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Research on the Coupling and Coordination of Land Use Efficiency and Land Ecological Security in Beijing-Tianjin-Hebei Urban Agglomeration

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Abstract: To elucidate the dynamic equilibrium between urban land use efficiency (ULUE) and ecological carrying capacity (ECC) and to devise a bi-dimensional regulatory strategy that enhances economic performance while establishing ecological safeguards, this study employs panel data from the Beijing-Tianjin-Hebei (BTH) urban agglomeration spanning the period from 2014 to 2023. Utilizing the SBM-Undesirable model, comprehensive index method, and coupling coordination degree model to construct the ULUE and land ecological security index systems, we assess the spatiotemporal dynamics of ULUE-ECC coupling coordination within the BTH region. Results indicate a differentiated evolutionary trend among the 13 cities' coupling coordination indices from 2014-2023. Beijing and Langfang exhibited persistently high coupling coordination, while Tianjin and Shijiazhuang showed significant increases in coupling coordination. Conversely, cities like Tangshan and Hengshui experienced degradation in later stages. Spatially, regional coordination displays a "core-periphery" gradient, with central cities maintaining high-quality coordination while south-central Hebei and resource cities exhibit moderate dysfunction. Cross-sectional data from 2023 reveal an overall evolution toward higher-order coupling coordination, with an increased proportion of high-quality coordinated cities. However, localized ecological security risks are evident, exemplified by Tangshan's plummeting coupling coordination index, underscoring the staged imbalance between ULUE and ecological protection.

Keywords: Land ecological security, Land use efficiency, Coupling harmonization

1. Introduction

As the basic carrier of economic and social development, the efficient allocation and structural optimization of urban land is the core demand of the current urbanization process. Rapid urbanization has led to problems such as population explosion, resource overconsumption, and industrial lag, which have aggravated ecological pressure. How to improve the efficiency of land use while guaranteeing ecological safety may become a key issue under the concept of sustainable development. With the promotion of national ecological civilization construction, exploring a synergistic path between efficient land use and ecological protection has become an urgent task for achieving sustainable urban development [1]. Some foreign scholars have analyzed land use efficiency through spatial econometric models [2] and multi-dimensional indicators [3, 4] (e.g., Zitti's efficiency study in Mediterranean region); domestic scholars have focused on DEA [5, 6] models (BCC, SBM, etc.),

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for example, Li Changjian has used the dual-objective DEA-SBM [7]to evaluate the land use efficiency of urban agglomerations. In the field of land ecological security, most of the foreign studies are based on satellite images to analyze cover change and security assessment [8] (e.g., Moarrab Y), while domestic scholars have constructed the index system through PSR model [9], DPSIR model [10], and EES model [11], etc., and combined with the comprehensive index method [12], ecological footprint method [13], etc., they have extended the in-depth studies to security early warning [14, 15], and diagnosis of obstacle factors[16, 17]. In recent years, with the deepening of the concept of sustainable development, some scholars have begun to pay attention to the coupling and coordination mechanism of land use efficiency and ecological safety [18] and explored the synergistic path between the two. In conclusion, while current research offers substantial insights into urban land use efficiency or land ecological security independently, further investigation is needed regarding their coupling and coordinated development. A spatiotemporal analysis of land use efficiency and ecological security coupling within the Beijing-Tianjin-Hebei (BTH) urban agglomeration, China's core northern economic zone, was conducted from 2014-2023. Employing the SBM-Undesirable model, comprehensive index method, and coupling coordination model across 13 BTH cities, this study informs regional ecological barrier construction and precision economic governance, offering evidence-driven policy recommendations for optimized land resource allocation and synergistic regional development-ecological protection strategies.

2. Study area & evaluation indicators

2.1. Study area

The Beijing-Tianjin-Hebei region, China's "Capital Economic Circle", encompasses Beijing, Tianjin, and 11 prefecture-level cities in Hebei Province, with a total area of 218,600 square kilometers, a population of approximately 110 million, and an urbanization rate of 68.7%. Although the region accounts for less than 3% of the country's area, its population and GDP account for 8.1% and 8.26% of the national total (GDP of 10.03 trillion yuan in 2022) [19, 20]. Regional economic expansion and population concentration exacerbate ecological and environmental challenges, threatening ecological security and sustainable development. This study examines the spatiotemporal dynamics and determinants of ecological security patterns across 13 Beijing-Tianjin-Hebei prefectural-level cities from 2014 to 2023. Data, sourced from national economic, social development, and environmental bulletins, underwent dimensionless processing via the extreme difference method for urban land ecological security evaluation.

2.2. Construction of the indicator system

2.2.1. Indicator system for evaluating land-use efficiency

Land-use efficiency, gauged by the input-output ratio per unit area, signifies land-use intensity. Current research predominantly assesses land-use efficiency via a two-dimensional "input-output" indicator system. In this study, we start from the three dimensions of inputs, desired outputs, and non-desired outputs, select evaluation indexes based on the principles of reasonableness, scientificity, and operability, and refer to the research of scholars such as Wen Ting [21], etc. To comprehensively consider the various benefits of land use, and finally select eight indexes to constitute the evaluation system of urban land use efficiency, as shown in Table 1.

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Table 1: Evaluation index system of land use efficiency of Beijing-Tianjin-Hebei city cluster

target level	standardized layer	clarification	indicator layer
Urban Land Utilization efficiency	throw oneself into	land input	Built-up area/km^2
		capital investment	Average land investment in fixed assets/10^4yuan - km^2
		labor input	Average number of secondary and tertiary industry workers/person -km^2
	Expected outputs	Economic Benefits Social Benefits Environmental benefits	GDP per capita / 10^4 yuan - km^2 Per capita disposable income of urban residents/yuan Greening coverage rate of built-up area/%
	Non-expected outputs	Negative environmental benefits	Average municipal sewage discharge/10^4 t-km^2 Average industrial emissions/103m^3 -km^2

2.2.2. Construction of urban land ecological security evaluation index system

In the existing research, scholars mostly adopt the "Pressure-State-Response" (PSR) model and its improved and extended models, such as DSR and DPSIR, to determine the ecological security evaluation index system. [22, 23] However, the interdependence of indices across levels in the aforementioned models may compromise the objectivity and validity of evaluation results due to potential state index influence on pressure and response indices. However, the indicators of each level in the above models are not relatively independent, and the indicators of pressure and response may be influenced by the state indicators and affect the evaluation results, which may affect the objectivity and scientificity of the evaluation results [24]. This study employs the EES model, evaluating 14 indicators across economic, social, and environmental dimensions. Indicator weights are determined via a combination of subjective and objective methodologies, specifically entropy weighting and hierarchical analysis. Due to space limitations, the specific formulas of the weight determination method are referred to the research results of Han Chenxiao and other [25] scholars, as shown in Table 2:

Table 2: Ecosystem indicator system and weights

target level	standardized layer	indicator layer	causality	Combined weights
urban land	economics	Per capita public expenditure/\$$10^4$ - km^2	+	0.187
		Share of tertiary sector in GDP/%	+	0.043
		GDP per capita/\$	+	0.053
	societies	Population density/person - km^2	_	0.149
		Completed housing area per capita/m^2	+	0.073
		Level of urbanization/%	_	0.042
	matrix	Forest cover/%	+	0.055
		Water resources per capita/m^4-person	+	0.066
		Green space per capita/m^2	+	0.045
		Composite air pollution index/μg -m3		0.057

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Table 2: (continued)

		Regional ambient noise/dB	_	0.037
		Municipal sewage treatment rate/%	+	0.036
		Per capita environmental expenditure/$\$10^4$ - km^2	+	0.157

3. Research methodology

3.1. SBM-undesirable modeling

This study adopts the improved SBM model [26] based on the traditional DEA model, and also considers the effects of slack variables, desired indicators, and non-desired indexes on the efficiency value of each decision-making unit, to improve the scientificity and accuracy of the measurement results. For the specific formula, see the research of Yang Qingke [27] and other scholars. The model formula is as follows:

$$\text{Min}\rho = \frac{1-\frac{1}{N}\sum_{n=1}^{N}\frac{s_n^x}{x_{n0}}}{1+\frac{1}{M+1}\left(\sum_{m=1}^{M}\frac{s_m^y}{y_{m0}}+\sum_{i=1}^{I}\frac{s_i^u}{u_{i0}}\right)} \tag{1}$$

$$S\cdot T\cdot \sum_{k=1}^{K} z_k\, x_{nk} + s_n = x_{n0}, n = 1,2,\cdots,N \tag{2}$$

$$\sum_{k=1}^{K} z_k\, y_{mk} - s_m^y = y_{m0}, m = 1,2,\cdots,M \tag{3}$$

$$\sum_{k=1}^{K} z_k\, u_{mk} + s_i^u = u_{i0}, i = 1,2,\cdots,I \tag{4}$$

$$\sum_{k=1}^{K} z_k = 1, z_k \geq 0, s_n^x \geq 0, s_m^y \geq 0, s_i^u \geq 0 \tag{5}$$

In the data envelopment analysis model, the efficiency coefficient ρ characterizes the comprehensive efficiency level of the decision unit, and its mathematical definition domain is (0,1]. Whenρ =1, it indicates that the decision unit is on the production frontier and all input and output indicators are Pareto-optimized, and the corresponding input slack variabless_n^x (input redundancy), undesired output slack variables_i^u (output excess), and desired output slack variables_m^y (output gap) are all equal to zero. Whenρ < 1, it reveals that there is an efficiency loss in the decision unit, and the Pareto improvement of the production system should be achieved by optimizing the allocation of inputs (reducings_n^x), improving the management of undesired outputs (reducings_i^u), and increasing the efficiency of desired outputs (reducings_m^y).

3.2. Composite index method

In this study, the urban land ecological security evaluation system constructed based on the environmental-economic-social (EES) system model adopts the linear weighted synthesis method of the multi-criteria decision analysis method to realize the quantitative integration of indicators. The mathematical model can be expressed as follows: the integrated safety index $u = \sum_{j=1}^{n} w_{ij} \times x_{ij}, \sum_{j=1}^{n} w_{ij} = 1$, wherew_{ij} characterizes the weight coefficients of the criterion layer, reflecting the relative importance of each subsystem, andx_{ij} represents the observed values of the indexes normalized by the extreme difference, eliminating the influence of the difference in the scale. Given the land ecological security characteristics and land resource endowment in the Beijing-Tianjin-Hebei region, as well as drawing on relevant research results, the five-level

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ecological security grading standards for the Beijing-Tianjin-Hebei urban agglomeration were established, as shown in Table 3.

Table 3: Criteria for grading the ecological security of urban land

safety value	[0,0.2]	[0.2,0.4]	(0.4,0.6)	[0.6,0.8]	(0.8,1.0)
security level	insecurity	less secure	criticality safety	safer	surety

3.3. Coupled coordination model

Coupling degree is a measurement index to measure the cooperation and synergistic development between two or more systems, and the coupling coordination degree is a mathematical model to further study the coordination state between the elements of the coupled system based on the coupling degree, and the coupling coordination model of this study draws on the research of Liao Chongbin[28] with the following specific formulas:

(1) The coupling degree model reflects the degree of coupling between the two systems and is given by Eq:

$$C = \left[\frac{u_1 u_2}{\left(\frac{u_1+u_2}{2}\right)}\right]^{\frac{1}{2}} \tag{6}$$

$$T = Af(x) + Bf(y) \tag{7}$$

$$D = \sqrt{C \times T} \tag{8}$$

In Eq. 6, C represents the coupling degree, u1 denotes the level of urban land use efficiency, and u2 denotes the level of urban land use security; in Eq. 7, T represents the degree of coordination, and A and B are the coefficients to be determined, and in this study, they are of equal importance, so they are all valued at 0.5; in Eq. 8 D represents the degree of coupling coordination, and the values involved in the above equations are all valued in the range of 0 to 1. Drawing on the research of Gu Yimin et al. [29] The degree of coupling coordination is divided into grades according to the corresponding criteria, and the specific grade classifications are detailed in Table 4. Based on the research of Gu Yingmin et al. , and combined with the actual situation of the Beijing-Tianjin-Hebei city cluster, the degree of coupling coordination is graded according to the corresponding standards, and the specific grade classification is shown in Table 4.

Table 4: Coupling harmonization level classification

Degree of coupling coordination D	(0,0.4]	(0.4,0.5]	(0.5,0.6]	(0.6,0.7]	(0.7,0.8]	(0.8,0.9]	(0.9,1.0]
developmental stage	severe disorder	moderate disorder	mild disorder	Initial coordination	mid-polar coordination	good coordination	Quality coordination

4. Analysis of temporal and spatial variations in results & coupling and coordination degrees

According to the coupling coordination model, based on the research results of the evaluation of urban land use efficiency and land ecological security in the Beijing-Tianjin-Hebei region, the coupling coordination degree of each city in the Beijing-Tianjin-Hebei region in 2014, 2017, 2020 and 2023 is calculated, and combined with the reclassification tool of ArcGis10.8.1, classified into, and Figure 1. the data of are visualized their development stages 2014, 2017, 2020 and 2023 and according to the corresponding criteriaas shown in Table 1 classify their development stages

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according to the corresponding standards, and the specific results are shown in Table 1 and Figure 1. According to the data in Table 1, the evolution of the coupled coordination degree of urban land use efficiency and land ecological security in the Beijing-Tianjin-Hebei region can be divided into three stages:

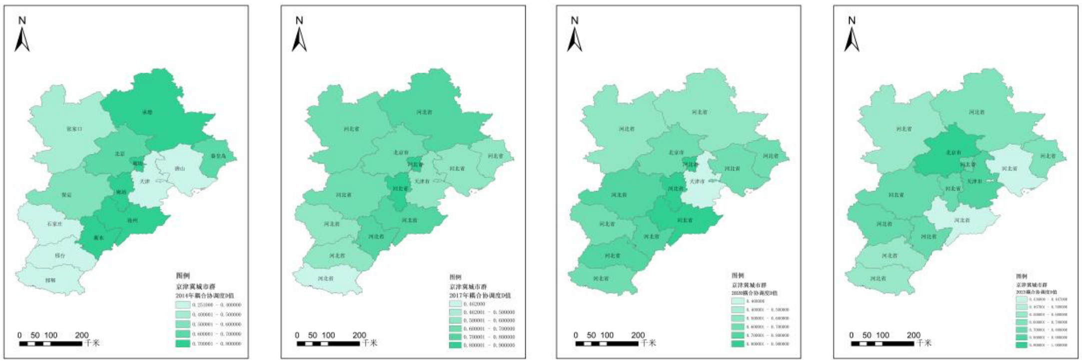

Figure 1: Evolution of the spatial pattern of the coupling coordination degree of the Beijing-Tianjin-Hebei urban agglomeration, 2014-2023

Table 5: Coupling harmonization of Beijing-Tianjin-Hebei city clusters, 2014-2023

city name	vintages			
	2014	2017	2020	2023
Beijing	0.612	0.613	0.611	0.916
Tianjin	0.331	0.518	0.468	0.825
Shijiazhuang	0.251	0.542	0.629	0.774
Tangshan	0.289	0.564	0.687	0.467
Qinhuangdao	0.688	0.591	0.653	0.687
Handan	0.379	0.462	0.641	0.596
Xingtai	0.396	0.541	0.726	0.564
Baoding	0.519	0.614	0.799	0.753
Zhangjiakou	0.466	0.604	0.52	0.542
Chengde	0.713	0.784	0.569	0.625
Cangzhou	0.707	0.703	0.815	0.438
Langfang	0.793	0.829	0.82	0.739
Hengshui	0.759	0.716	0.747	0.8

From 2014 to 2017, most cities exhibited imbalanced coupling coordination, with cities like Tianjin and Shijiazhuang showing coordination degrees below 0.5 due to land-use efficiency and ecological safety imbalances. Between 2018 and 2020, coordination degrees fluctuated, with Beijing and Langfang maintaining high coordination while Tianjin and Baoding improved through industrial restructuring. However, Tangshan and Cangzhou faced setbacks due to traditional industrial dependence. From 2021 to 2023, overall coordination significantly improved, with core cities exceeding 0.8 due to technological innovation and ecological governance. Shijiazhuang and Baoding improved through green transformation, while Tangshan and Cangzhou still showed moderate dissonance, emphasizing the need for industrial structure optimization.

Spatially, the Beijing-Tianjin-Hebei region exhibits a "high-core, low-periphery" coupling coordination pattern. High coupling coordination in Beijing, Langfang, and Chengde is attributed to a

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robust tertiary sector, ecological restoration, synergistic land use efficiency, and ecological security. Medium coupling coordination in Baoding and Shijiazhuang reflects transitional industrial upgrading and ecological protection. Low coupling coordination in Tangshan, Cangzhou, and Handan necessitates green technology adoption and intensive land use to address "efficiency lag" and "ecological deficit."

5. Summary and recommendations

5.1. Summary

From 2014 to 2023, the coupled coordination degree of urban land use efficiency and land ecological security in the Beijing-Tianjin-Hebei city cluster showed a fluctuating upward trend. The spatiotemporal distribution of coupling coordination within the Beijing-Tianjin-Hebei city cluster reveals a core-east high, west-north low pattern. Beijing, Tianjin, Langfang, and Chengde exhibit the highest coordination degrees, followed by Baoding, Cangzhou, and Hengshui. Zhangjiakou, Shijiazhuang, Xingtai, and Handan demonstrate comparatively lower levels of coupling coordination throughout the study period.

5.2. Recommendations

About the plight of the Beijing-Tianjin-Hebei urban agglomeration in terms of the coupling of land ecological security and low utilization efficiency, it is recommended that a cross-regional ecological compensation mechanism be constructed, an "ecological bank" be established based on the Baiyangdian-Yongding River ecological corridor, and a linkage between increasing and decreasing the amount of land used for construction be promoted. In Xiong'an New Area, pilot the "digital twin + multi-planning" platform to optimize land allocation through remote sensing dynamic monitoring. Implementing differentiated development models based on ecological safety zoning (e.g., strict protection of wetlands in the Tongzhou sub-center of Beijing and implementation of full life-cycle management of industrial land in the Binhai New Area of Tianjin). The study also points out that it is necessary to construct a multi-dimensional evaluation model covering indicators such as carbon sink increment, biodiversity, etc., and deeply analyze the mechanism of the "70% of blue and green space" plan of Xiong'an New Area on the degree of coupling and coordination, to provide a paradigm to support the sustainable development of high-density urban agglomerations.

6. Conclusion

Spatio-temporal analysis reveals a "core-periphery" gradient in the coupling coordination degree within the Beijing-Tianjin-Hebei (BTH) urban cluster. Core cities exhibit sustained high-quality coordination, while resource cities face degradation, leading to ecological risks and uneven development. Peripheral cities require industrial transformation and ecological governance to address the "efficiency-ecology" imbalance.

Data limitations constrain the indicator system's comprehensiveness, potentially biasing results towards rationalization over optimization. Furthermore, the study's spatial analysis lacks a systematic application of spatial statistical techniques, limiting the comprehensive mining of regional spatial heterogeneity.

Differentiated control strategies are recommended based on the spatio-temporal characteristics of land use efficiency and ecological security in the BTH region. Core cities should leverage "Digital Twin + Multi-Planning Integration" to optimize land allocation. Transition cities should balance efficiency and ecology through construction land linkage mechanisms. Resource cities urgently

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need to address the "efficiency lag - ecological deficit" dilemma via industrial land lifecycle management and low-carbon transformation.

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