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Unveiling the mechanisms and pathways toward sustainable urban human settlements in post-industrial regions: an SDG-based assessment of coupling coordination and obstacle factors in Northeast China

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Abstract: Rapid industrialization and urbanization have significantly transformed urban human settlements (UHS), making sustainable development a global priority. Dynamic spatiotemporal sustainability assessments track UHS evolution and inform evidence-based policy-making. Focusing on Northeast China's old industrial bases—Liaoning (LN), Jilin (JL), and Heilongjiang (HLJ)—this study develops an SDG-based indicator system to evaluate UHS sustainability. By integrating spatial correlation analysis, the coupling coordination model, and the obstacle degree model, it establishes a comprehensive framework of 'multidimensional assessment—spatiotemporal tracking—root cause analysis'. The sustainability of UHS is examined across 34 prefecture-level cities in the three northeastern provinces (TNP) from 2000 to 2023. The main findings are: (1) From 2000 to 2023, the sustainability quality of UHS in TNP improved steadily, with the Human Settlements Sustainability Development Index (HSSDI) rising from 0.2615 in 2000 to 0.4543 in 2023, a 73.7% increase. (2) Spatially, a pattern characterized by 'strong in the south, weak in the north; coastal leadership; core support; marginal stagnation' emerged. (3) The coupling degree of TNP's sustainable development systems has fluctuated upward to a high level, while the coordination degree has steadily improved but remains preliminary, indicating room for enhancement. (4) Constraint analysis shows that social security and economic development are primary system-level barriers. In contrast, key indicator constraints include the proportion of expenditure on science and technology, the number of books in public libraries, broadband internet access in households, and per capita green space in parks.

Keywords: Sustainable Development Goals (SDGs); Urban human settlements; Sustainability assessment; Coupling coordination; Obstacle degree; Northeast China; Old industrial base

1. Introduction

The ultimate aim of contemporary urban construction and development is the sustainable development of human settlements; this objective also serves as an important benchmark for assessing the quality of urbanization (Zhou et al., 2024, 2021). Since Zoksiadis first introduced the concept of 'human settlement science' in the 1950s, the question of how to improve the human settlements has gradually become a key focus in urban planning worldwide (Doxiadis, 1975; Saharan et al., 2022). The so-called human settlement is, in essence, the physical environment that supports people's communal living and daily activities (Luo et al., 2021). A people-centered approach has always guided the development and research of human settlements. The theoretical framework of human settlement science, established by the Chinese scholar Academician Wu,

defines human settlements as the living spaces where residents live and gather; they are human settlements constructed to meet basic human survival needs and to rely on the natural environment. This framework primarily encompasses five major systems, namely the human system, the social system, the support system, the natural system and the residential system (Wu, 2001). The 2030 Agenda for Sustainable Development, adopted by the United Nations General Assembly in 2015, sets out the direction for the development of sustainable human settlements across three dimensions: economic, social and environmental (Encenzo et al., 2023).

Since the second half of the 20th century, most cities worldwide and their surrounding areas have undergone rapid expansion (Berisha et al., 2022). The year 2008 marked a crucial turning point, when the urban population exceeded the rural population for the first time; according to the latest forecasts, the global urbanization rate is expected to reach 70% by 2050 (The United Nations, 2019). The rapid pace of urbanization often leads to dramatic changes in the UHS; this phenomenon is particularly pronounced in developing countries, and the situation in China is highly representative of this trend (Coffey and Riley, 2006; Wu et al., 2023). Since the launch of the Reform and Opening-up policy in 1978, with the continuous expansion of the urban population and the ongoing expansion of industrial areas, the process of land urbanization in China has accelerated significantly, whilst at the same time, imbalances have emerged in the spatial distribution of the population (Chen G. et al., 2016; M. Chen et al., 2016). Against the backdrop of an increasingly global trend towards sustainable development, urban sustainability is becoming ever more significant amid China's rapid urbanization and economic development (He and Zhang, 2022). In 2015, the United Nations General Assembly formally adopted the 2030 Agenda for Sustainable Development and set out 17 Sustainable Development Goals (SDGs) to promote harmonious and sustainable development across the environmental, social and economic dimensions. (Colglazier, 2015; The United Nations, 2015). The setting of this objective has provided a new perspective for re-examining and reassessing the level of development of the UHS (Tasnim et al., 2022).

Currently, research on the assessment of human settlements has developed several key areas of focus, primarily including suitability assessment (Peng et al., 2025; Yurui et al., 2020; Zhu et al., 2024), resilience assessment (Han and Dong, 2026; Liu et al., 2024), vulnerability assessment (Kim et al., 2025; Yang et al., 2023), and sustainability assessment (Jia et al., 2024; Liu et al., 2026), amongst others. Existing research on the assessment of UHS has spanned a variety of spatial scales, covering a comprehensive hierarchical system ranging from the macro to the micro level. Wu et al. constructed a global POI database covering six major categories of infrastructure—housing, healthcare, education, leisure, public transport and employment—and assessed the accessibility of essential everyday services for residents worldwide (Wu et al., 2025). Wu et al. established a theoretical framework for the human settlements based on the natural, human, economic, social, and residential subsystems, and assessed its suitability across 30 provinces in China (Wu et al., 2023). Taking a comprehensive perspective that integrates natural and human settlements, Zhang et al. developed a framework for assessing the quality of the human settlements in arid urban areas. They conducted a detailed assessment of the human settlements in six administrative districts of Urumqi (Zhang et al., 2025). Jin et al. conducted a dynamic assessment of the quality of the rural human settlements in 47 counties in the Dabie Mountains from the perspective of rural revitalization (Jin et al., 2025). Zhang et al. designed a comprehensive framework that covers aspects such as environmental hygiene and comfort, housing comfort, transport accessibility, urban safety and the convenience of daily life, using residential neighborhoods as the unit of analysis to assess the quality

of the human settlements in Beijing (Zhang et al., 2024). This multi-scale research framework reflects the academic community's widespread interest in issues related to urban human settlements. It demonstrates that assessments of the human settlements at different levels have specific foci and complement one another (Jiang et al., 2026). In evaluative research, the choice of weighting method is crucial; commonly used weighting methods include the entropy weighting method (Fang et al., 2022), the Analytic Hierarchy Process (AHP) (Chen, 2023; Xu et al., 2022), and the CRITIC method (Wang et al., 2017), amongst others.

This study incorporates the SDGs set out in the 2030 Agenda for Sustainable Development, formally adopted by the United Nations General Assembly, into the assessment of the sustainability of the urban human settlements. It has established a research framework for the urban human settlements based on the SDGs, comprising 'multidimensional assessment, spatiotemporal tracking and root-cause analysis' (Fig. 1). Specifically, we have developed an evaluation indicator system for the sustainability of the UHS, based on three subsystems: economic development, social security, and resource and the environment. At the same time, we employed a coupling and coordination model to assess the degree of coupling and coordination between sustainable human settlements development systems. We introduced a barrier index model to measure the level of barriers at both the system and indicator levels of sustainable urban human settlements development, with a view to analyzing the primary factors hindering the sustainable development of the human settlements in the study area.

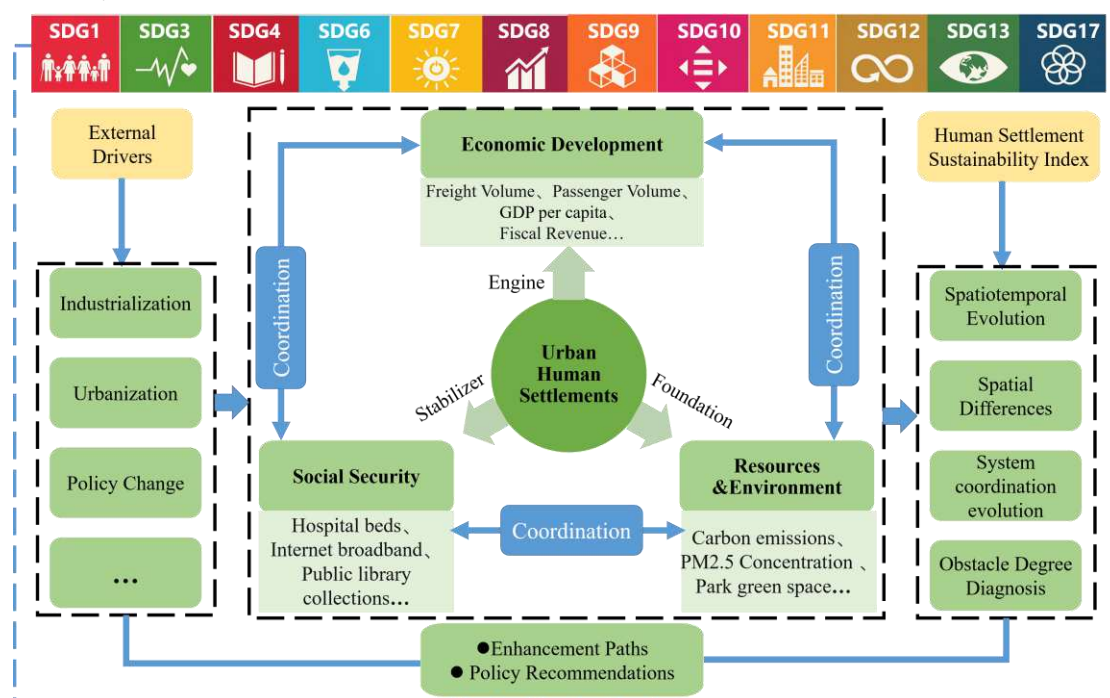


Fig. 1. Research Framework Diagram.

2. Research Design

2.1. Study area

The TNP (38° 43' ~53° 30' N, 118° 50' ~135° 09' E) is located in north-eastern China and comprises three provincial-level administrative regions: LN, JL and HLJ, which together include 34 prefecture-level cities, one autonomous prefecture and one autonomous county (Fig. 2). The southern parts of the TNP border the Yellow Sea and the Bohai Sea; they share land borders

with North Korea and Russia and lie across the sea from South Korea and Japan. Their total area is 787,300 km². The topography of the TNP is characterized mainly by plains and mountains. They boast vast areas of arable land and are rich in natural resources, including abundant forests and mineral resources such as coal, oil, and natural gas. The TNP has a temperate, humid, and semi-humid continental monsoon climate. Influenced by thermal differences between land and sea, summers are hot and rainy, whilst winters are dry and long, with marked seasonal variations. It should be noted that, due to limited data availability, this study does not include the Greater Khingan Range region or the Yanbian Korean Autonomous Prefecture. The sustainable development of the UHS is of great significance to the three provinces of Northeast China. Since the implementation of the ‘Revitalization of the Old Industrial Bases in Northeast China’ strategy, the region has undergone large-scale infrastructure development and urban restructuring, with economic development and resource exploitation becoming, at one stage, the focal points of regional development (Ji et al., 2024). As we enter a new phase of high-quality development and the State’s strategy for the comprehensive revitalization of the Northeast is vigorously advanced, the standard of living for residents in the TNP continues to rise, whilst their demands regarding the human settlements are becoming increasingly diverse and personalized. This shift in demand patterns is profoundly influencing the direction of the region’s human settlements.

Against this background, this study examines 34 prefecture-level cities in the TNP, focusing on three systemic levels—economic development, social security, and resources and the environment—to scientifically assess the level of sustainable development of their human settlements, reveal patterns in their spatiotemporal evolution, and provide a basis for the formulation of differentiated regulatory policies.

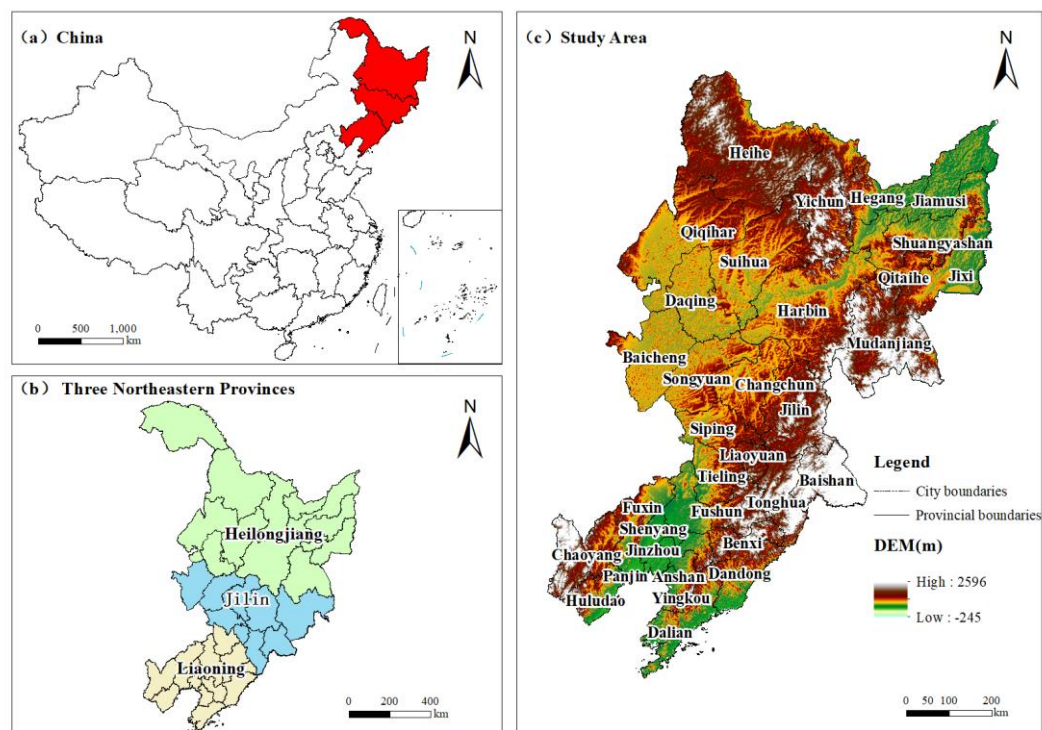


Fig. 2. Location of the study area.

2.2. Data sources

The study covers the period from 2000 to 2023, with data collection points in 2000, 2005, 2010,

2015, 2020, and 2023. The study area comprises 34 prefecture-level cities in the TNP. The data used in this paper include socio-economic and geospatial data. The socio-economic data were sourced from various statistical yearbooks, statistical bulletins on national economic and social development, and local government websites for each province over the years; where data were missing, they were supplemented using data from neighboring years or linear interpolation. **Table 1** shows the detailed sources of the data.

Table 1

Data Sources and Description.

Data name	Data description	Data source
Socio-economic data	GDP, population, industrial structure, and other indicators	LN, JL, and HLJ Provincial Statistical Bureaus (https://tjj.ln.gov.cn) (https://tjj.jl.gov.cn) (https://tjj.hlj.gov.cn)
DEM data	Digital Elevation Model for mapping; 1 km resolution	Geospatial Data Cloud (https://www.gscloud.cn)
Administrative boundary data	Extraction of study area boundaries	Geospatial Data Cloud (https://www.gscloud.cn)
PM2.5 data	Provided by Wei & Li (University of Maryland); 1 km resolution; processed with ArcGIS 10.8	National Tibetan Plateau Data Center (https://data.tpdac.ac.cn)
CO ₂ emission data	Annual CO ₂ emissions calculation; 11.1 km resolution; processed with ArcGIS 10.8	EDGAR (https://edgar.jrc.ec.europa.eu)

2.3. Evaluation and calculation Method

2.3.1. Evaluation of UHS sustainability based on the SDGs

Sustainable development of human settlements is a comprehensive concept that closely integrates human settlements with the principles of sustainable development, aiming to ensure the quality and sustainability of human settlements whilst meeting the needs of economic development, social justice and environmental protection (Xu et al., 2025). In this study, taking into account the actual development status and current state of sustainable development in the study area, an SDGs-based sustainable development evaluation indicator system was constructed in accordance with the principles of scientific rigor, systematic approach, dynamism and feasibility. The sustainable development of the UHS in the TNP was categorized into three dimensions: economic development, social security, and resource and the environment, with a total of 21 indicators selected (**Table 2**).

Table 2

Evaluation index system of UHS sustainability.

Goal level	System level	Indicator level	Unit	Nature	SDGs
The	Economic	GDP per capita (X1)	yuan/person	+	SDG8
evaluation	development	Road freight volume	10,000 tons	+	SDG9
index		(X2)			

system of UHS sustainability in the TNP	Road passenger traffic (X3)	10,000 people	+	SDG9
	The proportion of expenditure on science and technology in total government expenditure (X4)	%	+	SDG9
	Per capita disposable income of urban residents (X5)	yuan	+	SDG10
	Fiscal revenue as a percentage of GDP (X6)	%	+	SDG17
	Social security			
	The proportion of education expenditure in total government expenditure (X7)	%	+	SDG1
	Number of hospital beds per 1,000 people(X8)	Number/1,000 people	+	SDG3
	Number of practicing doctors per 1,000 people (X9)	Number/1,000 people	+	SDG3
	Pupil-teacher ratio in primary and secondary schools (X10)	%	+	SDG4
	Public library collections per 1,000 people (X11)	Number/1,000 people	+	SDG4
	Number of internet broadband subscribers(X12)	10,000 households	+	SDG9
	Number of buses per 10,000 people(X13)	Number/10,000 people	+	SDG11
	Road area per capita(X14)	m²	+	SDG11
	Resource and environment			
	Centralized sewage treatment rate(X15)	%	+	SDG6
Electricity consumption per	kWh/10,000 yuan	-	SDG7	

10,000 yuan of GDP(X16)			
Urban green space coverage(X17)	%	+	SDG11
Annual average PM2.5 concentration(X18)	μg/m ³	-	SDG11
Per capita park green space(X19)	m ²	+	SDG11
SO ₂ emissions per 10,000 people(X20)	tons	-	SDG12
Total annual greenhouse gas emissions(X21)	10,000 tons	-	SDG13

2.3.2. Data normalization

As the selected indicators have different units of measurement and exert varying positive or negative effects on the sustainable development of the UHS, it is not possible to directly compare or calculate the raw data for each indicator. Therefore, the raw indicator values are converted to dimensionless form using the range-standardization method, so that the processed data fall within the range [0, 1]. The calculation formula is as follows:

Positive indicators:

$$Y_{ij} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} \quad (1)$$

Negative indicators:

$$Y_{ij} = \frac{x_{\max} - x_{ij}}{x_{\max} - x_{\min}} \quad (2)$$

Where Y_{ij} represents the standardized value of the j th indicator for the i th city, x_{ij} represents the raw value of the j th indicator for the i th city, $x_{\min}$ represents the minimum value among all indicators j , and $x_{\max}$ represents the maximum value among all indicators j .

2.3.3. Calculating the weights of the indicators

Given the complexity of the evaluation system and the large number of selected evaluation indicators, this study employs a combined objective and subjective approach to determine indicator weights and to establish them as accurately as possible. First, the indicator weights were calculated separately using the Analytic Hierarchy Process (AHP) and the Entropy Weighting Method (EWM); the combined weights were then obtained by combining the weights from both methods using the principle of minimum information entropy. This approach strikes a balance between subjective and objective weighting, thereby avoiding the arbitrariness inherent in a single method whilst also overcoming the information loss in the entropy weighting method caused by its over-reliance on data dispersion (Liu et al., 2024).

Step 1: The objective weights of each evaluation indicator x_{ij} are calculated using the EWM and denoted as W_{ij} , using Equations (3)-(5)

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^n x_{ij}} \quad (3)$$

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^n P_{ij} \ln P_{ij} \quad (4)$$

$$W_{1j} = \frac{1 - e_j}{\sum_{i=1}^n (1 - e_j)} \quad (5)$$

where P_{ij} represents the proportion of the j th indicator in city i relative to the total sum of that indicator; e_j denotes the entropy value of the j th indicator; the higher the entropy value, the greater the influence on the evaluation result; n denotes the number of indicators; m denotes the number of research subjects; and W_{1j} denotes the objective weight of the j th indicator.

Step 2: Next, based on the clearly structured evaluation system for the sustainable development of the UHS, and using the higher-level indicators as a benchmark, pairwise comparisons are made between indicators at the same level to construct a decision matrix. A consistency test is then carried out to derive the subjective weight of the j th indicator, denoted as W_{2j} .

Step 3: Finally, calculate the composite weights W_j . The composite weights W_j are derived from the objective weights W_{1j} and the subjective weights W_{2j} . To ensure that W_j , W_{1j} , and W_{2j} are as consistent as possible overall, this study constructs a corresponding objective function based on the principle of minimum relative entropy:

$$\varpi_j = \sqrt{\varpi_{1j} \varpi_{2j}} / \left(\sum_{j=1}^n \sqrt{\varpi_{1j} \varpi_{2j}} \right) \quad (6)$$

The final weighting results are shown in **Fig. 3**.

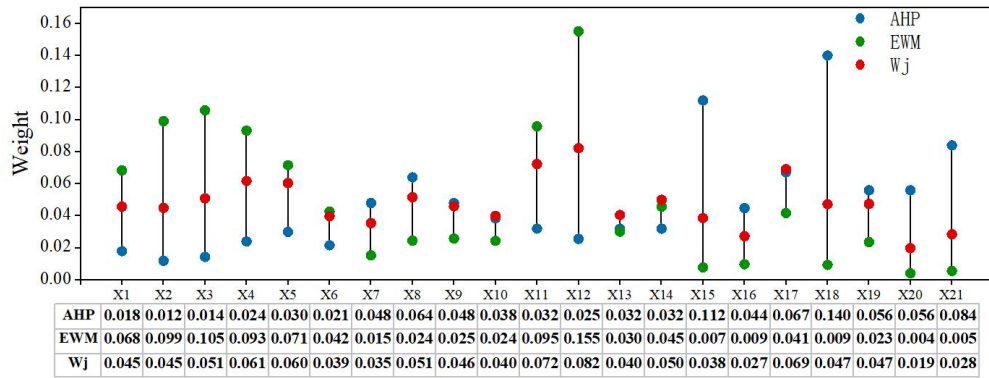


Fig. 3. Indicator weights.

2.3.4. Calculating the HSSDI

Based on the model for evaluating the level of sustainable development of the UHS, the HSSDI is calculated using the weighted summation method:

$$CI_i^t = \sum_{j=1}^n W_j \times Y_{ij}^t \quad (7)$$

where CI_i^t represents the HSSDI for city i in year t ; W_j is the composite weight for indicator j ; and Y_{ij}^t is the standardized value for city i , year t , and indicator j .

2.4. Model construction

2.4.1. Spatial autocorrelation models

Spatial autocorrelation models assess whether the distribution of spatial variables exhibits clustering and are important tools for analyzing spatial patterns. Spatial autocorrelation models comprise both global and local analyses. Moran's I is typically used to indicate the degree of autocorrelation in spatial features; this value lies within the range $[-1, 1]$ (Zhao et al., 2017). A value of 0 indicates no spatial correlation; the distribution is spatially random. A value greater than 0 indicates positive spatial correlation, whilst a value less than 0 indicates negative spatial correlation.

2.4.2. Coupling coordination model

The coupling coordination Degree model is primarily used to assess the synergy and consistency of interactions between different systems. This model not only determines whether there is positive interaction between systems, but also captures the evolutionary process by which they gradually transition from a state of disharmony to a coordinated and orderly pattern, thereby comprehensively reflecting the dynamics of the systems' coordinated development (Guan and Pan, 2025; Sun et al., 2024; Tan et al., 2025). A coupling coordination model among the three subsystems will be developed to investigate the extent of interactions and coordinated development within the UHS:

(1) Calculation of Coupling Degree

$$C = \left[\frac{U_1 \times U_2 \times U_3}{\left(\frac{U_1 + U_2 + U_3}{3} \right)^3} \right]^{\frac{1}{3}} \quad (8)$$

where C represents the degree of coupling; a higher value of C indicates a stronger interaction between the three subsystems, whilst U_1 , U_2 and U_3 represent the sustainable development indices of the economic development, social security and resource and environment subsystems, respectively. The degree of coupling is categorized into levels, as shown in **Table 3**.

Table 3

Classification of coupling degree

Coupling degree (C)	Coupling level
$0 < C \leq 0.3$	Low-level coupling
$0.3 < C \leq 0.5$	Antagonistic coupling
$0.5 < C \leq 0.8$	Running-in coupling
$0.8 < C \leq 1.0$	High-level coupling

(2) Calculation of Coupling Coordination

$$T = \alpha_1 U_1 + \alpha_2 U_2 + \alpha_3 U_3 \quad (9)$$

$$D = (C \times T)^{\frac{1}{2}} \quad (10)$$

where T represents the comprehensive and coordinated sustainable development index for the UHS; α_1 , α_2 , and α_3 are coefficients to be determined; and D represents the degree of coupling and coordination between the subsystems of the sustainable development of the UHS. The classification criteria for the degree of coupling and coordination are shown in **Table 4**.

Table 4

Classification of coupling coordination degree.

Coupling coordination degree (D)	Coordination level
$0 < D \leq 0.1$	Extreme disorder
$0.1 < D \leq 0.2$	Severe disorder
$0.2 < D \leq 0.3$	Moderate disorder
$0.3 < D \leq 0.4$	Mild disorder
$0.4 < D \leq 0.5$	On the verge of disorder
$0.5 < D \leq 0.6$	Barely coordinated
$0.6 < D \leq 0.7$	Primary coordination
$0.7 < D \leq 0.8$	Intermediate coordination
$0.8 < D \leq 0.9$	Good coordination
$0.9 < D \leq 1.0$	Excellent coordination

2.4.3. Obstacle model

The core logic of the obstacle model is that the higher the obstacle degree, the more pronounced the indicator's restrictive effect on the composite score (Liu et al., 2024). Building on this, we have developed this model in conjunction with the indicator system for evaluating the sustainable development of the UHS:

$$P_j = \left[(1 - Y_{ij}) \times W_j / \sum_{j=1}^n (1 - Y_{ij}) \times W_j \right] \times 100\% \quad (11)$$

where P_j represents the degree of obstruction for the j th sustainable development indicator in the UHS; Y_{ij} is the standardized value of the j th indicator for the i th city; and W_j is the weight of the j th indicator.

3. Results

3.1. Spatio-temporal patterns of sustainability in the UHS

2000-2023: The overall level of sustainability of the UHS in the study area has generally risen, with the HSSDI increasing from 0.2615 in 2000 to 0.4543 in 2023—an increase of 73.7%—indicating that the sustainability of the UHS in this area has improved steadily over the past two decades (**Fig. 4****Fig. 5**). LN leads the three provinces in the HSSDI; its index rose from 0.2661 in 2000 to 0.4655 in 2023, with no significant fluctuations. JL started from a slightly lower baseline than LN but demonstrated strong growth momentum after 2010; in particular, its growth rate exceeded LN's between 2015 and 2023, with the index standing at 0.4471 in 2023. HLJ has long remained at a relatively low level among the TNP; its index stood at just 0.2638 in 2000 and reached 0.4460 in 2023, which is slightly lower than that of LN and JL, although the gap has been narrowing year on year.

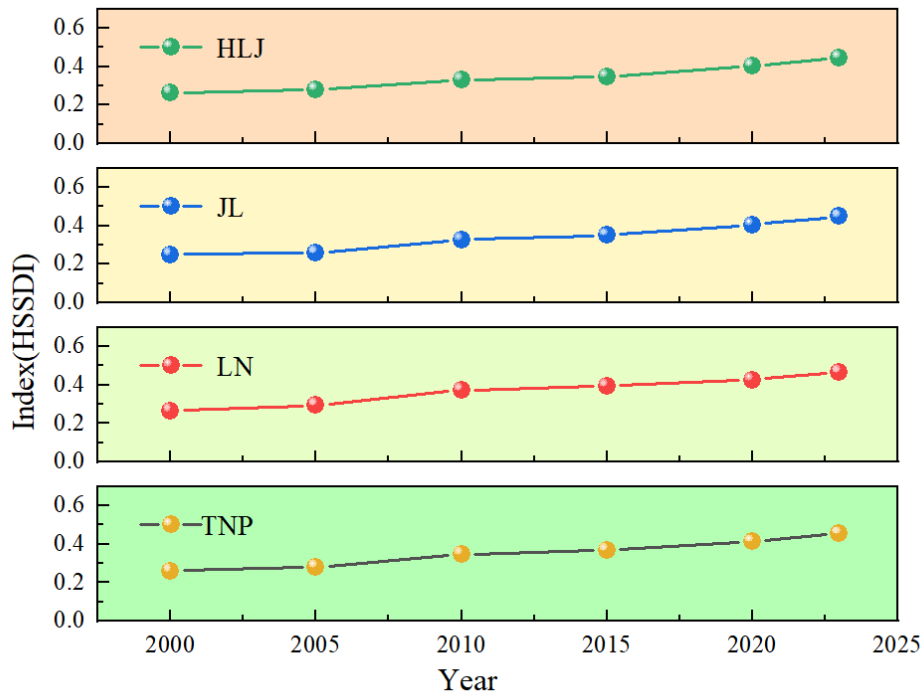


Fig. 4. Trends of the HSSDI in the TNP, 2000–2023

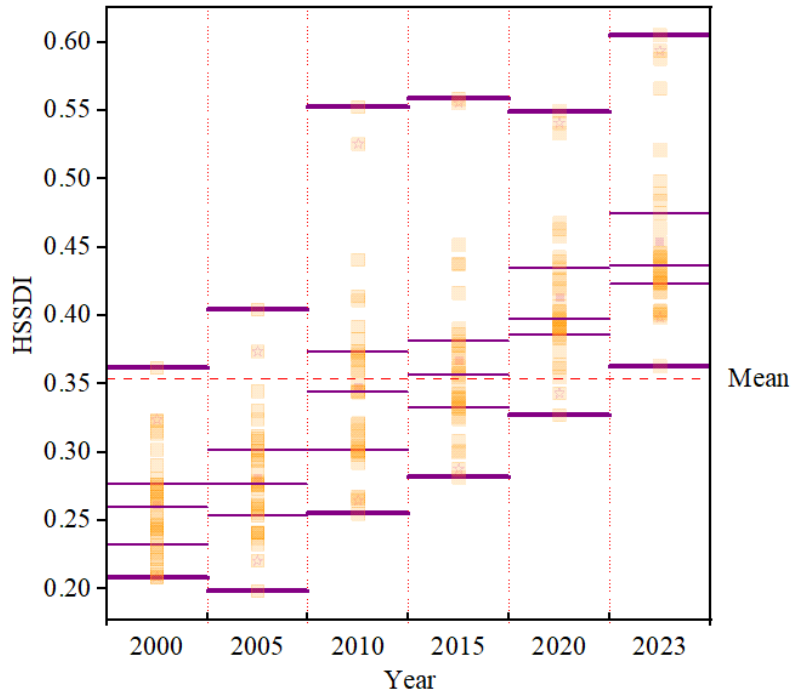


Fig. 5. X-boxplot of the HSSDI in the TNP, 2000–2023

To provide a clearer and more intuitive picture of the spatial evolution of the level of sustainable development of the UHS in the TNP, this paper utilizes the natural-breaks classification method in ArcGIS 10.8 to classify the HSSDI for these provinces from 2000 to 2023 into five categories: low sustainability, lower-middle sustainability, medium sustainability, upper-middle

sustainability and high sustainability (Xiao et al., 2026; Yin et al., 2024).

From 2000 to 2023, marked spatial disparities in the HSSDI across the TNP revealed a pattern characterized by ‘stronger performance in the south and weaker in the north, with the coastal areas leading the way, the core regions providing support, and the peripheral regions stagnating’(Fig. 6). A key spatial characteristic is the ‘strong south, weak north’ pattern: the southern part of LN has long maintained a leading position due to its favorable climate and industrial base, whilst the northern part of HLJ and western JL have lagged for a long time, constrained by extreme cold and reliance on resource-based industries. The ‘coastal leadership’ effect is pronounced: the Liaodong Peninsula, centered on Dalian, has maintained ‘high sustainability’ for many consecutive years by leveraging its ports and export-oriented economy, becoming the region’s core growth pole. The three provincial capitals—Shenyang, Changchun and Harbin—have played a ‘core supporting’ role, demonstrating strong development resilience and consistently remaining in the ‘medium-high’ range; by 2023, all had entered the ‘high sustainability’ category. In contrast, cities in the ‘peripheral stagnation’ zone—such as Fuxin and Heihe, which are either resource-depleted or border cities—have long remained in the ‘low’ or ‘medium-low’ range due to their limited geographical location and industrial diversity.

In terms of spatial patterns, the region exhibits distinct ‘north–south divergence’ and ‘east–west disparities’. The north–south trend (green curve) follows an inverted U-shaped pattern, with higher values in the north and lower in the south; high-value areas are primarily concentrated in central JL and northern LN. The east–west trend (blue curve), however, shows a slight ‘higher in the east, lower in the west’ or ‘W-shaped’ fluctuation. In terms of temporal evolution, spatial disparities underwent a process of ‘initial widening followed by convergence’: from 2000 to 2010, as overall standards rose, the gap between the central core and peripheral areas widened, exacerbating spatial imbalances; whereas from 2010 to 2023, the curve gradually flattened, indicating that development gaps between regions are narrowing and the spatial pattern is tending towards optimization and equilibrium (Fig. 7).

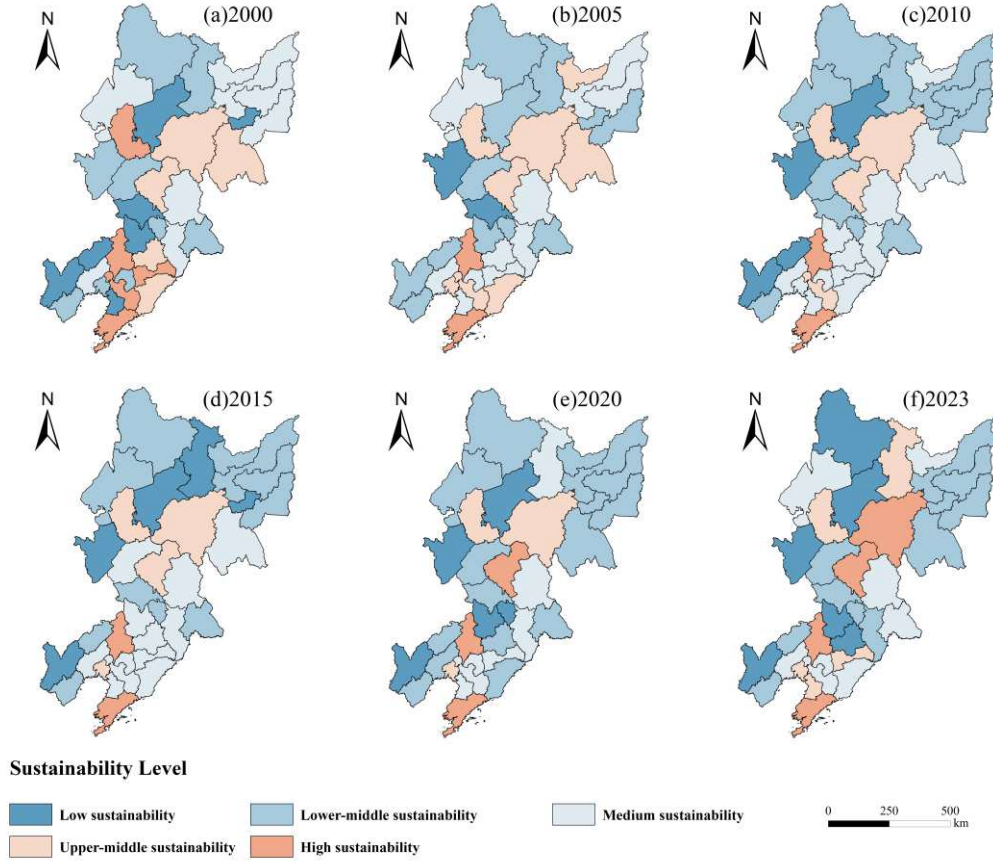


Fig. 6. Spatial pattern evolution of the HSSDI in the TNP, 2000–2023.

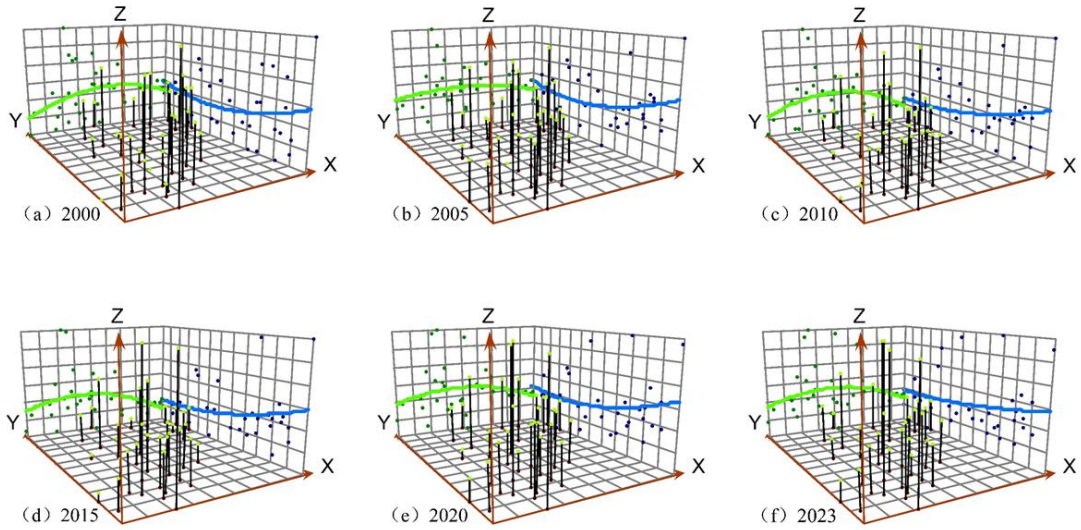


Fig. 7. Three-dimensional trend analysis of the HSSDI in the TNP, 2000–2023.

3.2. Dynamic evolution of the spatial pattern of the HSSDI in the TNP

Based on an analysis using standard deviation ellipses and center-of-gravity migration models covering the period 2000–2023, the spatial patterns of the sustainable development index for the UHS across the TNP show markedly differentiated evolution and phased dynamics.

The standard deviation in LN is elliptical and approximates a circle; its spatial distribution is

relatively uniform, and the shift in its center of gravity generally follows a ‘south-east to north-west’ trend, albeit to a minimal extent (**Fig. 8**). From 2000 to 2010, there was a steady shift towards the north-west; from 2010 to 2015, there was a marked reversal towards the north-east; and since 2015, there has been a slight shift back towards the north-west. These fluctuations are linked to the coordinated development of the Shenyang core region and coastal economic belts, including Dalian and Yingkou, reflecting the relative maturity and stability of LN’s urban system.

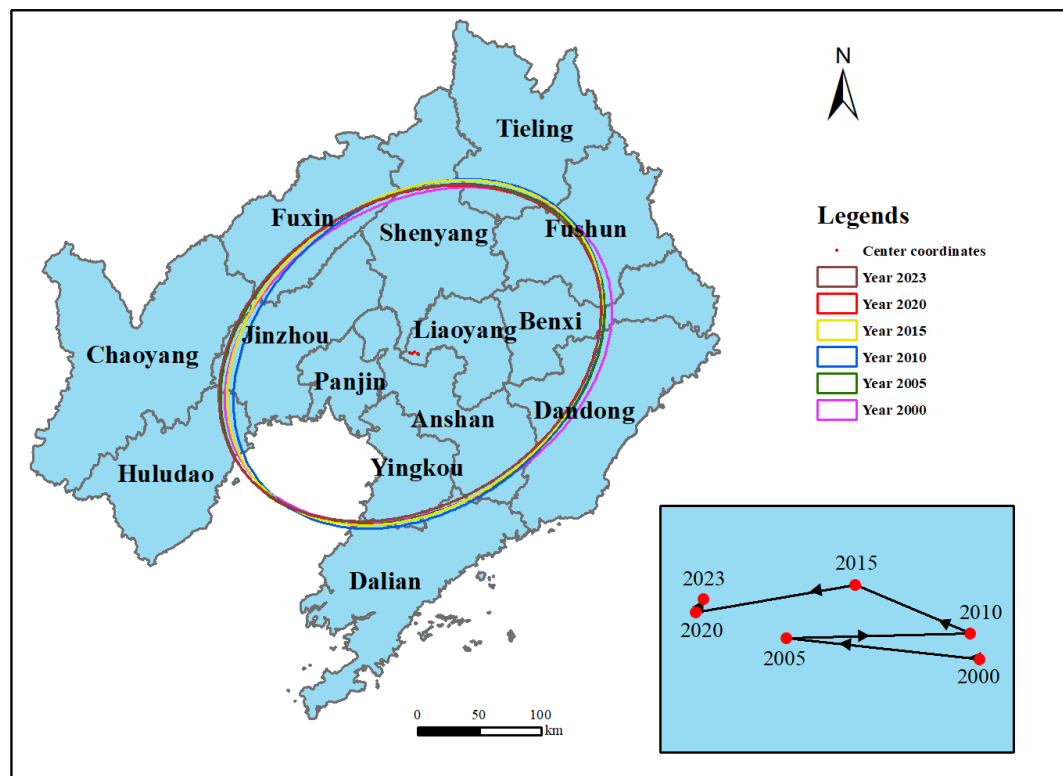


Fig. 8. Migration trajectory of the HSSDI center of gravity in LN, 2000–2023.

In JL, the standard deviation ellipse follows a ‘north-east–south-west’ trend, exhibiting distinct band-like clustering, whilst the center of gravity’s trajectory follows a regular unidirectional pattern from ‘south-east to north-west’(**Fig. 9**). In 2000, the center of gravity was close to Baishan City; between 2005 and 2010, it shifted significantly north-westwards; in 2015, it briefly shifted back south-westwards; and between 2020 and 2023, it shifted significantly north-westwards again. This reflects the growing central role of the Changchun metropolitan area and cities in the central and western regions, as well as a shift in the advantages of the human settlements from the eastern mountainous areas to the central and western plains.

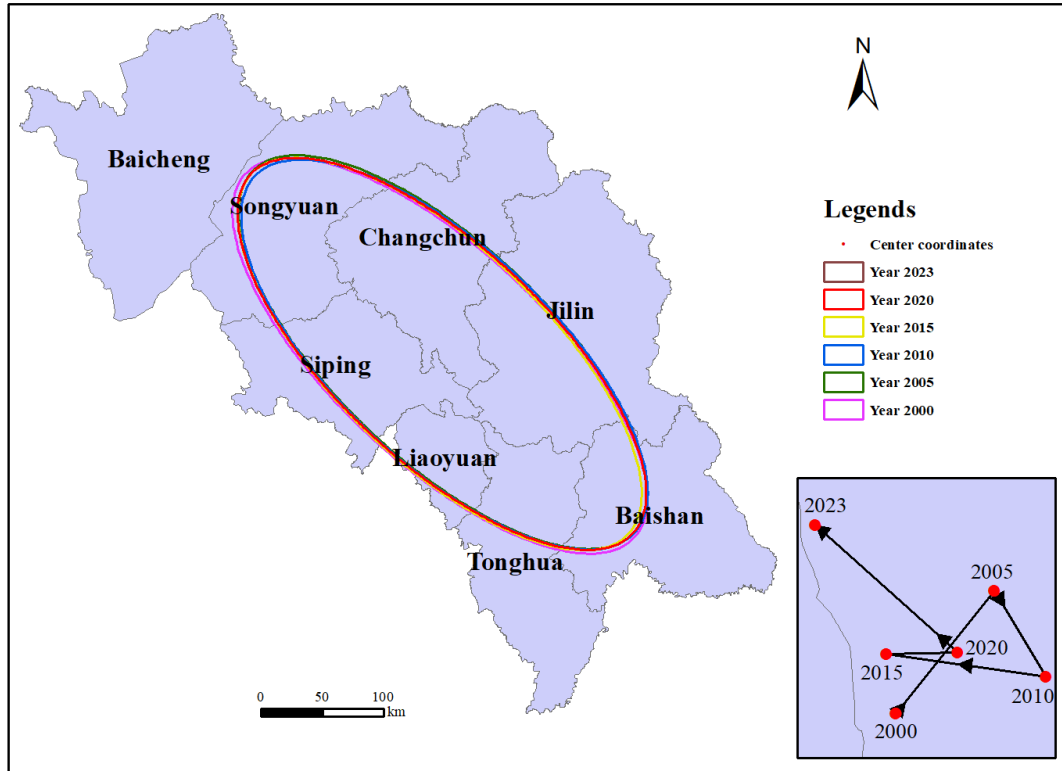


Fig. 9. Migration trajectory of the HSSDI center of gravity in JL, 2000–2023.

In HLJ, the standard deviation ellipse runs east-west and is slightly flattened; the center of gravity shows the greatest amplitude of fluctuation, oscillating periodically (**Fig. 10**). In 2000, it was located in the far east; between 2000 and 2010, it shifted significantly towards the south-west; between 2010 and 2015, it shifted back towards the north-east; between 2015 and 2020, it shifted significantly eastwards to the far north-east; and from 2020 to 2023, it shifted back towards the south-west once more, exhibiting an alternating pattern of ‘westward shift – eastward shift – further westward shift’; spatial competition between eastern and western cities has yet to stabilize.

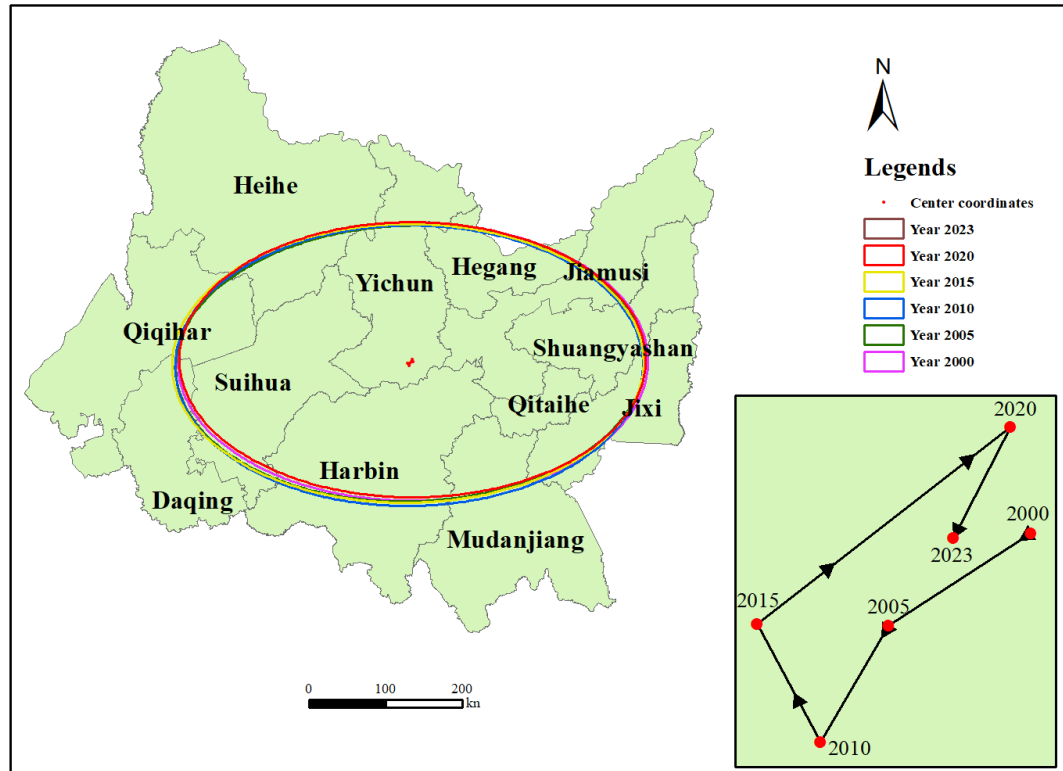


Fig. 10. Migration trajectory of the HSSDI center of gravity in HLJ, 2000–2023.

3.3. Spatial Aggregation Analysis of the HSSDI

From 2000 to 2023, the Global Moran's I values ranged from 0.013 to 0.130. This indicates that, at the regional scale, the sustainable development of the UHS in the TNP has not produced significant spatial clustering; its spatial distribution pattern generally exhibits characteristics of a non-significant random distribution, lacking clear overarching spatial structural constraints (**Table 5**).

Table 5

Statistical analysis of Global Moran's I for spatial autocorrelation

Year	Global Moran's I	$Z(I)$	Year	Global Moran's I	$Z(I)$
2000	0.013	0.385	2015	0.086	1.094
2005	0.012	0.386	2020	0.015	0.418
2010	0.130	1.486	2023	0.056	0.327

To further explore the relationships between each city in the TNP and its neighboring cities, LISA clustering maps for the period 2000–2023 were produced based on the results of the Local Moran's I calculations (**Fig. 11**).

In 2000, the "High-High" cluster was observed only on the Liaodong Peninsula, indicating that this region was the sole area with nascent spatial synergy advantages at the time. By 2005, the "High-High" cluster on the Liaodong Peninsula had expanded slightly, encompassing more cities, suggesting that the agglomeration effect in southern LN had begun to strengthen. Concurrently, the number of "Low-High" outliers increased compared with 2000, reflecting intensified urban differentiation during the early stage of market-oriented reforms—some cities "stood out" due to industrial transformation or policy preferences, while their surrounding areas failed to keep pace,

thereby widening spatial disparities. The year 2010 marked a turning point in spatial structure: Shenyang and its surrounding areas were formally incorporated into the "High-High" cluster, forming a preliminary "Southern–Central Liaoning" dual-core linkage with Dalian. Meanwhile, a "Low-Low" cluster emerged in northern HLJ, signaling that border and resource-based cities had fallen into a long-term decline trap. By 2015, the Shenyang–Dalian "High-High" cluster had further integrated into a more stable core area of the Central–Southern Liaoning urban agglomeration, while the "Low-Low" cluster in the north had contracted. Notably, Daqing began to exhibit a "High-Low" outlier, forming a typical "island effect". From 2020 to 2023, the "Low-Low" cluster disappeared, leaving only the "High-High" cluster, "High-Low" outliers, and "Low-High" outliers. This suggests that the development of human settlements in the TNP has entered a complex new normal characterized by "depolarization but greater fragmentation".

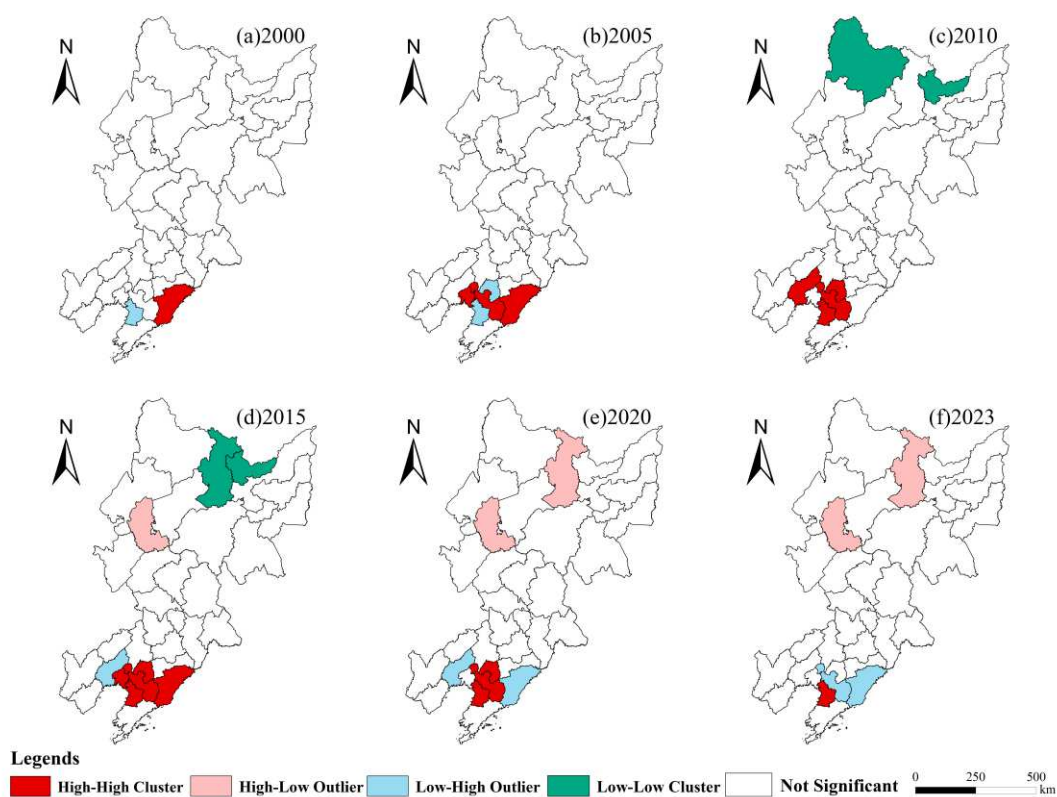


Fig. 11. LISA cluster of HSSDI in the TNP, 2000-2023

3.4. Analysis of the coupling and coordination of systems for the sustainable development of the UHS

The sustainable development of the UHS in the TNP comprises three interlinked and mutually reinforcing subsystems: economic development, social security, and resource and the environment. This paper examines these subsystems to explore their intrinsic mechanisms of action and the extent of their coordination. The study quantifies the coupling and coordination between subsystems, classifies them according to **Table 3** and **Table 4**, and supports the sustainable development of the UHS.

During the study period, the degree of coupling within the sustainable development systems of

the TNP and the other provinces showed a fluctuating upward trend, with the TNP's overall C-value rising from 0.823 to 0.940. In terms of spatial distribution, the three provinces exhibited a pattern of 'LN > JL > HLJ'. LN consistently ranked first among the TNP, with its C-value rising from 0.908 in 2000 to 0.959 in 2023. Although JL and HLJ started from a lower baseline—with C-values of 0.776 and 0.724, respectively, in 2000—they grew rapidly and came very close to LN's level by 2023. HLJ, in particular, rebounded rapidly in 2023 after a brief dip in 2020, indicating that the balance of development within the region is strengthening (**Fig. 12****Fig. 14**).

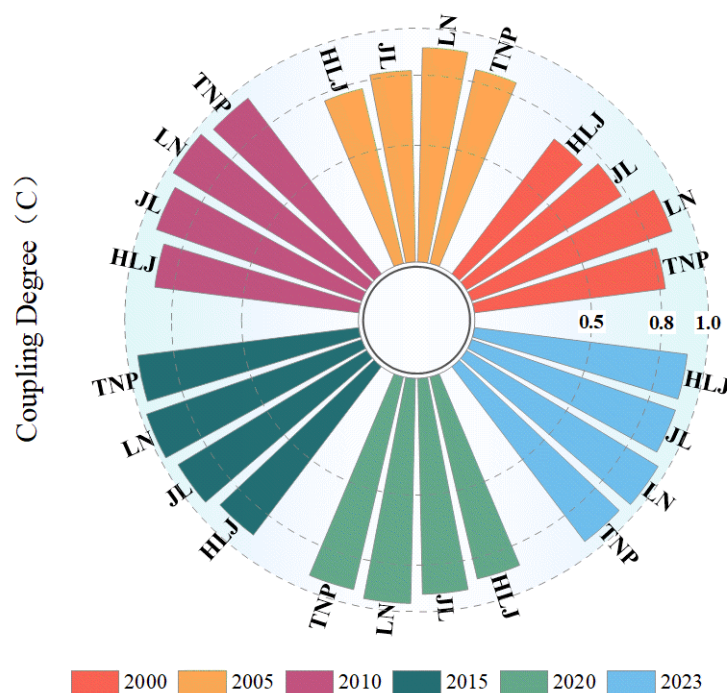


Fig. 12. Three-dimensional evolution of coupling degree for UHS in the TNP,2000-2023.

From 2000 to 2023, the degree of coupling and coordination in the UHS across the TNP showed a steady upward trend, which can be divided into three phases. Phase One: Period of Low-Level Coordination (2000–2005). The coupling and coordination of the overall sustainable development system across the TNP stood at merely 0.405, placing it on the brink of ‘dysfunction’. Although links existed between the systems at this time, the overall level of development was low, characterized by ‘low-level synchronous decline’ or ‘low-level synchronous stagnation’; Phase Two: Rapid Convergence and Improvement Period (2005–2015). During this period, the curve’s slope was at its steepest, with the degree of coupling and coordination between systems rapidly surpassing the 0.50 ‘barely coordinated’ threshold and advancing towards the 0.60 ‘primary coordination’ threshold; Phase Three: Period of Deepening High-Level Coordination (2015–2023). By 2023, the overall coordination level of the TNP had exceeded 0.60, marking the entry into the ‘primary coordination’ stage (**Fig. 13**).

The degree of coupling and coordination in the sustainable development of the UHS in the TNP has generally shown an upward trend; however, there is significant spatial heterogeneity in development levels, rates of progress and stage-specific characteristics, resulting in a tiered distribution pattern characterized by ‘LN in the lead, JL in the middle and HLJ catching up’(**Fig. 15**).

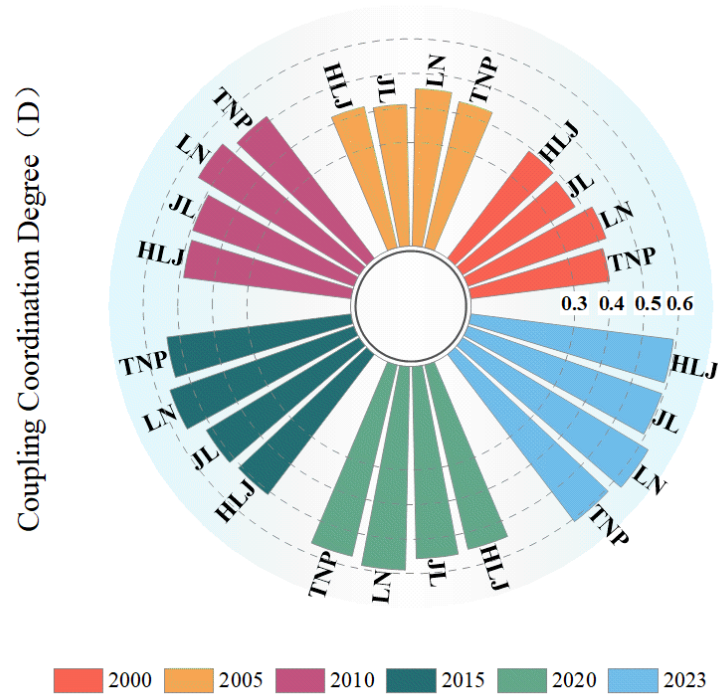


Fig. 13. Three-dimensional evolution of coupling coordination degree for UHS in the TNP, 2000-2023.

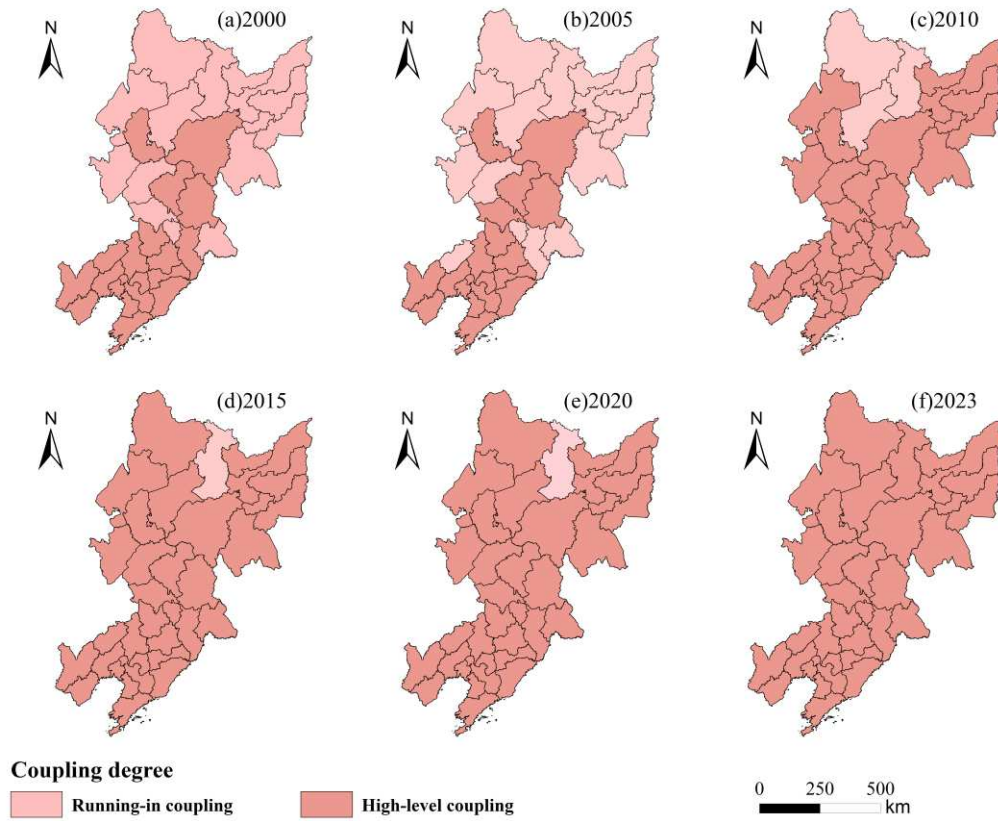


Fig. 14. Spatial pattern of three-dimensional coupling degree for UHS in the TNP, 2000-2023.

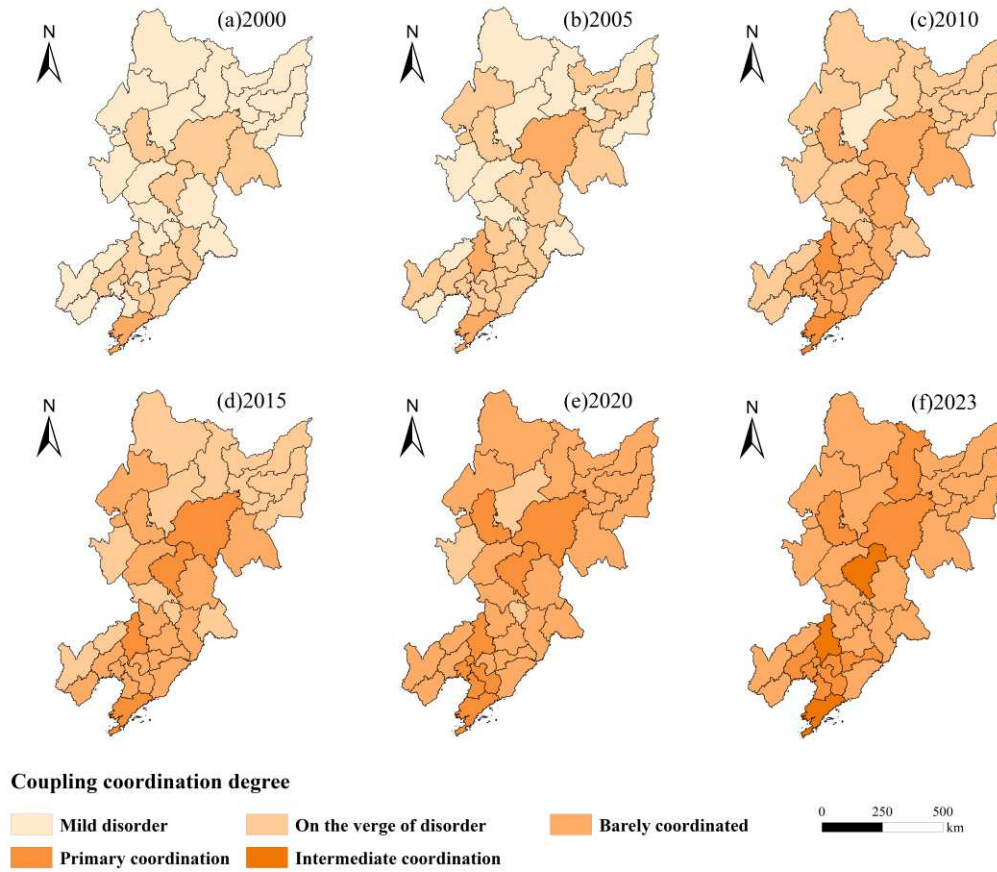


Fig. 15. Spatial pattern of three-dimensional coupling coordination degree for UHS in the TNP, 2000–2023.

3.5. Analysis of obstacle factors for the sustainable development of the UHS

The obstacles to sustainable UHS development in the TNP are primarily concentrated in the social security and economic development subsystems. Among these, social security is the dominant obstacle, with its obstacle level remaining the highest across all years, rising from 43.49% in 2000 to 46.43% in 2023. Economic development is the second-largest obstacle, exhibiting a "U-shaped" trend over the period 2000-2023—decreasing from 37.40% in 2000 to 33.77% in 2015, then rebounding to 37.49% in 2023. In contrast, the resource and environment subsystem has the lowest obstacle level, showing a fluctuating downward trend from 19.11% in 2000 to 16.07% in 2023 (**Fig. 16**).

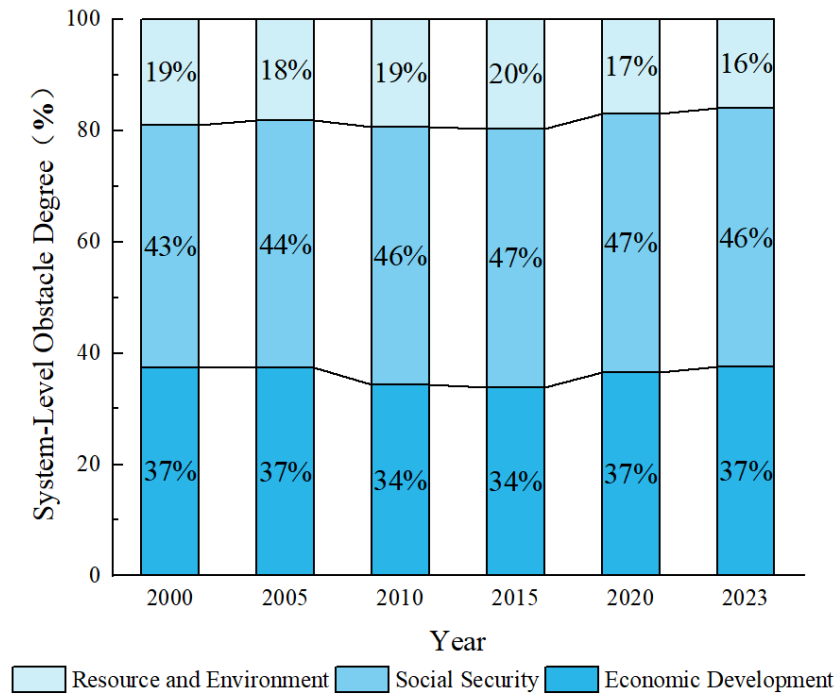


Fig. 16. System-level obstacle degrees for sustainable UHS in the TNP, 2000–2023.

Using the obstacle degree model, this study measured the obstacle degrees of 21 indicators for sustainable urban human settlements in the TNP from 2000 to 2023. Over the study period, four core indicators—the proportion of expenditure on science and technology in total government expenditure (X4), public library collections per 1,000 people (X11), the number of broadband internet subscribers (X12), and per capita park green space (X19)—consistently remained in the deep-red zone, indicating long-standing constraints on the sustainable development of human settlements in the region.

Specifically, the obstacle degree of X4 increased from 7.53% in 2000 to 9.86% in 2023, a growth of 31.0%, indicating that investment in scientific and technological innovation has lagged behind the actual demand for sustainable human settlement development. X11 maintained an obstacle degree between 9.36% and 11.19% over 2000–2023, with a mean of 10.23%, ranking as the second-highest obstacle indicator and reflecting the significant constraining effect of insufficient public cultural service provision. X12 showed a sharp upward trend, rising from 11.04% in 2000 to 12.04% in 2023, making it the single indicator with the highest degree of obstacle by 2023. X19 remained at a persistently high obstacle degree throughout the study period. In addition, three indicators—highway freight volume (X3), the proportion of education expenditure to fiscal expenditure (X7), and the student-teacher ratio in primary and secondary schools (X10)—have shown increasing obstacle degrees in recent years, signaling tighter allocation of educational resources and the impact of population out-migration on transport service demand. These emerging deteriorating indicators warrant close attention (**Fig. 17**).

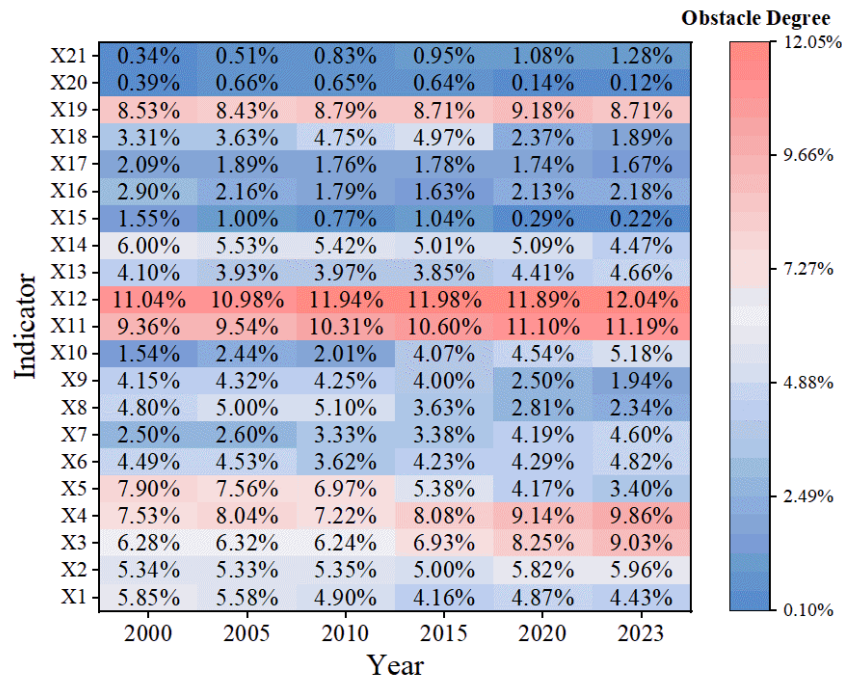


Fig. 17. Heatmap of indicator-level obstacle degrees for sustainable UHS in the TNP, 2000–2023.

4. Discussion

4.1. The intrinsic evolutionary logic and phased characteristics of sustainable human settlement development in the TNP

This study found that from 2000 to 2023, the HSSDI of Northeast China rose from 0.2615 to 0.4543, representing an increase of 73.7%. This steady upward trend was not merely linear but the result of a phased evolution deeply embedded in national regional development strategies and local economic transformation processes. The peak growth period from 2005 to 2010 coincided with the implementation of the first five-year plan under the ‘Revitalization of the Old Industrial Bases in the Northeast’ strategy, during which large-scale investment in infrastructure and industrial restructuring directly drove a significant improvement in the physical conditions of the human settlements. Conversely, the slowdown in growth after 2010 reflected the Northeast’s economy’s difficult transition from an investment-driven to an innovation-driven model, necessitating a shift in the development of the human settlements from ‘extensive expansion’ to ‘intensive improvement’.

The emergence of a spatial pattern characterized by ‘strong in the south, weak in the north; coastal leadership; core support; marginal stagnation’ is rooted in the TNP’s differing geographical endowments and industrial structures. It is no coincidence that LN has long led the way: its southern coastal region, leveraging its port advantages, was the first to integrate into global value chains, and the fiscal revenue generated by its export-oriented economy has provided a solid foundation for public service provision. By contrast, the catch-up trajectories of JL and HLJ have followed distinct paths of transformation: JL’s accelerated growth since 2015 has benefited from a ‘dual-engine drive’ fuelled by the expansion of the Changchun metropolitan area and the green transition of the automotive industry, whilst HLJ’s leapfrog development since 2020 has been closely linked to the emergence of new economic drivers, such as the winter sports economy and the advancement of

agricultural modernization. This ‘latecomer’ catch-up model demonstrates precisely that: once the path dependence of traditional industrial models is broken, improvements in the human settlements must be underpinned by new economic growth poles.

This finding is broadly consistent with the assessment by Fang et al. (2022b) regarding the overall and sustained improvement in China’s urban human settlements, as well as the conclusion by Zhou et al. (2021b) that urban sustainability in the Northeast region is at a lower-middle level, thereby reinforcing the reliability of this study’s findings. However, through a 23-year longitudinal analysis, this study further reveals that the improvement in the human settlements in the Northeast has not progressed at a uniform pace, but rather exhibits marked policy sensitivity and path dependence—whilst the intervention of national strategies can rapidly raise overall standards, it is the profound adjustment of local economic structures that ultimately determines sustainability. Existing research has largely focused on cross-sectional comparisons of a single year or short time series (Li et al., 2024; Liu et al., 2023), making it difficult to capture the logic of phased transitions characterized by ‘policy-driven—structural constraints—cultivation of new growth drivers’; this is precisely where the added value of this study lies.

4.2. The underlying mechanisms of spatial pattern evolution

The seemingly ‘anomalous’ result—that the global Moran’s I consistently failed to pass the significance test—provides profound insight into the structural contradictions in the Northeast region’s internal development. Traditional regional development theory predicts that core cities should drive the formation of a “High-High” cluster in surrounding areas through spatial spillover effects (Anselin, 1995). However, the three provinces of the TNP exhibit a fragmented pattern characterized by ‘high-level and low-level cities interspersed and existing in an isolated, island-like manner’, which is consistent with the findings of Chen and Zhang (2021) regarding the significant disparity between core cities such as Dalian and Shenyang and resource-depleted cities. The underlying causes are, first, that administrative barriers and industrial homogeneity hinder the flow of factors of production, leading to redundant resource allocation and making it difficult for cities to complement and collaborate; second, the ‘cliff-like decline’ of resource-based cities has severed spatial continuity, with places such as Fuxin and Heihe trapped in ‘low-level lock-in’, creating a ‘high–low’ contrast with the influence zones of provincial capitals; third, geographical barriers and climatic differences exacerbate the north–south divide; the disparity in natural conditions between HLJ’s frigid border regions and LN’s temperate coastal areas makes it difficult for spatial linkage effects to be transmitted across latitudes.

4.3. The underlying causes of the asymmetric structure of system-level coupled (coordinated) scheduling

The degree of coordination has reached only the ‘primary coordination’ level and exhibits an asymmetrical structure—where ‘resource and environmental improvements lead, whilst economic and social development lags’—which stems from the unique transformation path of the old industrial base in the Northeast. Over the past two decades, the TNP has achieved significant results in environmental governance, greening initiatives and pollution control. This is attributable, on the one hand, to the environmental protection momentum driven by the philosophy that ‘lucid waters and lush mountains are invaluable assets’, and, on the other hand, to the direct reduction in pollution-emission intensity resulting from the scaling back of heavy industrial capacity. However, as the ‘supporting core’ of human settlements, improvements in economic development and social security

rely on ‘additive’ measures: economic growth depends on the restructuring of the industrial sector, whilst social security depends on sustained fiscal investment and population concentration. When the Northeast experiences population outflow, industrial hollowing out and fiscal pressures, improvements in the ‘economic–social’ subsystem naturally lag those in the ‘environmental’ subsystem.

This asymmetric structure echoes the findings of Guan et al. (2018) regarding the bottlenecks in coordinating social equity and economic growth in China’s urbanization process, as well as the argument put forward by He and Zhang (He and Zhang, 2022) regarding how the uneven allocation of public services exacerbates regional disparities. However, this study highlights the unique characteristics of the Northeast: in the south-eastern coastal regions, high economic growth has provided the financial underpinning for environmental improvement and social development, with all three areas advancing in tandem; whereas in the Northeast, the lag in economic transformation has left environmental improvement lacking sustainable fiscal support, whilst social security faces the dilemma of diminishing returns in terms of ‘input–output’ efficiency due to population outflow.

4.4. Underlying mechanisms of obstacle factors

The degree of obstacles in social security has consistently ranked highest. It has continued to rise, while those for economic development, resource and the environment have shown a “U-shaped” recovery and a persistent decline, respectively. This differentiated evolutionary trajectory reflects a historic shift in the focus of human settlement development in Northeast China. From 2000 to 2010, the obstacle to economic development remained high, primarily due to insufficient “hardware” such as infrastructure and industrial capacity. The decline observed from 2010 to 2015, however, did not signify the resolution of structural contradictions, but rather a temporary masking of deep-seated problems by investment-driven growth under the “Revitalize the Northeast” strategy. The subsequent rebound after 2015 indicates that, once the investment effects faded, the constraints imposed by the traditional development model re-emerged. The persistently high and rising obstacle degree of social security reveals a more profound structural contradiction: while basic subsistence needs have been largely met, residents’ demands for “software” aspects—such as public service quality, digital lifestyles, and cultural rights—have continued to escalate, whereas the supply-side response has lagged notably, resulting in a widening mismatch between supply and demand. This evolutionary logic at the system level is further corroborated by the changing patterns observed at the indicator level.

These findings engage in a valuable dialogue with existing research. Liu et al. (2023) noted that social systems have always been a core factor influencing the quality of the human settlements in the North-East; this study quantifies this assertion using a barrier index model and further elucidates its mechanisms: social security barriers are not static ‘weak links’, but rather a ‘moving target’ that evolves dynamically with each stage of development—from early-stage infrastructure deficiencies, through mid-stage disparities in the equalization of public services, to the current gaps in digital and cultural needs, its scope is constantly expanding. This contrasts with the findings of national studies, which suggest that economic factors dominate improvements in the human settlements (Li et al., 2022; Wang et al., 2024; Zhu, 2023), which stems from the differing developmental stages of the study regions: the south-eastern coastal regions have entered a virtuous cycle where ‘the economy drives society, and society in turn nourishes the environment’, whilst the north-east remains in a period of transition marked by ‘environmental pressures forcing transformation, with that transformation advancing with great difficulty’.

4.5. Policy Implications

Based on the results of the above analysis, the following policy recommendations are put forward:

(1) Implement differentiated regional regulatory strategies. In response to the imbalanced spatial pattern, measures should be tailored to specific categories: core cities such as Shenyang and Dalian should focus on upgrading the existing stock, advancing the renovation of ageing residential estates and the development of smart communities; resource-based cities such as Daqing and Anshan should pursue ecological restoration and improvements to the human settlements in tandem; and border and resource-depleted cities such as Heihe and Yichun need to increase fiscal transfers and incentives for talent return to prevent their human settlements from becoming ‘locked into a low-level state’.

(2) Address shortcomings in social security and public services. In response to the persistent top ranking for social security barriers and the pronounced digital divide, ‘new infrastructure’ should be prioritized within the human settlements agenda, with a focus on narrowing the digital infrastructure gap in small and medium-sized cities; in areas experiencing population outflow, explore flexible public service delivery mechanisms, promote the integration and intensive allocation of educational resources, and offset scale reductions through quality improvements.

(3) Promote economic diversification and green transition. The resurgence in the economic development index indicates that the economic downturn is constraining the sustainable development of human settlements. New growth drivers should be cultivated in line with local conditions: LN should develop its marine and digital economies; JL should deepen the dual-core drive of the automotive industry’s green transition and eco-tourism; and HLJ should capitalize on the winter sports economy and modern agriculture. Concurrently, a “Special Programme for Human Settlements Science and Technology” should be established to reverse the lag in investment in science and technology.

(4) Establish dynamic monitoring and cross-regional coordination mechanisms. Given that the level of systemic coupling and coordination remains rudimentary, a dynamic monitoring platform covering the three major subsystems, complete with early-warning thresholds, should be established. Efforts should be made to promote the coordinated development of human settlements in metropolitan areas such as Shenyang–Dalian and Changchun–Jilin, breaking down administrative division barriers to allow best practices and resources to flow freely between cities. Furthermore, governance experiences and lessons learnt from various regions should be compiled into a case study database to provide practical reference for future policy-making.

4.6. Research limitations and prospects

This study has several limitations. Firstly, due to constraints on the availability of statistical data, the indicator system does not fully cover all dimensions of UHS's sustainability, and analysis at the prefecture-level city scale struggles to reveal spatial differentiation within cities. Secondly, although the six cross-sections outline overall trends over more than two decades, they still fail to capture short-term fluctuations and phased policy shocks. Furthermore, due to space constraints, this paper has only provided a preliminary exploration of the interaction pathways and transmission mechanisms between subsystems; further in-depth analysis is required. Future research could be advanced in the following areas: at the data level, by introducing continuous time series and high-resolution spatial data; at the methodological level, by integrating questionnaire surveys, in-depth

interviews, or text semantic analysis to construct a comprehensive assessment paradigm that cross-validates subjective and objective data; and at the theoretical level, by establishing a case database on urban human settlements governance to systematically analyze the coupling and feedback pathways between subsystems, with a view to providing more robust empirical support for the formulation of differentiated policies.

5. Conclusion

The study establishes an evaluation framework for the sustainable development of the UHS from the perspective of the Sustainable Development Goals (SDGs), drawing on three dimensions: economic development, social security, and resource and the environment. By examining the sustainable development capacity of the UHS in 34 prefecture-level cities across the TNP from 2000 to 2023, this study reveals the evolutionary process and spatio-temporal patterns of this capacity in the region. Building on this, the Coupling Coordination Index model is employed to measure the level of coupling and coordination in the sustainable development of the UHS. Finally, the Obstacle Index model is utilized to analyze the factors hindering the sustainable development of UHS. The results indicate that:

(1) From 2000 to 2023, the HSSDI in the TNP increased from 0.2615 to 0.4543, showing a steady upward trend. In terms of spatial distribution, a pattern of "strong in the south, weak in the north; coastal leadership; core support; marginal stagnation" emerged.

(2) The coupling degrees of the UHS sustainability systems in the TNP exhibited a fluctuating upward trend, with growth rates gradually slowing and ultimately reaching a high-level coupling stage. The coupling coordination degree showed a steady improvement, yet it only reached a "primary coordination" level by the end of the study period.

(3) At the system level, obstacle degrees were primarily concentrated in the social security and economic development subsystems. At the indicator level, the proportion of expenditure on science and technology in total government expenditure (X4), public library collections per 1,000 people (X11), the number of internet broadband subscribers (X12), and per capita park green space (X19) were identified as the core limiting factors constraining the sustainable development of human settlements in the region.

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Data availability:

The original data supporting this study were sourced from publicly accessible repositories: the China City Statistical Yearbook(<https://tjj.ln.gov.cn>,<https://tjj.jl.gov.cn>,<https://tjj.hl.gov.cn>), the Geospatial Data Cloud (<https://www.gscloud.cn>), the National Tibetan Plateau Data Center (<https://data.tpdac.ac.cn>), and the Emissions Database for Global Atmospheric Research (<https://edgar.jrc.ec.europa.eu>). The process and result data are presented in the paper in the form of figures and tables.

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