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Habitat Quality and Urban Development Level in Arid Xinjiang, China: Improved Coupling Coordination and the Spatiotemporal Impacts of Urban Development

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Abstract

Understanding the coupling coordination between habitat quality (HQ) and urban development and their spatial interactions can inform coordinated ecological and socioeconomic development in Xinjiang, China. This study established an integrated evaluation framework for habitat quality and urban development across 14 prefecture-level units in Xinjiang, using observed data from 2012 to 2024 and projected data for 2027. Entropy-weighted TOPSIS, non-seasonal exponential smoothing, CA–Markov modeling, and an improved coupling coordination model were combined with bivariate spatial autocorrelation, geographically and temporally weighted regression (GTWR) and XGBoost–SHAP were employed to assess development patterns, spatial relationships, and influencing factors. During the observation period, habitat quality remained relatively low but showed a fluctuating upward trend, with significant differences between northern and southern Xinjiang. The average coupling coordination degree across the region steadily increased from 0.317 to 0.381. High-value clusters centered on Urumqi and Ili Prefecture and declined toward surrounding areas, while Turpan remained severely uncoordinated. Urban development and habitat quality showed stable negative spatial agglomeration, and GTWR indicated that their centers of influence shifted from Aksu toward Bayingolin. Analysis of the results incorporating the projected data showed that the mean coupling coordination degree across Xinjiang is expected to reach 0.39 in 2027. The dual-system association network exhibited a hierarchical transmission pattern comprising four block types: core output, linkage transit, marginal association, and bidirectional interaction. GTWR revealed significant spatial bidirectional effects, with the strongest negative effects in Kizilsu and Kashgar, while Aksu and Hotan showed relatively stable positive reciprocal feedback. XGBoost–SHAP analysis identified educational resource concentration as the primary negative driver, whereas rational urban land-use planning provided positive support across regions. The driving factors also differed between northern and southern Xinjiang. Accordingly, habitat quality should be incorporated into development performance assessments, differentiated management should be implemented according to block functions, and the allocation of educational resources and land use should be optimized to promote high-level mutual reinforcement between urban development and habitat quality.

Keywords: arid regions; habitat quality; urban development; coupling coordination; spatiotemporal heterogeneity

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1. Introduction

Over the past decade, while sustaining economic growth, China has placed greater emphasis on ecological protection and the preservation of "lucid waters and lush mountains." Compared with the rapid-growth phase from 1978 to 2012, national economic growth has moderated; however, ecological and environmental problems that accumulated during the earlier development period have gradually been remedied and restored. Following the completion of the first Centenary Goal, China has entered a new stage oriented toward building a modern society through high-quality development. To prevent a vicious cycle in which accelerated urbanization squeezes ecological land, degrades environmental quality, undermines public well-being, and in turn constrains economic growth, the Chinese leadership has emphasized that green and low-carbon development should serve as the fundamental strategy for resolving ecological and environmental problems, that green modes of production and consumption should be accelerated, and that the environmental foundation of high-quality development should be further strengthened. Accordingly, Xinjiang has moved beyond conventional development models and integrated new quality productive forces and green production systems into its high-quality development trajectory, striving to advance ecological protection and social-economic progress in a coordinated manner. The synergistic enhancement of ecological quality and economic development is crucial for human well-being and sustainable socio-economic development [1,2], and exploring such dual-improvement pathways has become a focal point in this field. In China's contemporary development process, Xinjiang continues to expand its economy, yet its unique ecological environment faces serious pressures; Notably, conflicts between ecological conservation and industrial expansion, as well as the pressure exerted by population concentration, rising residential demand, and construction-land expansion on ecological land, have become increasingly salient. Therefore, a scientific and objective assessment of the current status and mechanisms underlying the relationship between ecological environments and urban development is of great practical significance for achieving coordinated socio-economic and ecological development in Xinjiang.

Habitat quality (HQ) refers to the degree to which the abiotic and biotic environment is suitable for the survival and persistence of species populations within a given habitat. Its condition is directly related to the capacity for sustainable coexistence among humans, natural ecosystems, and biodiversity. International studies on habitat quality have primarily focused on how habitat conditions within ecological zones influence species extinction risk [3], reproductive behavior [4], and population dynamics of seasonal or migratory species [5,6], or have assessed regional habitat quality through species-habitat suitability evaluation [7,8]. Some scholars have concentrated on the development, calibration, and application of habitat-quality models [9]. However, relatively little attention has been paid to how urban development affects habitat quality at the regional scale [10]. Domestic studies, by contrast, have tended to focus on habitat-quality assessment, prediction, and impact analysis at the scales of ecological zones [11], river basins [12,13], or urban economic belts [14,15], and have increasingly incorporated habitat quality into coupling coordination analyses with other systems. With the advancement of human–land system theories, research has moved beyond the single-dimensional measurement of regional habitat-quality change and has begun to integrate measures such as urban development level (UDL) [16,17] and construction-land expansion [18,19] into unified analytical frameworks to examine the coupling and coordination relationship between habitat quality and development systems [20].

Mechanistically, urban development and habitat quality interact with one another. Urban expansion, driven by infrastructure construction, industrial growth, and population concentration, promotes economic growth and improves living standards; at the same time,

it exerts pressure on habitat quality by squeezing ecological space through the conversion of ecological land into urban and residential land [21,22], and by degrading environmental elements through industrial emissions [23,24]. Conversely, habitat quality also conditions urban development: high-quality habitats can provide ecosystem services, attract talent, and support industrial development [25], whereas habitat degradation may amplify natural hazards, intensify resource scarcity, and constrain the sustainable development of urban systems. Previous studies have shown that the relationship between urban development and habitat quality exhibits pronounced regional heterogeneity [26–28]. Urban development may intensify pressures on habitats through land-use expansion [29], resource consumption [30], and anthropogenic disturbances. Meanwhile, industrial restructuring, ecological management, and investment in conservation may improve habitat quality. Thus, the relationship between the two depends on factors such as the regional development stage, baseline ecological conditions, and governance capacity. For example, in the Tianshan North Slope Economic Belt in Xinjiang [31], rapid urban development has generated heavy habitat pressure and thereby produced an antagonistic relationship, whereas regions with favorable ecological endowments, such as the lower reaches of the Yellow River [32], can achieve synergistic progress in ecological protection and economic development.

However, most existing studies still rely on one or only a few proxy indicators—such as urban expansion or industrial scale—to analyze the effects of development activities on habitat quality, or they examine the relationship solely through aggregated coupling coordination analysis. Social development and ecological environment research should instead be grounded in the overall interaction between the two subsystems. Regional development encompasses far more than urban expansion and economic growth alone. Therefore, if habitat-quality impact assessments or coupling analyses are conducted using only a few indicators, the underlying principles of regional development–ecology interactions may not be fully captured. A more scientific approach is to construct a multidimensional indicator system for regional development, evaluate regional development levels in a comprehensive manner, and then examine the coupling coordination characteristics and driving mechanisms between habitat quality and regional development from a system-level perspective. Taken together, existing habitat-quality studies still lack a framework that systematically analyzes coupling coordination and its interaction patterns from the dual perspectives of development and ecosystem systems. Against the backdrop of simultaneous economic growth and ecological protection, it is therefore important and meaningful to investigate the interactive relationship between the two systems in Xinjiang as a representative case. Such research is valuable for achieving a win–win outcome between urban development and ecological preservation, and it can provide scientific support for policy formulation and for promoting greater harmony between human development and the natural environment.

Xinjiang, located in the core zone of the Silk Road Economic Belt, occupies a strategically important position. Since 2012, Xinjiang's economy has grown rapidly, accompanied by population concentration, talent inflows, and continuous expansion of construction and residential land, which has intensified the conflict between ecological conservation and urban development. Against this backdrop, systematically examining the coupling coordination characteristics and evolutionary tendencies between habitat quality and urban development in Xinjiang is of considerable practical significance for achieving regional sustainable development. Drawing on the theoretical insights of the environmental Kuznets curve regarding the relationship between environment and development, this study takes the 14 prefecture-level administrative units in Xinjiang as the research subjects for 2012–2027. It constructs a comprehensive evaluation system for habitat quality and urban development, and integrates entropy weighting–TOPSIS, an improved coupling coordination degree model, bivariate spatial autocorrelation, geographically and temporally weighted regression

(GTWR), XGBoost–SHAP, and the CA–Markov forecasting model to perform evaluation, prediction, and attribution analyses. The study aims to (1) reveal the spatiotemporal evolution of regional habitat quality; (2) clarify the coupling coordination levels and spatial differentiation patterns between habitat quality and urban development across multiple temporal and spatial dimensions; (3) identify the spatial agglomeration characteristics of the influence of urban development systems on habitat quality; and (4) explain the spatiotemporal evolutionary patterns and key driving factors underlying the coupling coordination relationship and mutual influence between the two systems. The findings are expected to provide useful marginal reference for promoting coordinated advancement of socio-economic progress and high-quality ecological development across prefectures in Xinjiang.

2. Study Area

The Xinjiang Uygur Autonomous Region (hereinafter referred to as Xinjiang) is located between 73°40′ E and 96°18′ E and between 34°25′ N and 48°10′ N. It covers a land area of approximately 1.6649×10^6 km^2 and has a temperate continental climate. Administratively, the region comprises 14 prefecture-level administrative divisions: five autonomous prefectures—Kizilsu Kirgiz Autonomous Prefecture (hereinafter referred to as Kizilsu), Ili Kazakh Autonomous Prefecture (hereinafter referred to as Ili), Bayingolin Mongolian Autonomous Prefecture (hereinafter referred to as Bayingolin), Bortala Mongolian Autonomous Prefecture (hereinafter referred to as Bortala), and Changji Hui Autonomous Prefecture (hereinafter referred to as Changji); four prefecture-level cities—Urumqi City (hereinafter referred to as Urumqi), Karamay City (hereinafter referred to as Karamay), Turpan City (hereinafter referred to as Turpan), and Hami City (hereinafter referred to as Hami); and five prefectures—Aksu Prefecture (hereinafter referred to as Aksu), Kashgar Prefecture (hereinafter referred to as Kashgar), Hotan Prefecture (hereinafter referred to as Hotan), Tacheng Prefecture (hereinafter referred to as Tacheng), and Altay Prefecture (hereinafter referred to as Altay). The geographical location, administrative divisions and topographic features of the study area are shown in (Figure 1).

The topography of the study area is complex and diversified and displays the characteristic intermontane pattern of "three mountain ranges alternating with two basins": arranged from north to south, the Altai, Tianshan, and Kunlun mountain ranges alternate with the Junggar and Tarim basins, the Tianshan Mountains forming the internal divide between the two. Rivers fed by glacial meltwater and precipitation and flowing across the northern piedmont of the Tianshan sustain the oases of the Tianshan North Slope Economic Belt (hereinafter the northern Tianshan slope belt), which hosts the densest concentration of towns and industry in Xinjiang. The Taklamakan Desert, the largest desert in China, accounts for 22.24% of the regional land surface and is characterised by extreme aridity and minimal precipitation. The Tarim River, the longest inland river in China, traverses the Tarim Basin, and the oases along its banks constitute the region's most important zone of agricultural settlement and urban growth.

Owing to its geographical position and to its role within the Belt and Road Initiative (BRI), Xinjiang has achieved substantial socio-economic development: its average annual GDP growth rate reached 5.4% during 2020–2025, its industrial structure has been continuously upgraded, and the region now hosts 86 development zones at various administrative levels, together with the China (Xinjiang) Pilot Free Trade Zone. Population agglomeration has intensified in parallel; according to the Seventh National Population Census, inter-provincial population inflow increased by 1.948 million persons relative to the Sixth National Population Census. Since the elimination of absolute poverty was declared in 2020, urbanisation has accelerated further, and the continued expansion of residential, industrial

and other construction land has increasingly encroached upon ecological land, thereby exerting greater pressure on regional ecological protection and restoration.

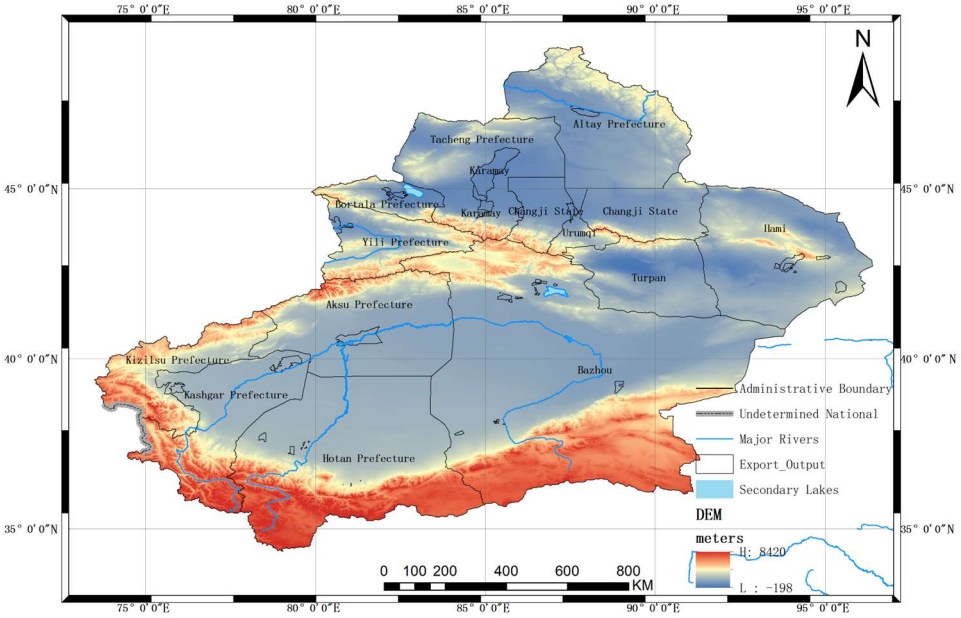


Figure 1. Geographical location of the study area. Basemap source: Standard Map Service System of the Ministry of Natural Resources (formerly the National Administration of Surveying, Mapping and Geoinformation). The boundaries shown on the basemap were not modified. Approval No. GS(2024)0650.

3. Research Framework and Methods

3.1. Theoretical Framework

The environment provides the physical foundation for natural resources and is itself a unique type of resource, referred to as environmental resources. It contributes to economic development in three ways: maintaining human health, enhancing production efficiency, and providing amenity services that improve residents' quality of life [25]. Continued scientific and technological progress is expected to gradually reduce, and ultimately eliminate, the dependence of social development on natural and environmental resources. In practice, however, technological progress primarily improves resource-use practices and efficiency. Regardless of the technologies developed or deployed, social development and human well-being remain constrained by natural resource endowments and environmental quality. Thus, the stock of natural capital continues to impose a critical constraint on economic growth [33].

Urban development and habitat quality exhibit complex interactions. On the one hand, urban expansion, land use change, and intensive human activities encroach upon, fragment, and disturb natural habitats, thereby exerting sustained pressure on habitat quality. On the other hand, habitat quality, as an integrated measure of regional ecosystem structure and functioning, both supports and constrains urban development. The relationship between the two is not simply linear but may shift dynamically between antagonism and synergy depending on the stage of development, baseline ecological conditions, industrial structure, and governance capacity. Based on this understanding, this study integrates urban development and habitat quality in Xinjiang into a unified analytical framework. A total of 10 indicators are selected across the two systems, and their weights are determined using the entropy weighting method. With reference to the evaluation criteria for habitat quality threat factors, urban development levels and habitat quality are assessed and projected for

each region, and the spatiotemporal distribution of habitat quality over the period 2012–2027 is analyzed. A two-system coupling coordination degree model and spatial autocorrelation analysis are then employed to examine the coupling coordination relationship between the two systems and the spatial clustering patterns of their interactions, with the aim of identifying the key factors influencing habitat quality. The analytical framework of this study is presented in Figure 2.

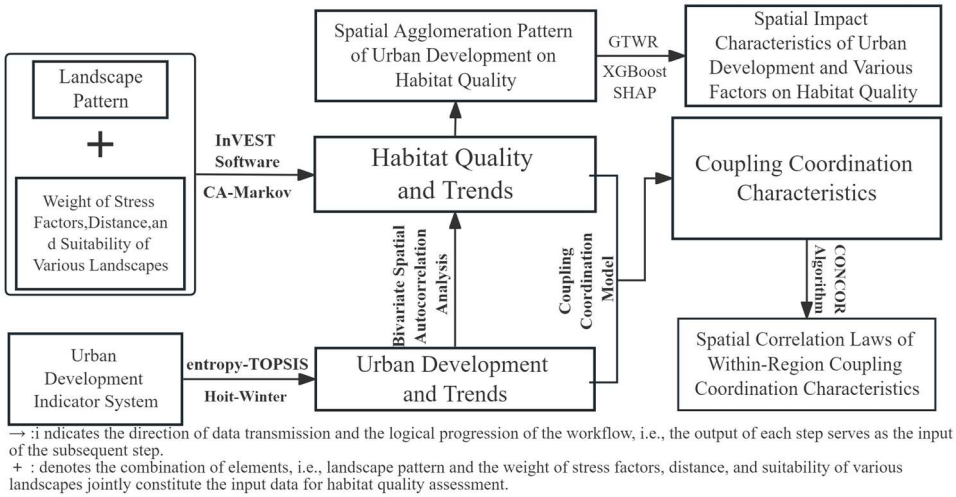


Figure 2. Conceptual framework and analytical workflow of the study.

3.2. Research Methods and Procedures

3.2.1. Calculation of Habitat Quality

This study employs the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model to assess HQ in the study area. The procedure comprises three steps: (i) identifying the principal ecological threat factors and specifying the distance-decay function (linear or exponential) for each factor; (ii) quantifying the degree of habitat degradation caused by each threat factor; and (iii) integrating habitat suitability for each land-cover class with threat-induced degradation to calculate the HQ index. HQ is calculated for Xinjiang for the period 2012–2027 to characterise spatiotemporal changes in habitat quality. The detailed assessment procedure is presented below.

Degree of degradation:

$$\begin{aligned} D_{ij} &= \sum_{r=1}^{R}\sum_{y=1}^{Y_r} r_y \left(\frac{\omega_r}{\sum_{r=1}^{R}\omega_r}\right) k_{ixy}\beta_i S_{jr} \\ k_{ixy} &= \exp\left(-\left(\frac{2.99\bar{d}_{xy}}{d_{r-\max}}\right)\right)(\text{exponential decay}) \\ k_{ixy} &= \left[1 - {}^{d_{iy}}/_{d_{r-\max}}\right](\text{Linear decline}) \end{aligned} \quad (1)$$

where D_{ij}—degree of habitat degradation, R—number of threat factors, Y_r—number of raster cells occupied by threat factor r; ω^r is the relative weight; ry—stress intensity of the threat exerted at cell y; k_{ixy}—threat of r, y to raster x; β_i is the resistance of land-cover class I; S_{jr}—sensitivity of land-cover class j to threat factor r; d_{xy}—distance between x land and y raster.

Habitat quality:

$$P_{ij} = Q_j\left[1 - \left(\frac{D_{ij}^z}{D_{ij}^z + k^z}\right)\right] \quad (2)$$

where P_{ij} is the habitat quality index of raster cell i covered by land-cover class j, varying between 0 and Q_j (a larger value denotes better habitat condition); Q_j is the habitat suitability

of land-cover class j for the assemblage of threatened species, rated on a scale of 0–1; D_{ij} is the composite degree of habitat degradation of cell i obtained from Equation (1); z is the normalisation constant that governs the curvature of the degradation–quality relationship and was set to the default value of 2.5; and k is the half-saturation constant, set to the default value of 0.5, at which P_{ij} equals one half of Q_j.

Based on the existing literature [34–36], the threat factor distance, weight, decline type, suitability and sensitivity scales were developed. The detailed results are presented in Tables 1 and 2:

Table 1. Maximum effective distance, relative weight and decay type of each threat factor.

Threat Factor	Max. Effective Distance (km)	Weights	Decay Type
Cropland	4	0.6	Linear
Urban and rural residential and construction land	8	0.4	Index
Unused land	6	0.5	Linear

Table 2. Habitat suitability of each land-cover class and its sensitivity to each threat factor.

Land-Cover Class	Habitat Suitability	Sensitivity to Cropland	Sensitivity to Residential & Construction Land	Sensitivity to Unused Land
Cropland	0.3	0	0.8	0.4
Forest land	1	0.8	0.4	0.2
Grassland	1	0.7	0.6	0.6
Water body	0.8	0.6	0.4	0.3
Urban and rural residential and construction land	0	0	0	0.1
Unused land	0	0	0	0

Note: Rows are the receptor (habitat) classes, and columns, after the first, are the threat sources; all values are dimensionless and lie in [0, 1]. Unused land is treated as a threat source as well as a receptor class because farmland conversion and settlement expansion in Xinjiang are accompanied by the spread of sand and saline-alkali land.

3.2.2. Calculation of Urban Development Levels

The entropy-weighted TOPSIS method is employed to assess UDL across Xinjiang's prefecture-level administrative units. To ensure interannual comparability, all annual observations for these units from 2012 to 2024 are pooled into a single evaluation dataset. First, the indicators are normalized using a common procedure across the pooled dataset. Second, entropy weights are calculated from the normalized data and used to construct the weighted normalized decision matrix, from which the positive and negative ideal solutions are determined. Finally, the distances of each administrative unit in each year from the positive and negative ideal solutions are calculated to derive its relative closeness coefficient, which serves as the composite UDL score. The evaluation procedure is detailed below:

Index weight matrix:

$$\left(P_{ij}\right)_{m\times n} = \frac{X_{ij}^{+/-}}{\sum_{i=1}^{m} X_{ij}^{+/-}} \tag{3}$$

Entropy calculation:

$$e_j = -\frac{1}{lnm}\sum_{i=1}^{m} P_{ij} lnP \tag{4}$$

Weights of each indicator

$$w_j = \frac{1 - e_j}{\sum_{i=1}^{m} 1 - e_j} \tag{5}$$

In the formula: i and j—evaluation objects and evaluation indicators; m and n—total number of indicators and total number of objects; E_j—entropy of indicators; w_j—weight of indicators; P—proportion of indicators; X_{ij}—the j indicator of i evaluation object.

TOPSIS model construction

The indicator weights determined using the entropy weight method are multiplied by the dimensionless indicator values to construct the weighted normalized matrix:

$$r_{ij} = w_j X_{ij}^{\sim} \tag{6}$$

Calculating positive and negative ideal solutions:

$$\begin{aligned} r_j^+ &= \max\left(r_{ij}\right) \\ r_j^- &= \min\left(r_{ij}\right) \end{aligned} \tag{7}$$

Calculate the distance from the positive and negative ideal solutions:

$$\begin{aligned} D_i^+ &= \sqrt{\sum_{i=1}^{n}\left(r_{ij} - r_j^+\right)^2} \\ D_i^- &= \sqrt{\sum_{i=1}^{n}\left(r_{ij} - r_j^-\right)^2} \end{aligned} \tag{8}$$

Post-progress:

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{9}$$

In the formula: $X_{ij}^{\sim}$ denotes the normalized value of X_{ij}, D_i is the distance between the evaluation object and the best or worst solution, r_j is the best or worst solution, S_i indicating the degree of closeness between the urban development level and the best development, with values ranging from $[0, 1]$. The closer S_i is to 1, the higher the urban development level, and vice versa; Therefore, in this paper, S_i represents the urban development level of sample i.

3.2.3. Improved Coupling Coordination and Fit-Degree Analysis of Habitat Quality and Urban Development Level

To characterise the dynamics and direction of the relationship between ecological conservation and regional development, an improved coupling coordination and fit-degree model is developed. In this model, the habitat quality (HQ) system and the urban development level (UDL) system are treated as two coupled subsystems, enabling the simultaneous assessment of their interaction intensity and coordination status. Conventional coupling coordination degree models quantify the degree of interaction between the two subsystems but do not adequately reveal their relative development status or the magnitude and direction of their disparity. Therefore, the fit-degree terms M and W are introduced to provide an additional diagnostic of the relative fit and development gap between HQ and UDL. The model is specified as follows:

$$C = \left[\frac{A \times B}{(a \times A + b \times B)^2}\right]^{\frac{1}{2}} \tag{10}$$

$$T = \mathrm{a} \times A + b \times B \tag{11}$$

$$D = \sqrt{C \times T}(11) \tag{12}$$

$$M = 1 - \frac{|W|}{U - 1} \tag{13}$$

$$E = cD + eM \tag{14}$$

where A and B are, respectively, the mean habitat quality index and the mean urban development level index of the study area obtained from Equations (9)–(11); C is the coupling degree of the two subsystems, i.e., the intensity with which they interact irrespective of their absolute levels, varying within $(0, 1]$; T is the comprehensive development index of the compound system, in which a and b are the contribution weights of the ecological and the developmental subsystem; D is the coupling coordination degree; M is the relative fit between the spatial patterns of HQ and UDL, with $M > 1$ and $M < 1$ indicating that habitat quality, respectively, leads and lags behind urban development; W is the disparity index defined as the mean absolute deviation between the standardised scores of the two subsystems, which quantifies the magnitude of the gap whose direction is signalled by M; E is the improved coupling coordination–fit index, a power-weighted composite of D and M; c and e are the corresponding coefficients, set to 0.6 and 0.4, so that coordination degree retains primacy while the fit term provides the diagnostic correction $(c + e = 1)$; and U is the number of prefecture-level administrative units, i.e., $U = 14$ in this study, used to normalise the summation terms. Equal weights $a = b = 0.5$ reflect the assumption that habitat protection and urban development are of equivalent importance in a fragile arid inland-river region [37,38] where neither subsystem may be traded off against the other; the coefficients c and e follow the calibration of previous studies $(c = 0.6, e = 0.4)$.

All indices are dimensionless and range from 0 to 1, with higher values indicating greater coordination or fit. Each unit–year observation was classified into the types listed in Table 3 based on the thresholds of EE and the difference between the standardized HQ (A) and UDL (B) scores: $|A - B| \leq 0.1$ indicates relative balance, $A - B < -0.1$ indicates relative lag in HQ, and $A - B > 0.1$ indicates relative lag in UDL.

Table 3. Classification criteria for the improved coupling coordination-fit index.

Coupling Coordination Level	Criterion for E	HQ-Lagging	Relatively Balanced	UDL-Lagging
Severe disorder	$0 \leq E < 0.25$	$A - B < -0.1$	$\|A - B\| \leq 0.1$	$A - B > 0.1$
Near disorder	$0.25 \leq E < 0.50$	$A - B < -0.1$	$\|A - B\| \leq 0.1$	$A - B > 0.1$
Basic coordination	$0.50 \leq E < 0.75$	$A - B < -0.1$	$\|A - B\| \leq 0.1$	$A - B > 0.1$
High-quality coordination	$0.75 \leq E \leq 1$	$A - B < -0.1$	$\|A - B\| \leq 0.1$	$A - B > 0.1$

3.2.4. Simulation of Future Land Cover and Urban Development

To project future trajectories of HQ, UDL, and their coupling coordination, a CA–Markov [39] model is employed to simulate future land-use patterns, while Holt's linear exponential smoothing is used to extrapolate the urban development indicator series. Both models adopt a common baseline period and consistent prediction intervals. The CA–Markov model projects land-cover changes based on observed land-use transition probabilities, whereas the exponential smoothing model extrapolates UDL indicators based on their historical trends during 2012–2024. The simulated land-cover maps are subsequently entered into the InVEST habitat quality module using the parameters listed in Tables 1 and 2 to estimate future HQ.

Historical backtesting was conducted to assess the reliability of the projections. For the CA–Markov model, data from 2012 to 2021 were used to simulate the land-use pattern in 2024, which was then compared with the observed pattern to assess predictive accuracy. For the Holt–Winters model, data from the observation period were used as the validation dataset, and a time-series model was fitted, with predictive performance evaluated using

the mean absolute error (MAE). Thus, the results for 2027 represent projections under the specified scenario rather than actual observations.

3.2.5. Bivariate Spatial Autocorrelation Analysis of HQ and UDL

Because the preceding coupling coordination analysis is conducted independently for each spatial unit and therefore does not explicitly account for spatial dependence, a bivariate spatial autocorrelation model is further employed to examine the spatial association between HQ and UDL. Specifically, the model evaluates whether the HQ of a given spatial unit is significantly associated with the UDL of its neighbouring units, thereby identifying high–high, low–low, high–low, and low–high spatial associations. The global bivariate Moran's I is calculated as follows:

$$I^{Whole} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})(y_i - \overline{y})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \tag{15}$$

$$I^{Local} = z_i \sum_{j=1}^{n} W_{ij} z_j \tag{16}$$

where I^{Whole} and I^{Local} are the global and local bivariate Moran's I statistics between HQ (row variable x) and UDL (column variable y); n is the number of analysis units ($n = 14$); x_i and y_j are the values of the two variables in the focal unit i and its neighbour j; $\overline{x}$ and $\overline{y}$ are their means; S^2 is the variance of the observations; z_i and z_j are the standardised values of x_i and yj; and w_{ij} is the (i, j) element of the spatial weight matrix [$w_{ij} = 1$ for adjacent units, 0 otherwise, $w_{ii} = 0$]. Positive (negative) values denote spatially assortative (disassortative) HQ–UDL association.

3.2.6. Geographically and Temporally Weighted Regression (GTWR)

Geographically and temporally weighted regression (GTWR) model can reveal how the effects of the urban development level (UDL) and its individual indicators on habitat quality (HQ) differ across space and time. For each prefecture-level administrative unit observation, the centroid coordinates of the prefecture-level unit and the corresponding observation year were specified as the spatial and temporal coordinates, respectively. The model regresses HQ in prefecture-level unit i at time t on the indicators of the urban development system, as follows:

$$y_i = \beta_0(u_i, v_i, t_i) + \sum_k \beta_k(u_i, v_i, t_i) X_{ik} + \varepsilon_i \tag{17}$$

where y_i is the HQ value of observation i, i.e., the dependent variable; X_{ik} is the value of the k-the urban development indicator at observation i, and $k = 1, 2, \ldots, p$ indexes the [$p = 9$] explanatory variables listed in Table 4; (u_i, v_i, t_i) is the space–time coordinate of observation ii, where u_i and v_i are the longitude and latitude of the geometric centroid of prefecture-level unit i and ti is the calendar year of the observation, so that a unit observed in several years contributes several observations that share the same (u_i, v_i) but differ in t_i; $\beta_0(u_i, v_i, t_i)$ is the local intercept (constant term) and $\beta_k(u_i, v_i, t_i)$ the local estimate of the regression coefficient of indicator k at that location and time, whose sign and magnitude are mapped to read the spatial differentiation of the effect; and ε_i is the random error term, assumed independently and identically distributed with zero mean.

Table 4. Indicator system for habitat quality and urban development level.

Primary Indicators	Secondary Indicators	Criteria for Selection	Original Data Sources
Habitat quality	Habitat quality index derived from land classification data of Xinjiang (six first-level classes, 2012, 2015, 2018, 2021 and 2024, with 2027 simulated)	Land classification data determine both habitat suitability and threat exposure, and constitute the required input of the InVEST habitat-quality module	Geospatial Data Cloud
Urban development level	Gross regional product per capita	Reflects the level of regional economic development	Xinjiang Statistical Yearbook
	Total retail sales of consumer goods	Reflects the scale of consumer demand of the population	Xinjiang Statistical Yearbook
	Student–teacher ratio in schools for students with special needs	Reflects the allocation of special-education resources	Xinjiang Statistical Yearbook
	Student–teacher ratio in primary and secondary schools	Reflects the endowment of basic-education resources	Xinjiang Statistical Yearbook
	Beds in medical and health institutions per 10,000 population	Reflects the inpatient capacity of local healthcare services	Xinjiang Statistical Yearbook
	Health technical personnel, including practising physicians, per 10,000 population	Reflects the labour input of local healthcare services	Xinjiang Statistical Yearbook
	Number of enterprise legal entities in active operation	Reflects the vitality of industrial and commercial activity in the region	Xinjiang Statistical Yearbook
	Combined share of the industrial and service sectors in GDP	Reflects the regional industrial structure	Xinjiang Statistical Yearbook
	Share of built-up land for buildings and urban and rural residential purposes in the total land area	Reflects the extent of built-up land occupation	Geospatial Data Cloud

3.3. Indicator Selection

To examine the interaction between the eco-environment and urban development, drawing on the conceptual definitions of eco-environmental quality [40–42] and social development [43,44], as well as their indicator systems in previous studies, this study uses habitat quality (HQ) to characterise the eco-environment and constructs an urban development evaluation system to represent the level of socio-economic development, from which the urban development level (UDL) is subsequently derived.

The measurement of HQ is based on land-cover vector data (representing the current land-use status) for the study area. These data are obtained from the Geospatial Data Cloud platform and classified into six first-level categories according to the land-use/land-cover classification system of the Chinese Academy of Sciences. HQ is then calculated using the InVEST habitat-quality module and the calibrated threat-factor ratings described in Section 3.2.1.

Urban development is a composite manifestation of regional economic and social development, encompassing the economic, educational, healthcare, and industrial-structural dimensions, together with the land it occupies. Considering the actual development conditions in Xinjiang and data availability, nine indicators are selected for the urban development subsystem: gross regional product per capita; total retail sales of consumer goods; the student–teacher ratio (number of students per full-time teacher) in schools for students with special needs; the student–teacher ratio in primary and secondary schools; beds in

medical and health institutions per 10,000 population; health technical personnel, including practising physicians, per 10,000 population; the number of enterprise legal entities in active operation; the combined share of the industrial and service sectors in GDP; and the share of built-up land for buildings and urban and rural residential purposes in the total land area.

Collectively, these indicators reflect the level of economic development, the scale of consumer demand, the allocation of educational resources, the availability of medical services, the industrial structure, and the extent of built-up land occupation in Xinjiang. The two student–teacher ratios are reverse-direction indicators and are normalised accordingly, whereas all other indicators are positively oriented. The observation window begins in 2012 and includes five temporal nodes at three-year intervals: 2012, 2015, 2018, 2021, and 2024. Details of the data sources and the rationale for indicator selection are provided in Table 4.

4. Results and Analysis

Using the calibrated weights assigned to the threat factors described in Section 3.2.1 and GIS-based spatial analysis, this study evaluated the spatiotemporal dynamics of habitat quality across the prefecture-level administrative regions of Xinjiang, as shown in Table 5. The results from both the observation period assessment and future projections indicate that the overall habitat quality index of Xinjiang increased with fluctuations from 0.322 in 2012 to 0.356 in 2024, and is projected to further increase to 0.364 by 2027. Specifically, the index exhibited minor fluctuations between 2012 and 2021, followed by a marked recovery from 2021 to 2024; this improving trend is projected to continue through the forecast year of 2027. This evolutionary trajectory may be attributed to the refinement of the regional ecological governance system since 2018 and the comprehensive implementation of the Forest Chief System in 2021. By promoting vegetation restoration and land cover improvement, these policy initiatives have exerted a positive lagged effect on habitat quality enhancement.

Table 5. Habitat quality of prefecture-level administrative units in Xinjiang, 2012–2027.

Year	2012	2015	2018	2021	2024	2027 Forecast
Region	**Habitat Quality**					
Urumqi	0.549	0.547	0.526	0.511	0.470	0.507
Karamay	0.314	0.308	0.305	0.293	0.276	0.299
Turpan	0.149	0.149	0.149	0.148	0.165	0.170
Hami	0.199	0.199	0.199	0.198	0.211	0.216
Changji State	0.361	0.357	0.394	0.388	0.383	0.390
Yili Prefecture	0.709	0.706	0.699	0.697	0.717	0.723
Tacheng Prefecture	0.524	0.522	0.52	0.52	0.522	0.519
Altay Prefecture	0.401	0.399	0.405	0.403	0.429	0.413
Bortala Prefecture	0.604	0.600	0.604	0.591	0.614	0.617
Bazhou	0.254	0.253	0.256	0.255	0.300	0.313
Aksu Prefecture	0.272	0.267	0.264	0.259	0.303	0.308
Kizilsu Prefecture	0.555	0.555	0.554	0.552	0.627	0.656
Kashgar Prefecture	0.346	0.341	0.338	0.333	0.400	0.413
Hotan Prefecture	0.251	0.251	0.249	0.249	0.302	0.313
Xinjiang	0.322	0.320	0.322	0.319	0.356	0.364

From a spatial perspective, the habitat quality indices in southern Xinjiang and the Tianshan North Slope Economic Belt (excluding Urumqi) remained below the overall average level throughout the study period, while the remaining regions exceeded this average. Southern Xinjiang, characterized by the extensive presence of the Taklamakan Desert, has a fragile ecological baseline, resulting in an overall lower habitat quality compared to northern

Xinjiang. Meanwhile, parts of the Tianshan North Slope Economic Belt face substantial ecological pressures driven by industrial activities and land development.

Temporal analysis revealed that habitat quality in Urumqi declined during the observation period but is projected to recover by 2027. Turpan, the five prefectures in southern Xinjiang, and Yili Prefecture recorded higher habitat quality indices at the end of the observation period than at its beginning, indicating overall improvement. The remaining regions remained relatively stable despite fluctuations. In recent years, desertification control, the rational development of unused land, and the transition towards greener industrial practices may have contributed to reducing ecological vulnerability and improving habitat quality. Overall, the coordinated implementation of ecological conservation, restoration, and green development measures appears to have contributed to improvements in habitat quality across Xinjiang.

Parameter sensitivity analysis and model backtesting were conducted to assess the robustness of the habitat quality estimates and the reliability of the projections. Given that the expansion of unused land, including deserts and Gobi surfaces, represents an important threat to habitat quality in arid regions, two alternative parameter configurations were developed by adjusting the weight assigned to unused land as a threat factor and the sensitivity of each land use type to this threat. For both configurations, differences between the normalized assessment results and the baseline results (Table 5) ranged from −0.003 to 0.003, indicating that the habitat quality estimates were robust to the parameter variations examined. In addition, land use data from 2012 to 2021 were used to simulate the spatial distribution of land use in 2024, which was then compared with the observed land use data for that year. The simulation achieved an overall accuracy of 0.98, indicating that the CA–Markov model reproduced the observed land use pattern with high accuracy. This finding supports the use of the model for scenario-based projections for 2027.

4.1. Coupling Coordination Between Habitat Quality and Urban Development

To characterise the coordination between the eco-environment and urban development across the prefecture-level administrative units of the Xinjiang Uygur Autonomous Region, we applied the improved coupling coordination degree model described in Section 3.2.3 and analysed the resulting coordination patterns in detail, the detailed results are presented in Table 6. The observational results indicate that the average coupling coordination degree (CCD) index in Xinjiang rose from 0.317 in 2012 to 0.381 in 2024, suggesting that the coupling relationship between habitat quality and urban development has transitioned from a stage of near imbalance to one of primary coordination, with the antagonistic interaction between the two systems gradually weakening over time. Regarding the predictive analysis, the habitat quality for 2027 was estimated using the InVEST model driven by land use data simulated via the CA–Markov model, while the urban development level (UDL) was extrapolated using Holt's exponential smoothing method. The smoothing parameters were calibrated based on the 2012–2024 observational series and validated against the observed values for 2018, 2021, and 2024, yielding prediction errors within the range of $[-0.002, 0.003]$. This demonstrates that the model is of adequate accuracy and that the projected results are mathematically well-grounded. The projection results show that the average CCD index in Xinjiang is expected to further increase to 0.390 by 2027, indicating that under the assumed development scenario, the coordination between the regional eco-environment and urban development is likely to continue improving.

At the prefecture level, most prefecture-level administrative units in the Xinjiang Uygur Autonomous Region remained within the borderline-imbalance range during most of the 2012–2024 observation period. The "borderline imbalance–urban-development-lagging" type was predominant, accounting for 54.7% of all coupling coordination types

and 85.2% of the borderline-imbalance cases. This finding suggests that lagging urban development was the principal factor constraining coordinated ecological and economic development in the Xinjiang Uygur Autonomous Region. The 2027 projections indicate that coupling coordination will improve further in some areas; however, most prefecture-level administrative units are expected to remain in a state of borderline imbalance, predominantly characterised by lagging urban development. Thus, although the upward trend in coupling coordination observed during 2012–2024 is expected to continue through 2027, inter-regional disparities and the relative lag in urban development are likely to persist.

Table 6. Characteristics of coupling and coordination of Improvement in Various Prefectures and cities in Xinjiang from 2012 to 2027.

Year	2012	2015	2018	2021	2024	2027 Predictions
Region	**Improved Coupled Coordination Features**					
Urumqi	0.704	0.864	0.990	0.973	0.921	0.969
Karamay	0.439	0.453	0.468	0.460	0.456	0.479
Turpan	0.161	0.168	0.174	0.179	0.196	0.205
Hami	0.210	0.226	0.242	0.256	0.278	0.295
Changji State	0.303	0.333	0.380	0.390	0.385	0.397
Yili Prefecture	0.441	0.485	0.522	0.533	0.455	0.418
Tacheng Prefecture	0.329	0.352	0.373	0.360	0.365	0.369
Altay Prefecture	0.289	0.299	0.311	0.314	0.333	0.332
Bortala Prefecture	0.377	0.415	0.450	0.433	0.455	0.468
Bazhou	0.238	0.246	0.257	0.265	0.271	0.273
Aksu Prefecture	0.201	0.219	0.235	0.248	0.286	0.302
Kizilsu Prefecture	0.339	0.350	0.361	0.365	0.370	0.371
Kashgar Prefecture	0.227	0.259	0.284	0.291	0.339	0.360
Hotan Prefecture	0.175	0.189	0.201	0.209	0.222	0.227
Xinjiang	0.317	0.347	0.375	0.377	0.381	0.390

In spatial terms, the coupling coordination level in the Xinjiang Uygur Autonomous Region exhibited a core–periphery pattern during the observation period, with Urumqi City and Ili Kazak Autonomous Prefecture serving as the principal cores and coordination levels generally declining towards southern, northern, and eastern Xinjiang. The 2027 projections largely maintain this spatial pattern. Turpan City remained in a state of severe imbalance characterised by the "dual-lag" type throughout the observation period, and no substantial change in its classification is projected for 2027. This result suggests that Turpan City's natural resource conditions and ecological baseline impose considerable constraints on the coordinated improvement of habitat quality and urban development. Karamay City was predominantly classified as experiencing borderline imbalance of the "dual-lag" type during the observation period, and the 2027 projections continue to indicate the simultaneous presence of urban-development pressures and ecological stress.

Urumqi City was predominantly classified as coordinated with an "ecological-lag" pattern during the observation period. Although the city has relatively high levels of resource endowment and economic development, its industrial structure and intensive human activity continue to exert substantial pressure on the ecological environment. The 2027 projections indicate that its coupling coordination level may improve, although the underlying ecological pressures are expected to remain. Southern Xinjiang and Altay Prefecture in northern Xinjiang were predominantly characterised by borderline imbalance of the "urban-development-lagging" type during the observation period. These areas have relatively fragile ecological conditions and economic structures dominated by agriculture and animal husbandry, with the service sector playing a supplementary role. The 2027 projections

suggest that coupling coordination may improve in some areas; nevertheless, the pattern of relatively lagging urban development is likely to persist.

4.2. Spatial Association Network of Coupling Coordination Between Urban Development Level and Habitat Quality

To characterise the spatial linkages associated with the coupling coordination between urban development and habitat quality across the prefecture-level administrative units of the Xinjiang Uygur Autonomous Region, this study employs a modified gravity model to measure the intensity of spatial associations among these units and constructs a spatial association matrix accordingly. On this basis, block model analysis is conducted using the CONCOR algorithm in Ucinet6.0. By integrating the block model results with the resource endowments and locational characteristics of the respective blocks, their functional roles within the overall network are identified. The blocks are subsequently classified into four relational types: linkage-intermediary, marginal-diffusion, core-output, and bidirectional-interaction types. This classification enables the association-output and association-reception characteristics of each block within the network to be examined, thereby revealing the spatial association pattern and structural characteristics of coupling coordination among the prefecture-level administrative units of the Xinjiang Uygur Autonomous Region. The spatial association relationships among blocks are visualised in (Figure 3), and the density and image matrix of block-model results are reported in (Table 7).

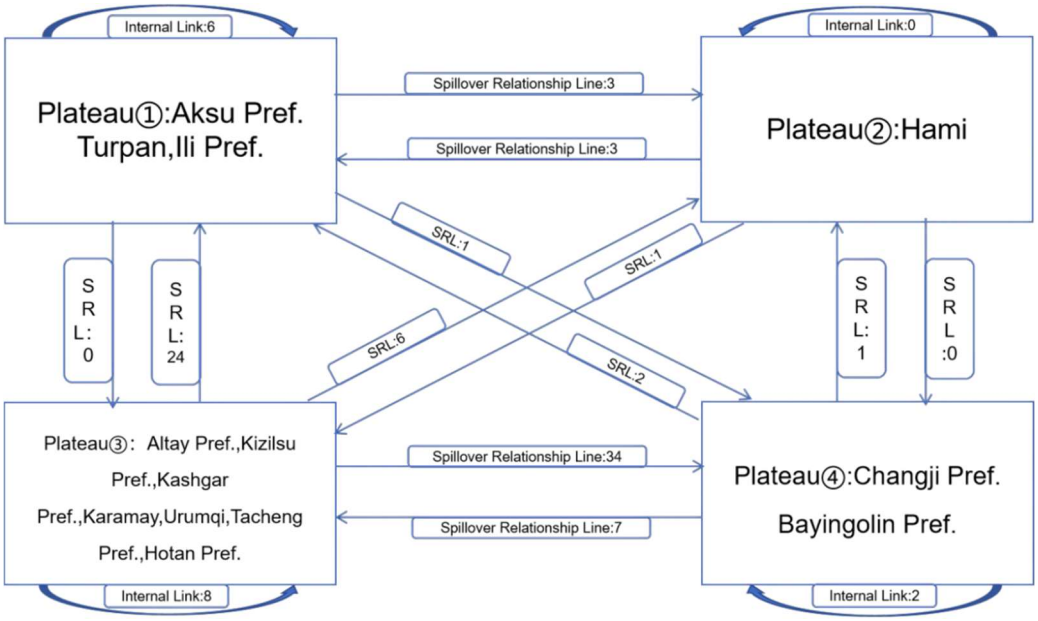


Figure 3. Spatial association relationships among the four blocks of the coupling coordination network between urban development level and habitat quality in the prefecture-level administrative units of the Xinjiang Uygur Autonomous Region.

Linkage–transit type (Block I)

Block I comprises three prefecture-level administrative units: Aksu Prefecture, Turpan City, and Ili Kazak Autonomous Prefecture. These units are located in southern, eastern, and western Xinjiang, respectively, and occupy strategically important positions as transport hubs. The block formed 10 ties in total, including 6 internal ties and 4 spillover ties, and received 29 ties from other blocks. Its actual internal association ratio was 60%, substantially higher than the expected ratio of 15.38%, indicating that the internal structure of the block was relatively stable.

Table 7. Spatial association strength matrix and image matrix of the four blocks.

Plaque	Density Matrix				Matrix			
	①	②	③	④	①	②	③	④
plaque ①	1	1	0	0.167	1	1	0	0
plaque ②	1	—	0.125	0	1	—	0	0
plaque ③	1	0.750	0.143	0.250	1	1	0	0
plaque ④	0.333	0.500	0.438	1	0	1	1	1

Note: The overall network density value is 0.324. When the plate density exceeds the overall network density, it is set to 1; otherwise, it is set to 0. The network density matrix was then transformed into an image matrix.

The mutual association intensities between Block I and Blocks II, III, and IV were 1.000, 0.000, and 0.167, respectively. In terms of transmission pathways, Block I was dominated by reception and maintained receiving relationships with all the other blocks. In particular, it received 24 ties from Block III, although the mutual association intensity between the two blocks was weak. At the same time, Block I generated outward ties with the other blocks, thereby functioning as a typical transit node within the network.

These three units possess distinct locational advantages: Aksu Prefecture serves as an important transport hub in Southern Xinjiang, Turpan City functions as an eastern gateway to Xinjiang, and Ili Kazak Autonomous Prefecture occupies a strategically important position along the Silk Road Economic Belt. These locational advantages enable the three units to transmit the effects of urban development and ecological conservation practices, making them important intermediary nodes for the flow of production factors.

Peripheral–diffusion type (Block II)

Block II consists solely of Hami City, which is located in the easternmost part of Xinjiang and serves as an important gateway for movement into and out of the region. Its resource base is dominated by coal and wind energy. Owing to its considerable distance from the regional centre, Hami City is positioned at the periphery of the autonomous region, and its spillover flows are mainly directed towards areas outside Xinjiang.

No internal association was identified within this block. The mutual association intensities between Block II and Blocks I, III, and IV were 1.000, 0.125, and 0.000, respectively. Block II generated four spillover ties towards Blocks I and III and received 10 ties of moderate intensity from Blocks I and IV. Located at the edge of the spatial association network and extending its spillover effects beyond the region, Block II mainly performs the function of extending the coordinated development of urban development level and habitat quality from Xinjiang towards the inland provinces of China.

Core–outflow type (Block III)

Block III comprises eight prefecture-level administrative units: Altay Prefecture, Kizilsu Kyrgyz Autonomous Prefecture, Bortala Mongol Autonomous Prefecture, Kashgar Prefecture, Karamay City, Urumqi City, Tacheng Prefecture, and Hotan Prefecture. These units contain a substantial proportion of the region's major natural and economic resources, giving Block III a dominant position in resource allocation within the overall network.

The block formed 50 ties in total, including 8 internal ties, 34 spillover ties, and 8 received ties. Its actual internal association ratio was 19%, substantially lower than the expected ratio of 53.8%, indicating that the internal structure of the block was relatively loose.

In terms of transmission pathways, Block III was dominated by outward spillover and maintained close links with the other blocks. Although the block as a whole has relatively favourable resource endowments, the economic and ecological development of its constituent units remains comparatively independent. Block III influences the development of other prefecture-level administrative units mainly through the radiating and driving

effects transmitted via Block I. It also extends its influence beyond the regional boundary through Block II and forms a pattern of complementarity and mutual feedback with Block IV.

Bidirectional–interaction type (Block IV)

Block IV comprises Changji Prefecture and Bayingolin Mongol Autonomous Prefecture. Changji Prefecture is adjacent to Urumqi City, whereas Bayingolin Mongol Autonomous Prefecture is the largest prefecture-level administrative unit in Xinjiang by area. Owing to their advantageous locations, the two units have become an important receiving zone for the functional spillovers generated by the core Block III.

Block IV formed 17 ties in total, including 2 internal ties and 10 spillover ties. Its actual internal association ratio was 16.7%, higher than the expected ratio of 7.6%, indicating that its internal structure was relatively stable. In terms of transmission pathways, Block IV was closely associated with the other blocks and formed bidirectional interactions with each of them. The numbers of ties with Blocks I, II and III were 3, 1 and 11, respectively, while the corresponding mutual association intensities were 0.333, 0.500, and 0.438.

By virtue of their locational advantages, Changji Prefecture and Bayingolin Mongol Autonomous Prefecture absorb the core spillovers generated by Block III and establish complementary and mutually reinforcing relationships with it. They therefore function as important transmission hubs connecting the core block with peripheral areas.

Overall network characteristics

Viewed as a whole, Block III functions as the core spillover zone. It not only extends its influence beyond the autonomous region through Block II as an intermediary, but also transmits spillover effects to other prefecture-level administrative units within Xinjiang through Block I. At the same time, it forms a pattern of complementarity and mutual feedback with Block IV.

Relying on their locational advantages and resource endowments, the eight units comprising Altay Prefecture, Kizilsu Kyrgyz Autonomous Prefecture, Bortala Mongol Autonomous Prefecture, Kashgar Prefecture, Karamay City, Urumqi City, Tacheng Prefecture, and Hotan Prefecture constitute a four-dimensional core spillover zone characterised by the combination of the Northern Xinjiang axis, the Southern Xinjiang axis, resource-based functions, and ecological functions. However, the relatively loose internal links among these units may limit the intensive utilisation of resources and collaborative ecological governance.

Within Block IV, Changji Prefecture has developed in coordination with Urumqi City because of its locational advantages and has become an important partner of Urumqi City in industrial extension and collaborative ecological governance. This relationship has gradually promoted the integrated development of Urumqi City and Changji Prefecture. Bayingolin Mongol Autonomous Prefecture, in turn, receives construction-related demand and ecological service functions from the core spillover zone, thereby promoting its own development while supporting the development of the core area.

Within Block I, Aksu Prefecture, Turpan City, and Ili Kazak Autonomous Prefecture are located in southern, eastern, and western Xinjiang, respectively. Benefiting from their locational advantages, these units serve as important economic hubs and carbon-sink functional areas within the region. Their strong internal links form a stable triangular hub that facilitates the flow of production factors, reduces resource mismatches, and promotes the convergence of urban green development towards the regional average.

Within Block II, Hami City, as the eastern gateway to Xinjiang, connects the region with the inland provinces of China and attracts investment from inland areas by capitalising on its wind-energy and coal resources. It therefore forms a bidirectional channel that exports economic outputs while importing green technologies into Xinjiang.

4.3. Bivariate Spatial Autocorrelation Between Habitat Quality and Urban Development Level

The above coupling coordination analysis indicates that habitat quality and the level of urban development in the Xinjiang Uygur Autonomous Region exert mutual influences on each other and exhibit significant spatial differentiation. To further reveal the spatial dependence between the two systems, this study constructs a bivariate spatial autocorrelation model to analyse the associative characteristics of the two systems across temporal and spatial dimensions. GIS spatial analysis techniques are employed to conduct a bivariate spatial autocorrelation analysis of the prefecture-level administrative units in the Xinjiang Uygur Autonomous Region. The spatial weight matrix is constructed based on the Queen contiguity rule and evaluated through 999 random permutation tests. The results show that from 2012 to 2027, the bivariate global Moran's I indices for ecology and development in the Xinjiang Uygur Autonomous Region were −0.084, −0.084, −0.083, −0.088, −0.092 and −0.108, respectively, exhibiting an overall negative spatial correlation clustering pattern, with the degree of clustering showing an increasing trend. The Moran's I indices for all years passed the significance tests, with the absolute Z-values exceeding 2.58 ($p < 0.01$), leading to the rejection of the null hypothesis, indicating that the probability of randomly generating this clustering pattern is less than 1%. A further verification analysis was conducted using a binary contiguity matrix. The results show that under different spatial weight specifications, the signs and overall trends of the bivariate global Moran's I indices remain broadly consistent, thereby verifying the spatial clustering effect between ecology and development in the Xinjiang Uygur Autonomous Region.

Furthermore, the bivariate local Moran's I index was calculated to identify the local spatial association patterns between habitat quality and the level of urban development, and a table of bivariate local spatial autocorrelation cluster types for the study area from 2012 to 2027 was compiled (Table 8). The results for the historical years were calculated based on the data for the corresponding years, whereas the results for 2027 were derived from model projections. Based on the standardised values of habitat quality for each prefecture-level administrative unit and the urban development level for neighbouring units, the significant local spatial associations were classified into four types: High–High, Low–Low, High–Low, and Low–High. Among these, High–High and Low–Low represent positive spatial associations, whereas High–Low and Low–High represent negative spatial associations. Prefecture-level administrative units that did not pass the significance test were classified as not significant. "High" and "Low" denote values above and below, respectively, the standardised values of the respective variables across the study area for the corresponding year.

Regarding positive spatial clustering, High–High clusters from 2012 to 2024 were mainly distributed in Altay Prefecture, indicating that habitat quality in the focal prefecture was relatively high and that the level of urban development in neighbouring prefectures was also relatively high. Low–Low clusters mainly occurred in Kashgar Prefecture and Hotan Prefecture, indicating that habitat quality in the focal prefecture was relatively low and that the level of urban development in neighbouring prefectures was also relatively low. Kashgar Prefecture exhibited Low–Low clustering in 2018 and 2024, and the model predicts that this pattern will persist in 2027. Hotan Prefecture exhibited Low–Low clustering in 2018 and subsequently shifted to the non-significant category. These results reflect a local positive spatial association between habitat quality in the focal prefecture and the level of urban development in neighbouring prefectures.

Regarding negative spatial clustering, Kizilsu Kyrgyz Autonomous Prefecture exhibited High–Low clustering in 2012 and 2015, indicating that its habitat quality was relatively high, whereas the level of urban development in neighbouring prefectures was relatively low. Thereafter, Kizilsu Kyrgyz Autonomous Prefecture shifted to the non-significant category.

This change may be related to variations in habitat quality in Kizilsu Kyrgyz Autonomous Prefecture and in the level of urban development in neighbouring prefectures relative to the overall mean for the study area, such that the original High–Low spatial combination no longer reached statistical significance. Turpan City consistently exhibited Low–High clustering during the observation period, indicating relatively low local habitat quality and a relatively high level of urban development in neighbouring prefectures. The model predicts that Altay Prefecture will also exhibit Low–High clustering in 2027.

Table 8. Classification of bivariate local spatial autocorrelation clusters in the study area, 2012–2027.

Year	H–H Clustering	H–L Clustering	L–H Clustering	L–L Clustering
2012	Altay Prefecture	Kizilsu Prefecture	Turpan	Kashgar Prefecture; Hotan Prefecture
2015	Altay Prefecture	Kizilsu Prefecture	Turpan	Kashgar Prefecture; Hotan Prefecture
2018	Altay Prefecture	—	Turpan	Kashgar Prefecture; Hotan Prefecture
2021	Altay Prefecture	—	Turpan	Kashgar Prefecture
2024	Altay Prefecture	—	Turpan	Kashgar Prefecture
2027 Forecast	—	—	Altay Prefecture; Turpan	Kashgar Prefecture

Note: "—" indicates that the result did not pass the significance test at the 5% significance level. The spatial weight matrix was constructed using Queen contiguity, and 999 permutations were performed for the permutation tests. The data for 2027 are model-based projections, whereas those for the other years are observed values. Source: Compiled by the authors based on the results of the bivariate local Moran's I analysis.

Overall, Bayingol Mongol Autonomous Prefecture, Urumqi City, Ili Kazakh Autonomous Prefecture, and Changji Hui Autonomous Prefecture did not exhibit significant local bivariate spatial associations during the historical analysis period. Kashgar Prefecture exhibited Low–Low clustering in some years, whereas Turpan City consistently exhibited Low–High clustering. The High–Low clustering observed in Kizilsu Kyrgyz Autonomous Prefecture and the Low–Low clustering observed in Hotan Prefecture shifted to the non-significant category in subsequent years, suggesting that their relatively low habitat-quality status may have gradually improved over time. The prediction results indicate that the cluster type of Altay Prefecture will change from High–High during the historical period to Low–High in 2027, suggesting that a potential decline in its relative habitat quality may be associated with urban development in the surrounding areas. These results may provide a reference for identifying areas requiring further assessment. Urban-development planning should formulate differentiated measures by considering local habitat conditions, the development characteristics of neighbouring areas, and ecological-protection requirements. The specific mechanisms underlying these relationships and the effectiveness of related policies require further investigation.

4.4. Effects of Urban Development on Habitat Quality

Basemap source: Standard Map Service System of the Ministry of Natural Resources of the People's Republic of China (formerly the National Administration of Surveying, Mapping and Geoinformation). The boundaries shown on the basemap were not modified. Approval No. GS(2024)0650.

To reveal the non-linear effects and spatial heterogeneity of urban development characteristics on habitat quality (HQ) across the prefecture-level units of Xinjiang, this study

employed a geographically and temporally weighted regression (GTWR) model to characterise the spatiotemporal non-stationarity of these effects. An XGBoost model combined with SHapley Additive exPlanations (SHAP) was further introduced to identify, from a machine-learning perspective, the marginal importance of each urban development factor in explaining HQ. This approach compensates for the limited ability of conventional linear regression to capture non-linear relationships and interaction effects. The results indicate that the overall goodness-of-fit (R^2) of the GTWR model reached 0.80, and both the global and local variables passed significance tests ($p < 0.1$), demonstrating the robustness of the model results. The model was constructed using GTWR v1.1005 software, with the longitude and latitude of the centroid of each study unit and the observation year representing the spatial and temporal dimensions, respectively. A fixed kernel function was adopted, and the AICc criterion was applied to automatically optimise the bandwidth and related parameters (with the search range for the spatiotemporal distance ratio set at 0.1–5, and the minimum weight set at 0.01). The spatial pattern of GTWR impact coefficients and the migration trajectory of the influence centre are displayed in (Figure 4). The above results and parameter settings jointly validate the effectiveness of this model in revealing the spatiotemporal evolution characteristics of the impact of urban development on habitat quality across the prefecture-level administrative units in Xinjiang from 2012 to 2027.

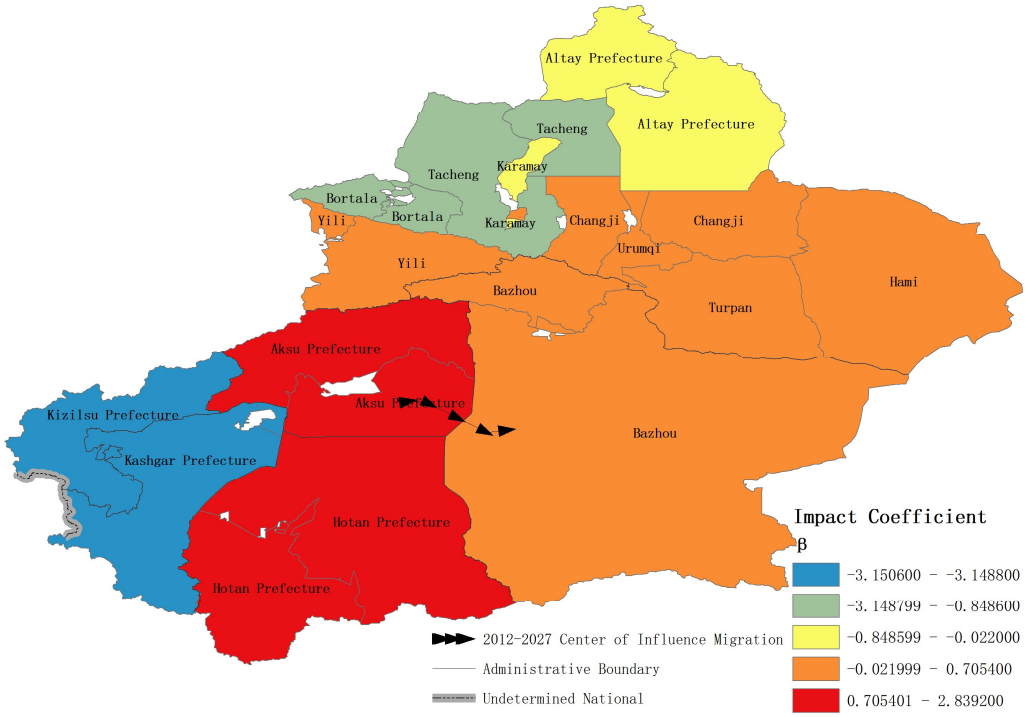


Figure 4. Spatially heterogeneous associations between urban development and habitat quality within the dual-subsystem framework.

Spatial heterogeneity and centroid migration of GTWR coefficients. The GTWR coefficients differed substantially across space, demonstrating pronounced spatial heterogeneity in the relationship between urban development and HQ. In terms of centroid migration, the centroid of the overall effect shifted progressively from the northwest towards the southeast during 2012–2027, moving from Aksu Prefecture towards the Bayingolin Mongol Autonomous Prefecture (Bayingolin). Meanwhile, the overall intensity of the negative effect gradually weakened. This finding indicates that the pressure exerted by urban development on HQ was alleviated over time, although its impact centroid moved south-eastwards within the study area.

Spatially, areas with strong negative correlations were concentrated in the northern and south-western parts of the study area, with the strongest negative effects observed in the Kizilsu Kyrgyz Autonomous Prefecture (Kizilsu) and Kashgar Prefecture. This suggests that ecological protection received insufficient attention during urbanisation in these areas, where urban development and habitat degradation occurred simultaneously. HQ in these units was also highly sensitive to urban development, further increasing pressure on the already fragile ecosystems of Southern Xinjiang. Only a small number of areas exhibited positive correlations, mainly in the southern, central and western parts of the region. Aksu Prefecture and Hotan Prefecture showed significant positive feedback effects. Located along the margins of the Taklimakan Desert, these areas have fragile ecological conditions. Their ecology-oriented development pathways have enabled improvements in urban development quality to occur alongside improvements in HQ, thereby forming a benign pattern of coordinated "ecology-urbanisation" development.

To further quantify the relative contributions of various urban-development factors to habitat quality, this study constructed an XGBoost gradient-boosted tree model and used SHAP (SHapley Additive exPlanations) values to decompose the marginal explanatory power of each factor. Given that the sample comprised only 70 prefecture–year observations, nested repeated five-fold cross-validation was employed to avoid bias in the importance rankings caused by a single training–testing split. The outer loop consisted of 10 repetitions of five-fold cross-validation, generating 50 independent test folds in total. The data were split by prefecture to prevent the same cross-sectional unit from appearing in both the training and testing sets, thereby avoiding data leakage. Within the training set of each outer fold, an additional five-fold cross-validation procedure was nested for hyperparameter selection, with constraints imposed on tree depth, learning rate, and regularisation strength. The optimal models selected across all 50 outer folds consistently converged on shallow trees (median depth = 2) with relatively strong L2 regularisation (median = 5), indicating that the model-building process actively controlled the risk of overfitting. After each fold model was trained, and the mean SHAP value of each factor and its proportion of the total SHAP values across all factors were calculated for that fold. The means, standard deviations, and median ranks across the 50 models were then summarised (Table 9).

Table 9. Regional GTWR coefficient estimates for the associations between urban development factors and habitat quality, with XGBoost–SHAP-based variable importance, 2012–2024.

Variables	Whole Region	Northern Xinjiang	Southern Xinjiang	Mean SHAP Contribution (%)	SHAP SD (%)	Median Rank
Student–teacher ratio in schools for students with special needs	0.00397	0.0235 **	−0.00319	2.0	1.5	8.5
	(−0.00797)	−0.00981	−0.00333			
Student–teacher ratio in primary and secondary schools	−0.0605 ***	−0.100 ***	−0.0369 ***	39.0	9.4	1
	−0.0162	−0.0241	−0.00612			
Beds in medical and health institutions per 10,000 population	0.00402	0.000884	0.000341	1.9	1.4	8.5
	−0.00323	−0.00632	−0.00326			
Total retail sales of consumer goods	0.000438 *	0.00112 ***	−0.00039	15.1	4.0	3
	−0.000236	−0.000243	−0.0003			
Number of enterprise legal entities in active operation	−0.196 ***	−0.247 ***	0.947 **	2.2	1.8	8
	−0.0535	−0.0475	−0.479			
Health technical personnel, including practising physicians, per 10,000 population	−0.00151	−0.000141	0.00421 ***	2.9	0.8	7
	−0.00238	−0.00465	−0.000939			

Table 9. *Cont.*

Variables	Whole Region	Northern Xinjiang	Southern Xinjiang	Mean SHAP Contribution (%)	SHAP SD (%)	Median Rank
Gross regional product per capita	−0.0158 *	−0.00785	−0.0571 ***	5.1	2.9	5
	−0.00835	−0.00843	−0.00825			
Combined share of the industrial and service sectors in GDP	−0.739 ***	−0.999 **	−0.138	7.6	4.4	4
	−0.24	−0.391	−0.499			
Share of built-up land for buildings and urban and rural residential purposes in the total land area	17.23 ***	14.87 ***	42.75 **	22.5	4.7	2
	−3.552	−3.458	−16.48			
Constant	1.464 ***	1.905 ***	0.751 *	—	—	—
	−0.208	−0.279	−0.426			
Time fixed effects	Yes	Yes	Yes	—	—	—
N	70	45	25	—	—	—
R^2	0.592	0.746	0.986	—	—	—

Note: Robust standard errors are in parentheses, and * in the table indicates: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Standard errors are reported in parentheses.

The SHAP-based importance ranking showed that the teacher–student ratio in primary and secondary education had an average SHAP proportion of 39.0 ± 9.4% and ranked first in all 10 independent repetitions (median rank = 1), making it the factor with the greatest relative contribution to habitat quality. The proportion of construction and residential land had an average SHAP proportion of 22.5 ± 4.7% and consistently ranked second (median rank = 2). Total retail sales of consumer goods had an average SHAP proportion of 15.1 ± 4.0% and ranked among the top three in 90% of the repetitions (median rank = 3). Together, these three factors accounted for approximately 76.6% of the total contribution and constituted the core explanatory dimensions of the impact of urban development on habitat quality. The average SHAP proportions of the remaining six factors were all below 8%, while their median ranks were lower than fourth and fluctuated considerably across folds, indicating unstable importance rankings. This ranking suggests that the degree of educational-resource concentration, the structure of urban construction land, and consumer-market vitality are key factors determining changes in habitat quality. By contrast, per capita GDP, a simple indicator of economic scale, had a contribution of only 5.1%, while the density of medical facilities also showed relatively weak marginal explanatory power for habitat quality.

Commonalities and differences in factor effects across Xinjiang, Northern Xinjiang and Southern Xinjiang. Combining the grouped regression results and SHAP importance estimates in Table 9, the core driving factors and their directions of association exhibit both commonalities and regional differences across Xinjiang as a whole, Northern Xinjiang and Southern Xinjiang. First, the student–teacher ratio in primary and secondary schools was significantly and negatively associated with HQ in Xinjiang as a whole ($\beta = -0.0605$, $p < 0.01$), Northern Xinjiang ($\beta = -0.100$, $p < 0.01$), and Southern Xinjiang ($\beta = -0.0369$, $p < 0.01$), and ranked first in SHAP importance (37.50%). This indicates that areas where population and school enrolment increase faster than educational-resource provision tend to experience greater pressure on HQ; rapid population and public-service agglomeration, rather than education itself, is likely to be a major source of habitat degradation.

Second, the share of built-up land for buildings and urban and rural residential purposes was significantly positive in all three panels, with coefficients of $\beta = 17.23$ ($p < 0.01$) for Xinjiang as a whole, $\beta = 14.87$ ($p < 0.01$) for Northern Xinjiang, and $\beta = 42.75$ ($p < 0.01$)

for Southern Xinjiang. Its SHAP contribution was 19.57%. This result suggests that the rational planning and compact arrangement of construction land can generally support HQ by reducing habitat fragmentation associated with urban sprawl.

Regional differences were also evident. In Northern Xinjiang, the student–teacher ratio in schools for students with special needs had a positive effect ($\beta = 0.0235$, $p < 0.1$), while total retail sales of consumer goods showed a strong positive association with HQ ($\beta = 0.00112$, $p < 0.01$; SHAP contribution: 15.63%). These results suggest that comparatively strong public-service provision and a dynamic consumer market in Northern Xinjiang tend to develop in tandem with improvements in HQ.

Southern Xinjiang exhibited a distinctive factor configuration. Health technical personnel, including practising physicians, per 10,000 population ($\beta = 0.00421$, $p < 0.01$) and the number of enterprise legal entities in active operation ($\beta = 0.947$, $p < 0.05$) both had significant positive associations with HQ. In contrast, the coefficient for health technical personnel was negative but statistically insignificant at the whole-region scale ($\beta = -0.00151$), while the number of enterprise legal entities was significantly negative for Xinjiang as a whole ($\beta = -0.196$, $p < 0.01$) and Northern Xinjiang ($\beta = -0.247$, $p < 0.01$). These contrasts imply that, in Southern Xinjiang, the equalisation of healthcare resources and the cultivation of market entities may provide specific support for HQ.

In summary, the XGBoost-SHAP results and the grouped regression estimates mutually corroborate each other. Educational resource allocation and urban land-use structure are generalisable key factors associated with HQ across Xinjiang, whereas the consumption-public service mechanism in Northern Xinjiang and the healthcare-enterprise vitality mechanism in Southern Xinjiang reflect heterogeneous associations under divergent regional development pathways. These findings provide a quantitative basis for differentiated ecological risk management and control policies.

5. Conclusions and Discussion

5.1. Conclusions

Based on an integrated assessment and simulation of habitat quality (HQ) and urban development level (UDL) in Xinjiang, this study employed an improved coupling coordination degree model to characterise coordination between the two subsystems during 2012–2027. Bivariate spatial autocorrelation, spatial association network analysis, geographically and temporally weighted regression (GTWR), and XGBoost–SHAP attribution were further combined to examine their spatial associations. The main conclusions are as follows.

(1) Characteristics of habitat quality. HQ was generally low across the prefecture-level administrative units, except in Kizilsu Kyrgyz Autonomous Prefecture (Kizilsu), but exhibited an upward trend. Low HQ in Southern Xinjiang was primarily constrained by unfavourable natural conditions, whereas that in Northern Xinjiang was associated mainly with ecological pressure from economic expansion. The mean HQ index increased from 0.322 in 2012 to 0.364 in 2027, representing an increase of 0.042. The 2027 estimates are simulated values and should therefore be interpreted as trend projections rather than observed conditions.

(2) Characteristics of coupling coordination. Coupling coordination improved steadily across the prefecture-level administrative units. The mean coupling coordination degree (E) increased from 0.317 in 2012 to 0.390 in 2027. Although the two subsystems remained within the verge-of-maladjustment interval, they moved progressively towards the threshold of basic coordination (E = 0.5). Spatially, a high-value core centred on Urumqi and Ili Kazak Autonomous Prefecture (Ili) was identified, with coordination declining towards the south, north, and east. Turpan City remained in a severely maladjusted, dual-lag state throughout both the observed and projected periods.

(3) Network associations of coupling coordination. Based on the gravity model and CONCOR blockmodeling analysis in UCINET6.0, four block types were identified: core-outflow, connector-transmission, peripheral-diffusion, and bidirectional-interaction. Together, these types form a hierarchical spatial association network. The core-outflow block, comprising eight units represented by Urumqi, occupied the dominant position. Its associations were transmitted through Hami City in the peripheral-diffusion block and through Aksu Prefecture, Turpan City, and Ili in the linkage-transit block. The linkage-transit block had an actual internal association ratio of 60%, substantially exceeding the expected ratio of 15.38%, demonstrating its role in absorbing core spillovers and transmitting production factors. Hami City had no internal association within its block and functioned as Xinjiang's eastern gateway. The bidirectional-interaction block, including Changji Hui Autonomous Prefecture and Bayingolin Mongol Autonomous Prefecture (Bayingolin), received core spillovers and maintained complementary associations with the core-outflow block, with an association intensity of 0.438. Overall, the network was organised around the core-outflow block and extended through the linkage-transit, bidirectional-interaction, and peripheral-diffusion blocks.

(4) Spatial association between the two subsystems. All global bivariate Moran's I values for 2012–2027 were statistically significant, indicating a relatively stable negative spatial association between UDL and HQ. In other words, units with relatively high values of one subsystem tended to neighbour units with relatively low values of the other. At the local level, Kashgar Prefecture, Aksu Prefecture, and Altay Prefecture generally exhibited positive spatial associations, whereas Turpan City showed a persistent negative association. Local associations in the remaining units were comparatively unstable.

(5) Spatial interaction characteristics of the dual system. Urban development and habitat quality were interrelated through significant bidirectional spatial effects. Negative drivers were mainly concentrated in the northern and southwestern parts of the study area, especially in the Kizilsu and Kashgar areas. In these areas, inadequate ecological protection during urban expansion rendered habitat quality highly sensitive to urbanization and intensified pressure on the already fragile ecosystems of southern Xinjiang. By contrast, positive feedback was mainly observed in the southern, central, and western areas, including Aksu and Hotan. There, ecologically oriented development pathways supported the coordinated improvement of urban system quality and habitat conditions. During 2012–2027, the centroid of the overall spatial effects shifted from the Aksu area toward the Bayingolin area along a northwest–southeast trajectory, while the magnitude of negative effects continued to weaken. This shift indicated that the pressure exerted by urban development on habitat quality was generally easing. From the perspective of driving factors, the high-intensity agglomeration of educational resources emerges as the primary contributor to habitat-quality degradation across Xinjiang. In contrast, the rational planning and compact spatial configuration of urban construction land exert a generally positive effect on habitat quality. At the subregional level, habitat quality in northern Xinjiang is supported primarily by the provision of public services and the vitality of consumer markets, whereas improvements in southern Xinjiang may be associated with enterprise agglomeration and the more equitable distribution of public services, particularly healthcare. These findings indicate pronounced regional differences in urban–ecological feedback mechanisms arising from distinct development trajectories.

5.2. Discussion

5.2.1. Interpretation of the Findings

Overall habitat quality in Xinjiang remained relatively poor but exhibited a delayed increasing trend, with pronounced regional differentiation. Areas with high habitat quality

generally possessed more favorable ecological endowments. The extents of both high-quality and low-quality habitats expanded [45,46], while habitat quality increased gradually across the study area. This pattern suggests that ecological restoration and ecosystem degradation coexisted in the region. Spatially, the coupling coordination types of prefecture-level divisions displayed a highly coordinated pattern centered on Urumqi and Ili, with coordination levels decreasing toward the southern, northern, and eastern margins. This spatial distribution was highly consistent with the four block-association types identified by the block-model analysis. The overall influence of urban development on habitat quality was negative, although localized positive effects also existed, and the impacts of individual factors within the urban development system differed markedly between northern and southern Xinjiang. The observed spatiotemporal coupling characteristics of habitat quality and urban development, together with the geographically differentiated effects of urban development level on habitat quality, provide empirical support for the coordinated dual-development model as a suitable pathway for high-quality development in Xinjiang. Clarifying spatiotemporal evolution patterns and inter-system relationships is essential for balancing ecological protection and socioeconomic development and for achieving simultaneous improvement in ecological conditions and development outcomes.

5.2.2. Methodological Implications

Based on the theoretical proposition of the Environmental Kuznets Curve regarding the relationship between environmental quality and economic development, this study selected habitat quality as an indicator of ecosystem environmental quality. An urban development evaluation system was constructed using indicators related to education, economy, healthcare, and development, which enhanced the scientific rigor, comprehensiveness, objectivity, and rationality of the dual evaluation systems. The entropy-weighted TOPSIS method and two forecasting methods were combined, and TerrSet2020, UCINET6.0, ArcGIS 10.8, and InVEST 3.16.1 software were used to measure urban development level and habitat quality in the study area. Coupling coordination characteristics across prefecture-level divisions were calculated, and a spatial-agglomeration model and a geographically weighted regression model were constructed. These analytical tools comprehensively characterized the coupling coordination between the urban development system and habitat quality, as well as the spatial aggregation pattern of their interactions.

5.2.3. Policy Recommendations

Based on the conclusions of this study, the following recommendations are proposed:

(1) Reinforce the steering role of habitat quality in socioeconomic development. Habitat quality is a fundamental support for social development and should be incorporated into local performance assessment systems. High-energy-consumption and high-pollution industries should be restricted in ecologically sensitive areas, and fiscal subsidies should be provided to regions that demonstrate notable habitat improvement. Ecological restoration projects should be encouraged, and the management of deserts and other underutilized land should be strengthened. The absolute area of low-quality habitats should be reduced, the expansion of high-quality habitats should be promoted, and undesired increases in medium-quality habitats should be controlled through progressive ecological upgrading, thereby forming a tiered and sustained pattern of habitat-quality improvement.

(2) Optimize development structures according to block functions and regional differences. Differentiated development strategies should be formulated in accordance with the functional roles of four block types: core-output, linkage-transit, edge-association, and bidirectional-interaction regions. The core-output regions represented by eight prefecture-level divisions, including Urumqi, should strengthen the internal coordination

of development factors and improve the efficiency of resource intensification and ecological governance. The linkage-transit regions, including Aksu and Turpan, should leverage their advantages as transportation hubs to construct ecological and economic corridors that facilitate the efficient circulation of key elements. The bidirectional-interaction regions, such as Changji and Bayingolin, should deepen complementarity and feedback with core-output regions to amplify the effects of coupling coordination. The edge-association region represented by Hami should exploit its locational advantage as an eastern gateway by introducing green and low-carbon technologies into energy and resource development, thereby coordinating outward economic spillovers with ecological protection.

Given the divergent driving mechanisms between northern and southern Xinjiang, southern Xinjiang should fully leverage the positive effects of enterprise agglomeration and the allocation of public services such as healthcare on habitat quality, and cultivate ecologically friendly industrial clusters. Northern Xinjiang should consolidate the positive feedback from public service provision and consumer-market vitality, while eliminating inefficient and energy-intensive production, restricting water-intensive traditional agriculture, and guiding industrial transformation toward cultural–tourism integration and new energy development. At the region-wide level, the spatial configuration of educational resources should be optimized to relieve their clustered pressure on habitat quality, and the scientific planning and compact layout of urban construction land should be strengthened to promote habitat improvement.

(3) Establish a precise spatial linkage and regulation mechanism based on the observed spatial pattern. Combining the hierarchical "core–transit–interaction–edge" association pattern with the spatial heterogeneity of the dual system, region-specific and type-specific control measures should be implemented. The areas characterized by distinct positive feedback, represented by Aksu and Hotan, and the areas with relatively stable positive effects, represented by Kashgar and Altay, should be treated as core zones. Coordinated ecological prevention and control should then be extended from these core zones to adjacent regions, thereby improving the overall spatial efficiency and resilience of the urban–ecological system.

This study is subject to certain objective limitations. Although full consideration was given to data processing, indicator construction, model selection, and result validation, and multiple methods were integrated to systematically analyse habitat quality and its influencing factors, the findings remain conditional owing to data availability, the scope of indicator measurement, and the applicability boundaries of the research methods. Specifically, land-cover projections, InVEST-based habitat-quality assessments, and socioeconomic projections all depend on the corresponding data foundations and scenario settings. In addition, the results of the entropy-weighting method, modified coupling coordination model, GTWR, and XGBoost–SHAP model may be affected by parameter settings and model structures. Although appropriate data-processing procedures, model specifications, and robustness tests were adopted to minimise these adverse effects as far as possible, it remains difficult to completely eliminate all potential uncertainties.

Furthermore, given the available data and sample conditions, some indicators were difficult to obtain, while the explanatory scope of the indicators that were available was constrained by their inherent meanings. The conclusions drawn from the GTWR, multivariate regression analyses by group, and XGBoost–SHAP analyses should therefore be interpreted in the specific context of this study. Overall, these limitations mainly arise from the objective constraints of the available data and the methodological boundaries of the research methods employed. They do not affect the overall assessment of the spatiotemporal characteristics of habitat quality and its associated factors in the study area. As data resources are further

improved, future research can build on the present study to supplement and deepen the relevant conclusions.

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