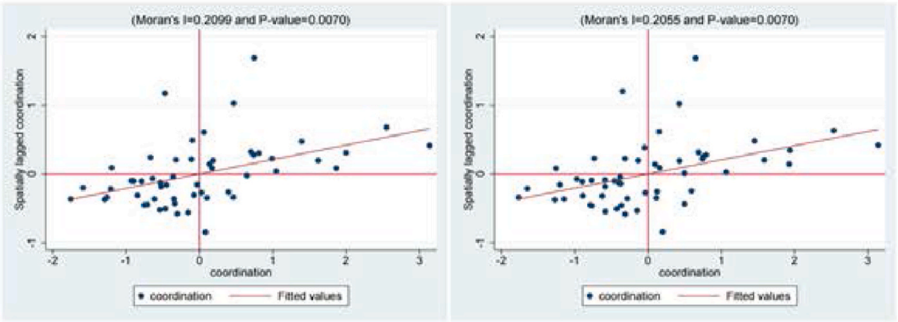
C. 2015

D. 2016



E. 2017

F. 2018



G. 2019

H. 2020

Fig. 6. Moran's I scatterplot of CCDUU in the YRB.

Using GeoDa software to calculate the global Moran's I of CCDUU in the YRB based on the geographic distance matrix to reflect spatial correlation, the results (Table 5) demonstrate that the global Moran's I for the years 2013–2020 are all positive and significant, with P-values less than 0.05, passing the confidence test at the 95 % level. This indicates that CCDUU in the YRB has significant positive spatial autocorrelation, characterized by "high-high clustering" or "low-low clustering."However, in terms of the magnitude of the global Moran's I, the Moran's I of CCDUU from 2013 to 2020 is all less than 0.244. This suggests that despite the significant positive spatial autocorrelation, the spatial association is not exceptionally strong. The socio-economic development and regional resource endowments vary considerably across the upstream, midstream, and downstream regions of the YRB. This disparity in spatial correlation implies that the regions have not formed a robust cohesive force. The overall spatial association could be characterized as "moderate-high clustering" or "moderate-low clustering," highlighting the need for further investigation into the underlying factors contributing to this spatial pattern.

(2) Local autocorrelation

Based on the results of the local Moran's I calculations and the scatter plot (Fig. 6), it is evident that the local spatial agglomeration degree of the coupling coordination levels among the 54 cities in the YRB shows a significant fluctuating trend. In 2013, the lowest value of the local Moran's I was 0.139, and it reached the highest at 0.244 in 2018. In 2020, the local Moran's I was 0.206. Most cities' coupling coordination levels are located in the first and third quadrants, indicating a noticeable positive spatial autocorrelation in the coupling coordination among cities in the YRB.

(1) Cities with high-value clustering in the first quadrant of the Moran scatter plot indicate high levels of coupling coordination in those cities, with high levels also observed in the surrounding cities. Key cities in this category include Xi'an, Yulin, Jinan, Zhengzhou, Zibo, Hohhot, Baotou, and others. Taking into account various factors such as economic and social influences, during the period of 2013–2020, the number of cities in the high-value clustering area decreased from 18 to 17.
(2) Cities with low-value heterogeneity in the second quadrant of the Moran scatter plot represent lower levels of coupling coordination in the city with higher levels observed in the surrounding cities. Major cities falling in this category include Yinchuan, Wuhai, Bayan Nur, and Jiaozuo. It's noteworthy that during the period of 2013–2020, Yan'an transitioned from a city with low-value heterogeneity to a city with high-value clustering, and Xining shifted from a city with low-value heterogeneity to a city with low-value clustering. Efforts are needed to enhance the coordinated development of Xining and its surrounding cities by promoting industrial transformation and social security policies.
(3) Cities with low-value clustering in the third quadrant of the Moran scatter plot signify lower levels of coupling coordination in both the city itself and the surrounding cities. This quadrant has the highest number of cities among the four quadrants. Major cities in this category include Anyang, Qingyang, Xinzhou, Yuncheng, Tongchuan, Linfen, Xinxiang, Yinchuan, Tianshui, and others. During the period of 2013–2020, most cities gradually shifted from the third quadrant towards the first and second quadrants.
(4) Cities with high-value heterogeneity in the fourth quadrant of the Moran scatter plot represent higher levels of coupling coordination in the city itself but lower levels in the surrounding cities. During the research period, the number of cities in the fourth quadrant gradually decreased. Key cities in this category include Ulanqab, Lvliang, and Heze. Notably, Lvliang gradually

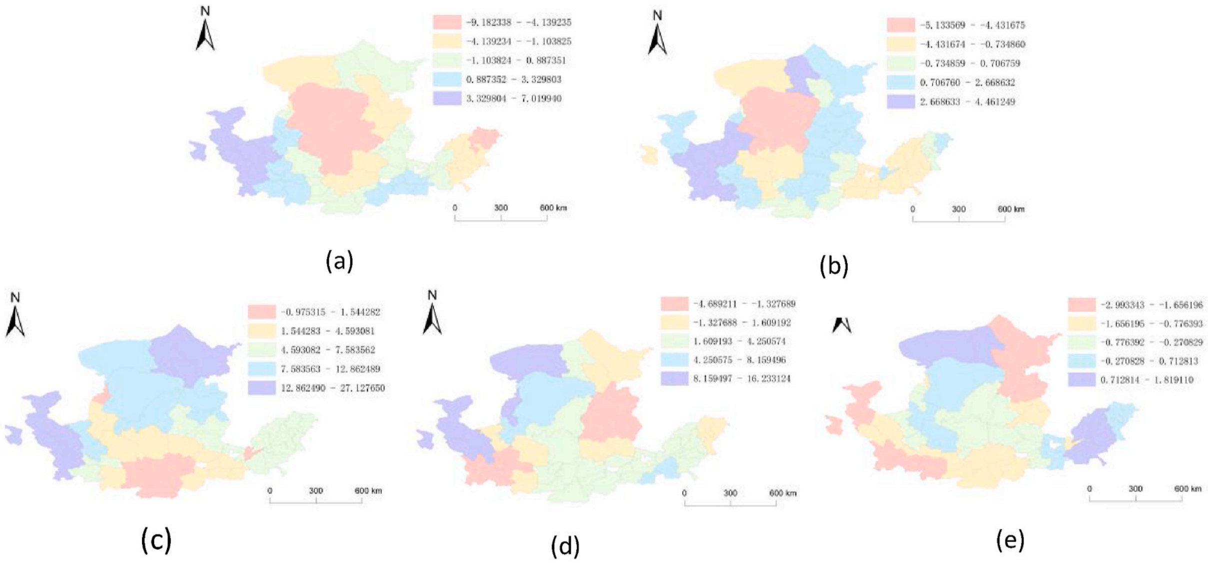


Fig. 7. Spatial distributions of the driving factors of CCDUU in the YRB.

shifted towards the third quadrant, emphasizing the need to strengthen coordinated development in Lvliang and its surrounding regions.

Overall, the 54 cities' coupling coordination levels in the YRB have formed a high coupling coordination clustering area centered around cities such as Xi'an, Yulin, Jinan, Zhengzhou, Zibo, Hohhot, and Baotou. These areas are mostly provincial capitals or economically developed cities, enjoying advantageous geographical locations and relatively developed industrial economies. Moreover, under the influence of policy support, these cities have not only exhibited high coupling coordination levels themselves but have also generated spatial spillover effects, accelerating the effective flow of development factors such as funds, information, labor, and technology in the surrounding regions and thereby promoting the coupling coordination levels of cities in those areas. On the other hand, the low coupling coordination clustering area is primarily centered around cities such as Anyang, Qingyang, Xinzhou, Yuncheng, Tongchuan, Linfen, Xinxiang, Yinchuan, and Tianshui. These cities are mainly located in geographically remote areas and have relatively underdeveloped economies. To address this, tailored approaches should be adopted to boost regional economies based on local circumstances, enhance inter-regional cooperation, and improve coupling coordination levels.

4.3. Analysis of influencing factors of CCDUU

Fig. 7(a), (b), (c), (d), and (e) respectively illustrate the spatial impact of factors including Government support, Population density, Urban regional innovation, The degree of openness, and The degree of urban-rural disparities on CCDUU.

The areas where government support has a significant impact on the improvement of CCDUU are mainly concentrated in the upstream of the YRB, while most of the negatively affected areas are in the middle and downstream. Overall, the impact decreases progressively from upstream to downstream. This is likely because the upstream cities are located in areas with steep terrain and fragile ecosystems. In comparison to the downstream areas, the governments in the upstream regions may place more emphasis on efficient resource utilization, environmental protection, and urban safety in these areas. Consequently, they have implemented stricter planning and control over land use, resulting in a higher level of government support in the upstream cities. On the other hand, the negative impact coefficients are mainly distributed in the middle and downstream cities of the YRB. These areas usually experience rapid economic development, have large urban scales, high population densities, and pronounced imbalances in land resource supply and demand. Governments need to strike a balance between limited resources and environmental protection. Moreover, governments in these areas may prioritize economic and industrial development in government investments, thus overlooking regulation and control in terms of land use efficiency and UR.

Population density has a significant impact on the promotion of CCDUU, which is concentrated in the upper reaches of the YRB. Most of the areas with negative impacts are in the economically developed middle and lower reaches. This is likely because the upper reaches of the YRB have a sparse population, and high population density means more people can share limited resources and services, including infrastructure, education, healthcare, etc., thereby improving the efficiency of resource utilization. Additionally, high population density contributes to industrial agglomeration, forming industrial clusters, promoting common development, collaborative innovation, and economies of scale. However, in the middle and lower reaches, despite relatively good economic development, a high population density with fewer resources can have a more negative impact on cities. In areas with fewer resources and a high population density in the lower reaches, land supply shortages occur, restricting the flexible use and efficiency of land. Furthermore, excessively high population density can also exert pressure on the environment, such as excessive emissions and over exploitation of natural resources, reducing the city's resilience and sustainable development capabilities.

96.3 % of urban regional innovation shows a positive correlation with the promotion of CCDUU, and its impact coefficient is significantly higher than other influencing factors, indicating a significant positive role of urban regional innovation in promoting CCDUU, and it is the most important factor for promoting CCDUU in YRB. There are multiple reasons for the enhancement of CCDUU by regional innovation. Firstly, regional innovation can drive economic structural upgrading and industrial transformation, leading development towards high value-added and high-efficiency areas, enhancing the city's economic competitiveness and risk resistance, thus improving the city's resilience. Secondly, the introduction of innovative technologies and concepts can optimize resource allocation and land use, achieve intelligent and efficient use of resources, avoid excessive land development, and improve land use efficiency. Thirdly, innovation often accompanies the development of green technologies and industries, helping to reduce environmental pollution, promote environmentally sustainable development, further enhancing the city's resilience and land use efficiency. Additionally, to support innovation, the city's governance system will be improved, and planning and land use planning will become more scientifically flexible, achieving coordinated and orderly urban development. Most importantly, innovation requires the aggregation of talents, promoting talent aggregation and intellectual intensity, nurturing high-quality talents, and enhancing the city's innovation capability and resilience.

In 80 % of the cities, the degree of openness shows a positive correlation with the promotion of CCDUU, and the cities with a negative correlation are located in Gansu Province and Shanxi Province. Firstly, this indicates that the overall influence of the degree of openness on CCDUU in the YRB is positively significant. This is likely because foreign investment often drives local economic development and growth, promotes industrial upgrading and innovation, increases employment opportunities, raises people's income levels, thus enhancing UR and improving land use efficiency. Secondly, foreign investment usually accompanies the introduction of advanced technology, management experience, and market networks, promoting technological upgrading and innovation of local industries, reducing the emissions of industrial pollutants, which is favorable for improving UR and land use efficiency. Furthermore, foreign investment can expand markets, improve the efficiency of circulation of goods and services, drive economic activities within the city, helping optimize the city's development structure and thus enhance CCDUU by improving the efficiency of land resource utilization. Additionally, foreign investment usually involves a substantial influx of funds for infrastructure construction and urban development, which can enhance city infrastructure, aid in optimizing the city's development structure, and thereby elevate CCDUU. Foreign investment can also optimize supply chains, improve production efficiency, and enhance the resilience of supply chains, making cities more competitive, thus exerting a positive impact on UR. Finally, foreign investment may introduce new industries, promoting diversified development of local industries, reducing the city's dependence on specific industries, and enhancing UR. Overall, foreign investment generates a positive impact in other regions mainly due to their positive contributions to the economy, technology, market, and infrastructure, which help improve the city's development status, enhance UR, and land use efficiency.

The degree of urban-rural disparities has a negative impact on CCDUU for the majority of cities, with a few cities in downstream Shandong Province showing a positive impact. The exacerbation of urban-rural disparities may lead to uneven resource allocation, imbalanced economic development, and unequal social services, hindering the improvement of UR and ULUE. Uneven resource allocation may lead to excessive concentration of urban resources, while rural areas lack necessary support and investment, thus affecting the resilience of cities and land use efficiency. Imbalanced economic development may bring short-term economic growth, but this growth is often unsustainable, and the economic instability may make cities more fragile. Additionally, unequal social services are also a significant factor. Urban areas have more comprehensive social services, while rural areas may face insufficient service, which could affect population mobility, urban resilience, and high-quality land use. Shandong Province, being a typical agricultural province, may see an increase in urban-rural disparities, encouraging farmers to shift to urban areas for employment, promoting urban prosperity and stability, optimizing industrial structure, and contributing to the enhancement of UR and ULUE.

5. Discussion

5.1. Regional differences in CCDUU in the YRB

CCDUU exhibited a year-on-year growth trend during the study period, with a rapid increase starting in 2015. The possible reason for this could be the formulation of the “National New Urbanization Plan (2014–2020)" in 2014, which advocated for the promotion of new urban construction and drove strategies like the Western Development and Central Rise. This plan required the strict implementation of a land intensive-use system. In this developmental context, the UR and ULUE of the YRB saw significant improvements [48]. The CCDUU of the YRB from 2013 to 2020 was lower reaches > middle reaches > upper reaches, aligning well with the economic development pattern of the YRB. This might be because the downstream areas, due to their favorable economic conditions, had ample funds and resources to balance high-quality and sustainable development [49]. Moreover, economically prosperous regions tended to focus on innovation and sustainable development in terms of industrial structure, making reasonable plans, thus ensuring a coordinated development of UR and ULUE. On the other hand, the upstream areas had higher and more vulnerable terrain making it unfavorable for intensive and efficient land use [50]. Additionally, these areas had weaker economic foundations and poorer infrastructure. They might only be capable of focusing unilaterally on either economic development or ecological safety without the ability to balance both aspects [51].

5.2. Analysis of influencing factors

The enhancement of CCDUU in the YRB is influenced by multiple factors, presenting specific spatial distribution characteristics and exerting varying degrees of influence on CCDUU. Firstly, the influence of government support on CCDUU enhancement is primarily concentrated in the upstream areas of the YRB. This may be because cities in the upstream region are located in areas with steep terrain and fragile ecological environments [52]. The government's investment in efficient resource utilization, ecological environment protection, and urban safety has a more effective impact on CCDUU. In contrast, cities in the middle and downstream regions may prioritize economic and industrial development, resulting in a negative impact. Secondly, the influence of population density on CCDUU is concentrated in the upstream region. The low population density in the upstream areas facilitates resource sharing and enhances resource utilization efficiency. Conversely, the high population density in the middle and downstream areas limits flexible land use and efficiency, causing environmental pressure and reducing UR and sustainable development capabilities [16]. Moreover, regional innovation has the most significant impact on CCDUU enhancement. Innovation drives economic structural upgrades and industrial transformation, enhancing a city's economic competitiveness and risk resilience. It also optimizes resource allocation and land use, promoting environmental sustainability, and strengthening UR and ULUE. Furthermore, the impact of the degree of openness on CCDUU shows a positive correlation. Foreign investment promotes urban infrastructure development and improves urban development structures, enhancing UR and ULUE. Finally, the influence of the urban-rural disparity level on CCDUU has a negative effect. Excessive urban-rural disparities may lead to uneven resource distribution, imbalanced economic development, and unequal social services, hindering the improvement of UR and ULUE. However, in Shandong Province, being an agricultural province, an increase in urban-rural disparities may encourage farmers to migrate to urban areas for employment, optimizing industrial structures and contributing to the enhancement of UR and ULUE. These influencing factors intertwine and profoundly impact the level and performance of CCDUU in YRB cities. Therefore, a comprehensive understanding and effective utilization of these influencing factors are crucial for achieving sustainable urban development and optimizing land use.

6. Conclusions

Based on panel data for the Yellow River Basin (YRB) from 2013 to 2020, the Coupling Coordination Degree (CCDUU) of the YRB was measured using a coupling coordination model. Exploratory spatial data analysis and kernel density estimation were introduced to characterize the spatiotemporal evolution characteristics of CCDUU. Combined with the GWR model, the driving mechanisms of CCDUU among different cities were analyzed. Our conclusions are as follows:

(1) From the perspective of CCDUU calculation results, at the regional level, there has been a continuous growth trend, with a slow increase in CCDUU from 2013 to 2015, followed by a steep increase after 2015. At the sub-basin level, CCDUU in the downstream region is higher than that in the middle reaches, and the upper reaches have the lowest CCDUU. However, the growth rate of CCDUU in the upper reaches is significantly higher than in other regions, indicating the highest potential.
(2) Regarding the spatiotemporal pattern evolution, CCDUU in the YRB continuously increased from 2013 to 2020. Areas with lower CCDUU showed a significant "catch-up effect" to higher areas. The differences in CCDUU among various regions are narrowing, alleviating the polarization phenomenon, and extreme values are gradually disappearing. Although there is a significant positive spatial correlation in CCDUU across the YRB, due to significant differences in socioeconomic development and regional resource endowments among the upper, middle, and lower reaches of the YRB, the spatial correlation is not tight enough, and a strong synergy among the regions has not been formed.
(3) In terms of the driving mechanisms, regional innovation has the most significant positive impact on CCDUU, followed by the degree of openness. These two factors have a positive influence on the entire region. However, for the upper reaches, where the ecological vulnerability is strong, the infrastructure is weak, and the economic foundation is poor, the impact of government support and population density on promoting CCDUU is mainly concentrated in the upper reaches of the YRB. In contrast, in the downstream areas where there is a concentration of population and better economic conditions, the impact is relatively small or even negative. The level of urban-rural disparity has a negative effect on CCDUU for most regions. However, as it can drive farmers to migrate to urban areas for employment, it has a positive effect on most cities in Shandong Province, which is primarily agricultural.

Ultimately, based on the analysis results, a series of policy recommendations are proposed to further promote UR and ULUE. Firstly, it is recommended to strengthen government support and planning control, with a special focus on supporting the upstream regions, to achieve efficient resource utilization, environmental protection, and urban safety. Reinforce strict land use planning and control measures to ensure rational distribution and utilization of land resources. Secondly, reasonable population density management policies should be implemented, encouraging rational population movement and distribution, particularly promoting population migration to upstream areas to alleviate population pressure in downstream cities and enhance resource utilization efficiency. Thirdly, it is advisable to enhance openness, attract foreign investment, optimize the business environment, vigorously promote regional innovation and industrial upgrading, formulate innovative policies, support the development of innovative technologies and green industries, drive economic structural upgrades and industrial transformation to improve UR and ULUE in cities. Lastly, efforts should be made to narrow the urban-rural disparity, promote integrated urban-rural development, and optimize resource allocation. These policy recommendations aim to comprehensively consider the impact of various factors on urban development, achieve sustainable development, optimize land use, and enhance CCDUU. Governments should formulate and implement these policies based on specific circumstances to propel the sustainable development of YRB cities.

Data availability statement

The authors are unable or have chosen not to specify which data has been used.

CRediT authorship contribution statement

Haiyang Li: Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Methodology, Formal analysis. **Mengying Zhu:** Writing – review & editing, Writing – original draft, Resources. **Zhaojun Wang:** Visualization, Resources, Data curation. **Jiarong Hong:** Writing – review & editing, Visualization, Resources, Data curation. **Ying Wang:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition.

Declaration of competing 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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