



OPEN Spatial and temporal evolution and influencing factors of human settlement environment quality in Xinjiang, China

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An understanding of the evolution process of human habitats and their correlation with geographical elements, as well as an exploration of the evolution mechanism of habitats in arid zones, is essential for examining the interactions between habitat sustainability and the geographical environment comprehensively. The polycentric governance theory and synergy theory form the basis of this study, which proposes a polycentric synergistic development model and constructs an evaluation index system for the quality of the human habitat environment in Xinjiang in terms of social services and security, comprehensive economic level, ecological, livable environment and population and cultural environment. The TOPSIS model is utilised to assess the integrated valuation of the quality of the human environment, facilitating analysis of the spatial and temporal trends and spatial correlations of the quality of the human environment. The geodetector model is also employed to identify the influencing factors of the habitat environment. From the perspective of sustainable development, the interconnections and synergistic development processes within the habitat system were elucidated, as well as how the various elements interacted with each other in shaping the habitat system from multiple perspectives. Furthermore, the cumulative effects of the influencing factors on the human settlement environment in arid zones were further verified through the interaction of multiple factors. Furthermore, it verifies the cumulative effect of the influencing factors on the arid environment through the interaction of multiple factors. This study provides theoretical support and empirical evidence for the study of the global arid zone habitat environment, and provides a reference for decision-making on sustainable development paths in specific geographical conditions.

Keywords Human settlement environment, Spatial and Temporal differentiation, Spatial correlation, Influencing factors, Xinjiang

As urbanisation progresses on a global scale, the expansion of urban populations in certain countries and regions is outpacing the growth of their respective urban areas¹. The severe demographic challenges that have become evident are diminishing the self-repairing and carrying capacity of ecosystems. Furthermore, transport, housing and service issues are hindering sustainable regional development. The issue of habitat deterioration is further exacerbated by these factors^{2,3}. Projections indicate that the global population is expected to reach 8.5 billion by 2030 and 9.7 billion by 2050⁴. Concurrently, approximately nine million individuals perish annually as a consequence of environmental contamination, representing approximately one-sixth of global mortalities⁵. The inhabitants may become trapped in a cycle of environmental health poverty⁶. As the most populous country in the world, China is experiencing rapid ageing and a significant urbanisation transition phase⁷. It is imperative that a humanistic perspective be integrated into the construction of habitats and that the intrinsic connection between population and development be managed effectively⁸. The impact of global warming has resulted in a significant climatic shift in arid regions in northwestern China, from a warm-dry climate to a warm-wet one, leading to glacier melting with severe implications for water resources and the ecological environment⁹. It is therefore imperative to study the arid zone habitat in order to gain an understanding of regional habitat stability and vulnerability.

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The term “human settlement environment” is defined as the environment in which humans survive, recreate and interact socially¹⁰. The concept of “human settlement” was proposed by Greek scholars in the mid-20th century¹¹, and this issue has also been the focus of geographic and environmental sciences, as well as other areas of concern. In the late 1990s, the establishment of “human settlement environment science” by academician Wu Liangyong, based on the theory of human settlement, led to the development of habitat system research. Human settlement environment comprises the entire human socio-political landscape, including cities, towns and villages, as well as all the social, physical, organisational, spiritual and cultural factors that engender and sustain it¹². It is a dynamic system¹³. The theory of human settlement proffers a thorough and methodical examination of human settlements, with the objective of establishing a scientific system and methodology to navigate society out of the paradoxical situation of “building and destroying simultaneously”. This methodology examines sustainable models for the construction and management of habitats¹⁴, addresses specific challenges associated with human settlements, and provides guidance on the creation of favourable living environments¹⁵. By analyzing the entirety of the human settlement environment and the interplay among its components, we can grasp the laws governing the development of the human settlement environment, leading to the creation of spaces conducive to human survival¹⁶. Moreover, the harmonious coexistence of nature and the city has been emphasised, with an emphasis on the development of eco-cities as a means of creating urban spaces where human settlement environment coexist in harmony with nature and where human well-being is enhanced through the relationship between human settlement environment and nature¹⁷.

The concept of human settlement environment vulnerability is attributable to the corresponding response of production, housing and basic life of the inhabitants under the disturbance of natural and human factors¹⁸. Chen et al. explored the spatio-temporal pattern of vulnerability of habitat quality and its sustainable development potential through the vulnerability evaluation model. The findings indicate a discernible downward trend in habitat quality, primarily influenced by social, public utility, employment, and infrastructure factors¹⁹. Zhong et al.²⁰ have developed a comprehensive evaluation index system for habitat environment quality, integrating the natural ecological environment, economic development environment, social environment, and personal settlement environment. Utilising the coupled coordination degree model and trend surface analysis facilitates the study of the spatial and temporal evolution of the habitat environment and its subsystems, as well as the causes of the spatial differentiation pattern. The objective is to provide scientific support for the optimisation of the habitat system. The current focus of related research is on three aspects. The first is a comprehensive evaluation and research on the patterns, characteristics, and influencing factors of the human habitat. This mainly encompasses resilience evaluation²¹, adaptability study²², sustainability evaluation²³, vulnerability evaluation²⁴, carrying capacity study²⁵, uncertainty evaluation²⁶ and other similar topics. The focus of this research is on areas with high levels of urbanisation²⁷, coastal cities²⁸, cities in watersheds²⁹, counties³⁰ and mountainous regions³¹. Second, the factors affecting the habitat system, including those pertaining to carbon emission²⁷, carbon stock dynamics³², urban innovation⁶, urban thermal environment³³, ventilation³⁴, spatial planning³⁵, population density and deforestation³⁶, exert a direct influence on the trajectory and quality of habitat development. Thirdly, the optimisation of the management path of the habitat system is required, including urban-rural integrated development³⁷, the balanced distribution of public services³⁸, the optimisation of the spatial pattern of settlements³⁹, and the structural adjustment of economic growth and energy consumption⁷. However, research on the interrelationships between the human habitat and nature, the internal operating mechanisms and interactions of the system, is still in its infancy. There has also been insufficient attention paid to the human habitat in the context of fragile ecosystems in arid zones. This has led to a limited development of a more profound understanding of the human habitat. Consequently, there is a pressing need to explore regional habitat issues in the context of environmental coercion, economic lag and location constraints⁴⁰.

China is currently undergoing a process of promoting high-quality development. The expansion of the economy has resulted in an enhanced demand for an elevated quality of life, with a particular emphasis on the comfort and sense of belonging provided by living spaces. Xinjiang, a representative example of an arid region in western China, is confronted with a multitude of geographic and environmental challenges, including drought, low rainfall, land desertification, and water scarcity. These factors present considerable challenges to the construction of human habitats in the region⁴¹. This study examines 14 prefectural and municipal cities in Xinjiang from a variety of perspectives, including economic development, urban construction, the ecological environment, population, education, and healthcare. A system of human habitat quality evaluation indicators based on the four dimensions of “social-economic-ecological-cultural” has been established⁴². On the basis of polycentric governance theory and synergy theory, the polycentric synergistic development model has been proposed as a theoretical guide to the integrated and coordinated development of human habitats in arid zones. The objective of this study is to establish an index system for evaluating the quality of human settlement environment, with a focus on social services and security, comprehensive economic development, ecological livability, population dynamics, and cultural environment. A systematic analysis will be conducted to examine the spatial and temporal characteristics of human habitat quality and to explore the laws governing its spatial and temporal evolution. Furthermore, this research intends to investigate the evolutionary processes of human settlement environment influenced by interactions within complex systems while diagnosing the spatial correlations and clustering characteristics of regional habitat quality. From the perspective of synergistic human-land relationships, the study seeks to identify key factors affecting the quality of the human environment in Xinjiang. Its focus will be on assessing the potential for sustainable development in this context, promoting effective governance of human settlement environment in arid regions, and exploring viable paths for enhancing habitat quality in the area.

Rationale and logical framework

Rationale

The theory of polycentric governance is applicable to the interaction among a multitude of actors, including governmental organisations, business entities, civic groups, interest groups, political party organisations, and individuals, engaging in mutual games, joint participation, management, and cooperation. This forms a collaborative model for the efficient management of public affairs and the provision of high-quality public services, as well as effectively resolving the tragedy of the commons and the dilemma of collective action. The synergy theory is of particular relevance to the study of complex systems and the constituent subsystems thereof. The theory suggests that optimal functionality and spatial structure within a system can be achieved through the close coordination of the flow of elements within the system and the interaction between subsystems. This results in the generation of synergistic effects, which serve to promote balance and harmonious interactions within the system. Habitat environmental systems comprise a range of interrelated systems, including natural, social, human, residential and support systems, and belong to a complex dissipative structure, with multiple centres formed independently of each other and interacting synergistically at the same time. In light of the intricate nature of the habitat system, this study puts forth a multi-center synergistic development model founded upon the tenets of multi-center governance and synergy theory (Fig. 1). The synergistic development model, which involves the government, market, residents, industry, and infrastructure, has the potential to reshape regional economic coordination, industrial agglomeration, and resource sharing patterns. This model fosters an organic link between polycentric synergistic development and the human habitat environment, offering a solution to the intricate challenge of evaluating the quality of the human habitat environment.

Logical framework

In order to provide a clear demonstration of the logical framework and research steps of this study, an analytical framework (Fig. 2) was developed. The framework is comprised of three principal components: the habitat environment evaluation index system, the spatial differentiation analysis of habitat environment quality, and the key influencing factors on the habitat environment. (1) Construction of evaluation index system: This system encompasses a social service and security subsystem, comprising elements such as social public services, social security, and livelihood protection. The comprehensive economic level subsystem is constituted primarily of economic strength, development efficiency, and income level. The ecological and liveable environment subsystem encompasses factors such as environmental pollution, urban greening, and the overall quality of the liveable environment. Finally, the population and cultural environment subsystem comprises educational resources and population environment indicators. (2) This study employs an enhanced TOPSIS model to evaluate the spatial and temporal differentiation patterns of Xinjiang's habitat quality. The spatial correlation of regional habitats is examined through the utilisation of the global *Moran's I* index and LISA clustering. (3) The geodetector model is utilised to examine the principal factors that shape the habitat environment in Xinjiang.

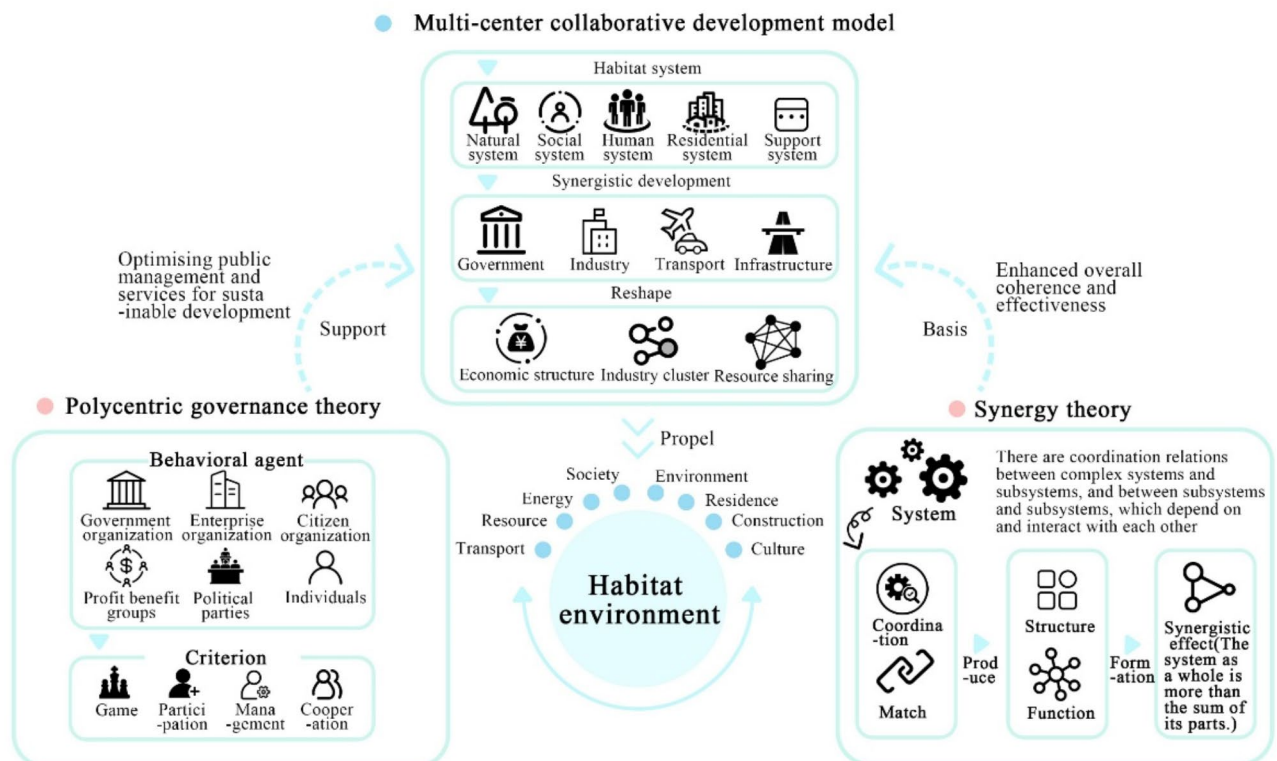


Fig. 1. Multi-centre synergistic development model map.

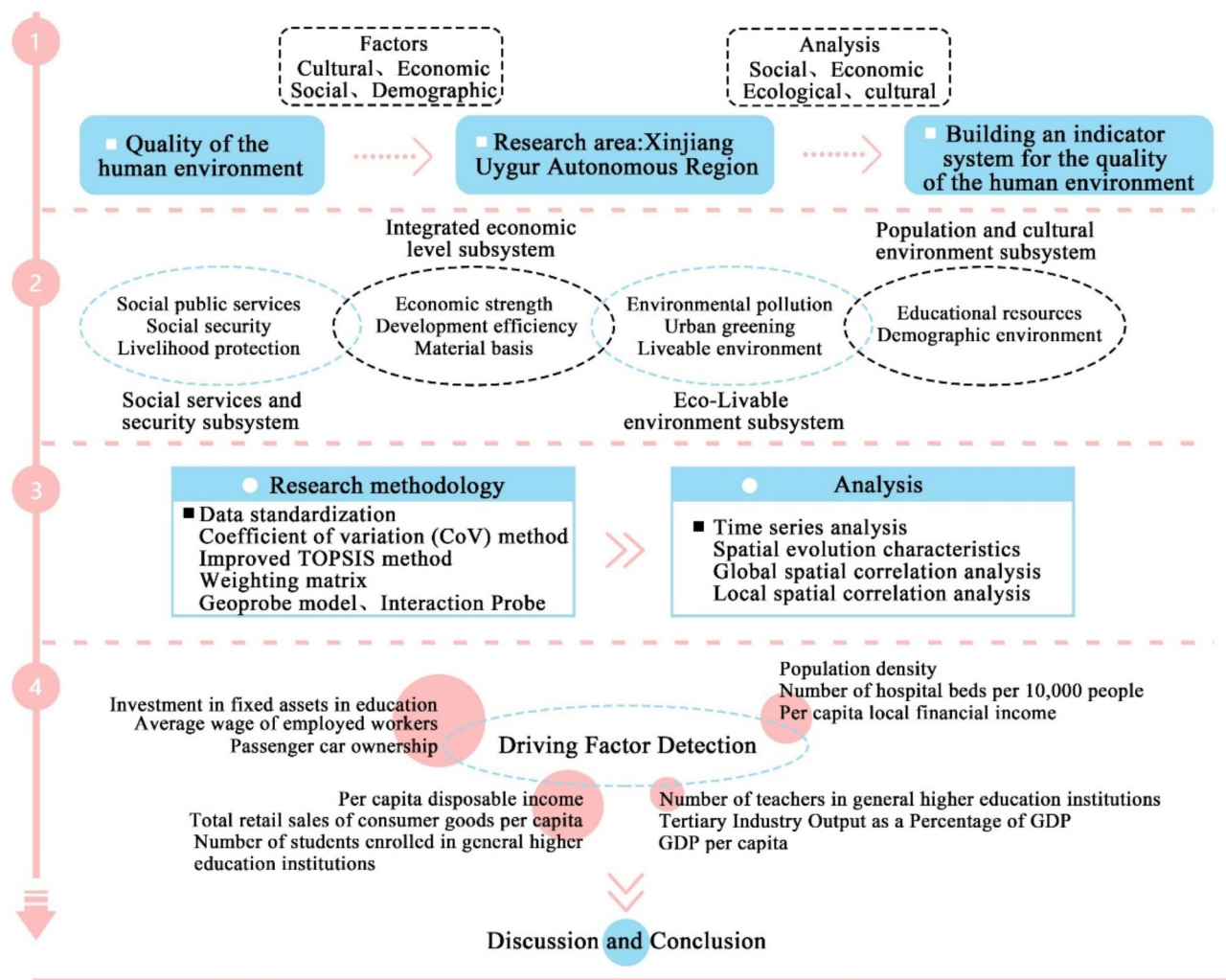


Fig. 2. Study structure and logical framework diagram.

A comprehensive assessment of the quality of the human habitat in Xinjiang, coupled with an investigation of the primary determinants of this quality, is of paramount importance for optimising and enhancing the human habitat in arid regions and fostering harmonious development between humans and nature, as well as among human and social systems.

Research methods and data sources

Overview of the study area

Xinjiang is located between latitudes 34°25' and 48°10' north and longitudes 73°40' and 96°18' east, covering an area of 1,664,900 km² in the heart of the Eurasian continent. It shares borders with five countries, including Russia, Kazakhstan, and Kyrgyzstan. The geography of Xinjiang is characterized by three mountain ranges and two basins. The Tianshan Mountain range runs through the central region of the province (Fig. 3). In 2023, statistical data indicates that Xinjiang had an average temperature of 9.7 °C, an average annual precipitation of 143.7 mm, total water resources amounting to 80.906 billion m³, and 28 nature reserves - consisting of 15 national nature reserves and 13 autonomous region-level nature reserves. Moreover, urban greenery covered 40.72% of the area, and the emission of sulfur dioxide was recorded at 102,200 tons. Since 2014, with the introduction of the “Belt and Road” initiative, Xinjiang has emerged as the central area of the Silk Road Economic Belt and a crucial gateway for China’s western outreach. The region has undertaken significant initiatives to enhance its diversified economic sectors, successfully implement the “Two Mountains Theory”, and fortify ecological and environmental governance, resulting in a gradual improvement in the quality of the local living environment.

Research methods

Data standardisation

In light of the extensive range of evaluation indicators employed to assess the quality of the human environment in this study, each with distinct scales, the polar deviation method is employed to standardise the weight of each feature dimension’s influence on the objective function. The objective of this normalization process is to mitigate

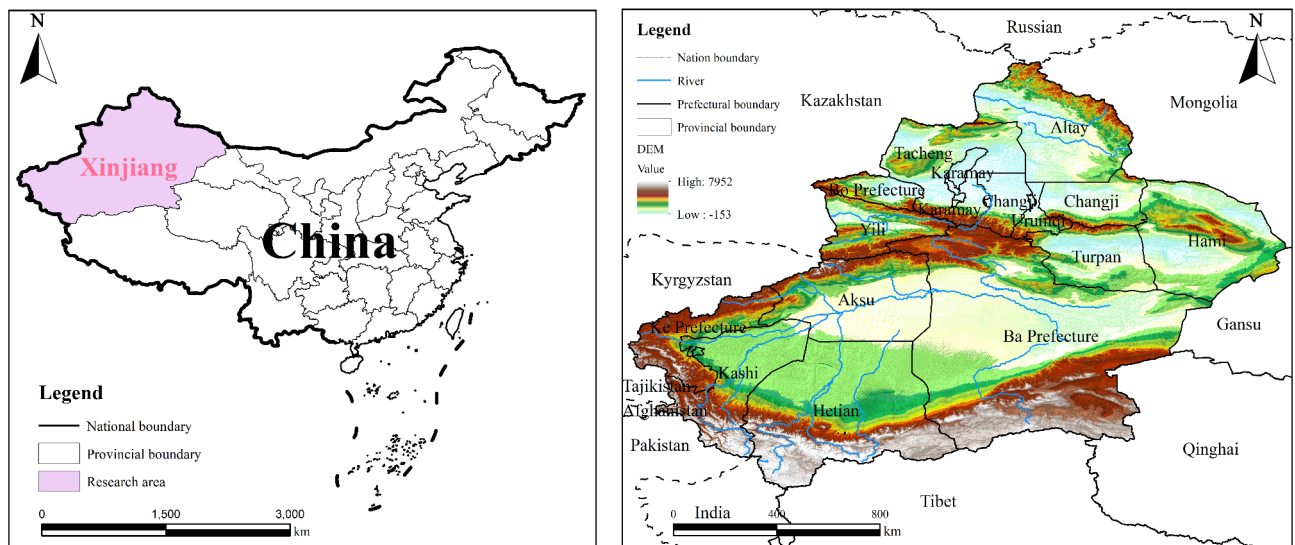


Fig. 3. The location of the research area.

the impact of scale differences on the data processing results. The characteristics of the indicators are classified as either positive or negative in accordance with their influence on the quality of the human environment. A positive indicator implies a favourable impact, whereas a negative indicator suggests a detrimental effect. The positive indicators are addressed using Eq. (1), whereas the negative indicators are handled with Eq. (2). This ensures that the standardised values fall within the range [0,1]. The specific formulas are as follows:

$$\text{Positive indicators: } R_{ij} = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)} \quad (1)$$

$$\text{Negative indicators: } R_{ij} = \frac{\max(X_j) - X_{ij}}{\max(X_j) - \min(X_j)} \quad (2)$$

Format: R_{ij} represents the normalised standard value, whereas X_{ij} denotes the original value, specifically the j th ($j=1,2,\dots,n$) indicator in year i ($i=1,2,\dots,m$). The $\max(X_j)$ and $\min(X_j)$ values are those of the j th indicator ($j=1,2,\dots,n$) in the evaluation system.

Coefficient of variation method

The coefficient of variation (CV) method is a statistical technique employed to quantify the dispersion of data and to assign weights to indicators. This is defined as the ratio of the standard deviation to the mean. The value of the coefficient of variation is positively correlated with the degree of dispersion of the data. Thus, the greater the difference in the value of the indicator, the more it reflects the gap with the unit being evaluated. By employing an objective weighting system for each evaluation indicator, the potential for bias resulting from subjective judgement and human factors in the assignment of weights is eliminated.

The precise formula for calculating the coefficient of variation of each evaluation indicator is presented in Eq. (3), while the specific formula for determining the weight of each evaluation indicator is shown in Eq. (4).

$$E_j = \frac{\partial_j}{\bar{R}_j} \quad (j = 1, 2, \dots, n) \quad (3)$$

$$W_j = \frac{E_j}{\sum_{i=1}^n E_j} \quad (j = 1, 2, \dots, n) \quad (4)$$

In Eq. (3) and Eq. (4), E_j represents the coefficient of variation evaluation of the j th indicator, ∂_j denotes the standard deviation of the j th evaluation indicator, $\bar{R}_j$ signifies the mean value of the j th evaluation indicator, and W_j is the weight of the j th evaluation indicator.

Improved TOPSIS method

The TOPSIS method, also known as the Distance to Optimal and Inferior Solutions method, is a scientific and operational approach to multi-objective decision analysis that ranks distances between objective solutions according to available data. The method should firstly establish the weighted normative matrix, then form the normative matrix through normalisation. Secondly, the optimal goal and the worst goal in the effective scheme (expressed by positive ideal solution and negative ideal solution respectively) should be identified. At the same time, the distances between each objective scheme and the positive ideal solution and the negative ideal

solution should be calculated. This is the basis for evaluating the advantages and disadvantages. Furthermore, to circumvent the potential subjectivity inherent in the traditional TOPSIS method when assigning weights, this study employs the coefficient of variation in conjunction with the TOPSIS approach. This strategy mitigates the reliance on solely numerical indicator values, thereby enhancing the precision and dependability of the multi-indicator assessment framework. The following steps are to be undertaken:

- (1) Initially, the normalisation matrix V_{ij} is established with regard to the weights, where the weights are W_j . This is achieved through the utilisation of the coefficient of variation method. In which case, i represents a value of 1, 2, 3, and so on, up to m , while j represents a value of 1, 2, 3, and so on, up to n . The normalisation matrix is shown in Eq. (5).

$$V_{ij} = W_j \times R_{ij} \quad (5)$$

- (2) The maximum value on each evaluation index in each column of V_{ij} represents the positive ideal solution V^+ , while the minimum value on each evaluation index in each column of V_{ij} represents the negative ideal solution V^- . Equation (6) and Eq. (7) represent the positive and negative ideal solutions, respectively.

$$V^+ = \{\max V_{i1}, \max V_{i2}, \dots, \max V_{in}\} \quad (6)$$

$$V^- = \{\min V_{i1}, \min V_{i2}, \dots, \min V_{in}\} \quad (7)$$

- (3) Calculate the distance from the evaluated target to the positive ideal solution S^+ [Eq. (8)] and the distance from the negative ideal solution S^- [Eq. (9)].

$$S^+ = \sqrt{\sum_{i=1}^m (V_{ij} - V_j^+)^2} \quad (i = 1, 2, \dots, m; 0 \leq S_i^+ \leq 1) \quad (8)$$

$$S^- = \sqrt{\sum_{i=1}^m (V_{ij} - V_j^-)^2} \quad (i = 1, 2, \dots, m; 0 \leq S_i^- \leq 1) \quad (9)$$

The value of S^+ indicates the proximity of each evaluation target to the optimal target. A smaller value of S^+ indicates a closer proximity of the evaluation target to the ideal target, thereby indicating a superior programme.

- (4) Calculate the closeness of the ideal solution C_i [Eq. (10)], that is, we obtain.

$$C_i = \frac{S^-}{S^+ + S^-} \quad (i = 1, 2, \dots, m) \quad (10)$$

A greater value of C_i indicates an improved state of the evaluation target. When C_i is equal to one, the evaluation target is in the optimal state. Conversely, when C_i is equal to zero, the evaluation target is in the worst state.

Spatial autocorrelation

Spatial autocorrelation is a series of methods used to determine whether there is a correlation between spatial entities within a certain range. These methods include global autocorrelation and local autocorrelation. Global autocorrelation describes the overall spatial distribution of an attribute within the study area, namely whether there is a spatial agglomeration. Local autocorrelation is employed to analyse the degree of correlation between an attribute within the study area and the same attribute in neighbouring areas, and to characterise the trend of agglomeration or dispersion within the internal range and neighbouring space. The global *Moran's I* index and local *Moran's I* calculation are presented in Eqs. (11) and (12), respectively.

Global *Moran's I* index formula:

$$I = \frac{n}{s_0} \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2} \quad (11)$$

$$s_0 = \sum_{i=1}^n \sum_{j=1}^n w_{ij} \quad (12)$$

Format: The global *Moran's I* value is represented by I , with n denoting the total number of samples in the study area. The observations at regions i and j , respectively, are represented by x_i and x_j . The spatial weight matrix between spatial elements i and j ($j = 1, 2, 3, \dots, n$) in the study interval is represented by w_{ij} . The average characteristic value of the human habitat in the study area is represented by $\bar{x}$. The aggregation of all spatial weights is represented by s_0 .

Localised *Moran's I* index formula:

$$I = \frac{n(x_i - \bar{x}) \sum_{j=1}^n w_{ij} (x_j - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2} \tag{13}$$

The *Moran's I* values were decomposed to each spatial unit using LISA, and LISA's aggregation map was formed by z-test, where: In this context, *I* represents the local *Moran's I* value. The observed values at study units *i* and *j*, denoted by x_i and x_j , respectively, are used to calculate the average eigenvalue of the habitat within the study area, denoted by $\bar{x}$, is also employed. The spatial weight matrix, represented by w_{ij} .

Geodetector

Geodetector models are statistical tools that are employed to identify spatial variations in univariate variables that serve as explanatory factors for a particular phenomenon⁴³. This method allows the determination of whether the impact of a specific variable, such as habitat quality *Y*, is enhanced or diminished when multiple influencing factors interact, and whether these factors act independently on habitat quality *Y*⁴⁴. The degree of spatial dissimilarity is quantified using the q-value, whereby a higher q-value signifies a greater explanatory power of the independent variable *X* on the dependent variable *Y*. In the present study, the factors influencing the spatial diversity of human environmental quality in Xinjiang are analysed using the q statistic, which is expressed as follows:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} = 1 - \frac{SSW}{SST} \tag{14}$$

Format: The value of q is within the range of [0,1]. In this context, *h*=1, 2, 3, ., *L* represents the number of spatial distributions of human environment quality, *N_h* is the number of units in stratum *h*, and *N* represents the number of units in the entire study area⁴⁵. σ_h^2 represents the variance of the *Y*-value of the categorical classification *h*. σ^2 denotes the total dispersion variance of the study area. *SSW* is the intra-stratum variance sum, while *SST* is the total region-wide variance.

The interaction detector is primarily employed to facilitate the identification of factor interactions through the examination of two-by-two interaction values. This enables the assessment of whether the explanatory power of habitat quality *Y* is enhanced or diminished when the independent variables of the influencing factors, X_i and X_j , interact, or whether the influencing factors act independently of each other on habitat quality *Y*. By analysing the $q(X_i \cap X_j)$, it is possible to ascertain the relationship that emerges subsequent to the factor interactions. The classification of two-by-two interaction factor relationships is presented in Table 1.

Indicator system construction

The habitat environment can be divided into five distinct levels: built monolithic, community, urban, regional, and global. The field of habitat science is concerned with the study of human settlements, which encompass a range of urban and rural communities, and the complex interrelationships between humans and the natural environment⁴⁶. This research is based on polycentric governance theory and synergy theory, and it develops a polycentric synergistic model for human settlements across four dimensions: social, economic, ecological, and cultural. In this context, social services and security are essential for human life, encompassing public services and social safety nets⁴⁷. The economic aspect entails the evaluation of regional economic development levels and efficiency, which are of vital importance for the sustenance of regional growth. An ecologically liveable environment is constituted by the quality of the natural environment, the presence of urban green spaces and the suitability of the living environment, all of which are crucial for human settlement⁴⁸. The population and cultural environment are fundamental to the stability and harmony of regional development, encompassing aspects such as population structure and cultural amenities⁴⁹. This study employs 31 indicator factors at various levels to establish an evaluation index system for human environment quality based on the aforementioned four dimensions (Table 2).

Data resource

The data employed in this study were sourced from a range of statistical yearbooks, including the Xinjiang Statistical Yearbook, Xinjiang Fifty Years, the China Urban Statistical Yearbook, and the statistical yearbooks of various cities and towns in Xinjiang. Additionally, data were obtained from the official website of the Bureau of Statistics and the Xinjiang Uygur Autonomous Region Bureau of Statistics (<http://tjj.xinjiang.gov>).

Basis of judgement	Interaction
$q(X_i \cap X_j) < \text{Min}(q(X_i), q(X_j))$	Nonlinear attenuation
$\text{Min}(q(X_i), q(X_j))$	Single-factor nonlinear attenuation
$q(X_i \cap X_j) > \text{Max}(q(X_i), q(X_j))$	Two-factor enhancement
$q(X_i \cap X_j) = q(X_i) + q(X_j)$	Independent
$q(X_i \cap X_j) > q(X_i) + q(X_j)$	Nonlinear enhanced

Table 1. Types of interactions.

Standard floor	Index level	Unit	Attributes	Weights
Social services and security (<i>S</i>)	Per capita domestic water consumption S_1	Litres	+	0.029 3
	Domestic electricity consumption per capita S_2	kW·h	+	0.036 2
	Urban road area per capita S_3	Square metres	+	0.025 3
	Postal and telecommunication services per capita S_4	Million	+	0.056 9
	Gas penetration rate S_5	Percent	+	0.026 2
	Number of hospital beds per 10,000 people S_6	PCS	+	0.030 0
	Number of hospital doctors per 10,000 people S_7	Person	+	0.028 3
	Passenger car ownership S_8	10 000 vehicles	+	0.041 4
	Average wage of employed workers S_9	10 000 yuan	+	0.035 5
Comprehensive economic level (<i>E</i>)	GDP per capita E_1	10 000 yuan	+	0.032 4
	Urbanisation rate E_2	Percent	+	0.031 5
	Per capita disposable income E_3	10 000 yuan	+	0.037 0
	Per capita local fiscal revenue E_4	10 000 yuan	+	0.034 2
	Foreign direct investment E_5	USD10 000	+	0.058 5
	The proportion of output value of tertiary industry in GDP E_6	Percent	+	0.031 1
	Total retail sales of consumer goods per capita E_7	10 000 yuan	+	0.032 1
	Per capita total investment in fixed assets E_8	10 000 yuan	+	0.035 8
	Profit and Tax Rate of Industrial Enterprises Above Scale E_9	Percent	+	0.030 9
	Energy consumption per unit of GDP E_{10}	Standard coal/10 000 yuan	-	0.023 3
	Electricity consumption per unit of GDP E_{11}	Kilowatt-hours/10 000 yuan	-	0.017 7
Ecological and livable environment (<i>L</i>)	Public green space per capita L_1	m ²	+	0.033 7
	Sulphur dioxide emissions per capita L_2	m ³	-	0.030 6
	Per capita soot emission L_3	10 000 tons	-	0.018 7
	Urban water penetration rate L_4	Percent	+	0.015 9
	Domestic waste removal L_5	10 000 tons	+	0.021 2
Population and cultural environment (<i>P</i>)	Population density P_1	Person/km ²	-	0.028 0
	Natural population growth rate P_2	Percent	-	0.063 2
	Number of students in general higher education institutions P_3	Person	+	0.029 2
	Number of teachers in general colleges and universities P_4	Person	+	0.023 6
	Expenditure on education in various types of schools P_5	10 000 yuan	+	0.036 2
	Number of cultural centres P_6	PCS	+	0.025 9

Table 2. Human environment quality evaluation indicator system.

cn/). The Xinjiang Statistical Bulletin of National Economic and Social Development was also consulted as a supplementary data source.

Characteristics of Spatial and Temporal variability in the quality of human settlement environment in Xinjiang

Human settlement environment quality time series analysis

The improved TOPSIS model was used to calculate the comprehensive evaluation value of the four subsystems of Xinjiang's habitat from 2001 to 2021, and the results are shown in Fig. 4.

- (1) The development of the social service and security subsystem initially displays considerable volatility, followed by a period of sustained growth. The evolution of the social service and security system between 2001 and 2005 displays a relatively unstable pattern, exhibiting a “W”-shaped trajectory of “decreasing-increasing-decreasing-increasing”. This is substantiated by a notable decline in the evaluation value, which decreased from 0.240 0 to 0.122 4, representing a 49% reduction. The overall trend demonstrates stability from 2006 to 2009, followed by a period of sustained growth from 2010 to 2019. However, there is a notable decline between 2020 and 2021, with the assessed value decreasing from 0.808 2 to 0.599 6, representing a 25.81% reduction. The development of the social service and security subsystem initially displays considerable volatility, followed by a period of sustained growth. In 2012, the Xinjiang region identified the protection and enhancement of the well-being of its residents as a priority. In order to achieve this objective, a series of substantial initiatives were implemented in the domains of employment, education, social security, and healthcare. These initiatives were designed with the objective of providing universal, basic, and grass-roots livelihood support. Notable examples include the “four-in-four” employment service, the “five projects” focusing on educational quality, and the “medical bottom-up” project, which aimed to equalise access to basic public services. The government closely monitored the population's livelihood situation, established a robust protection network, and promoted three significant housing projects: “Settling and Enriching the

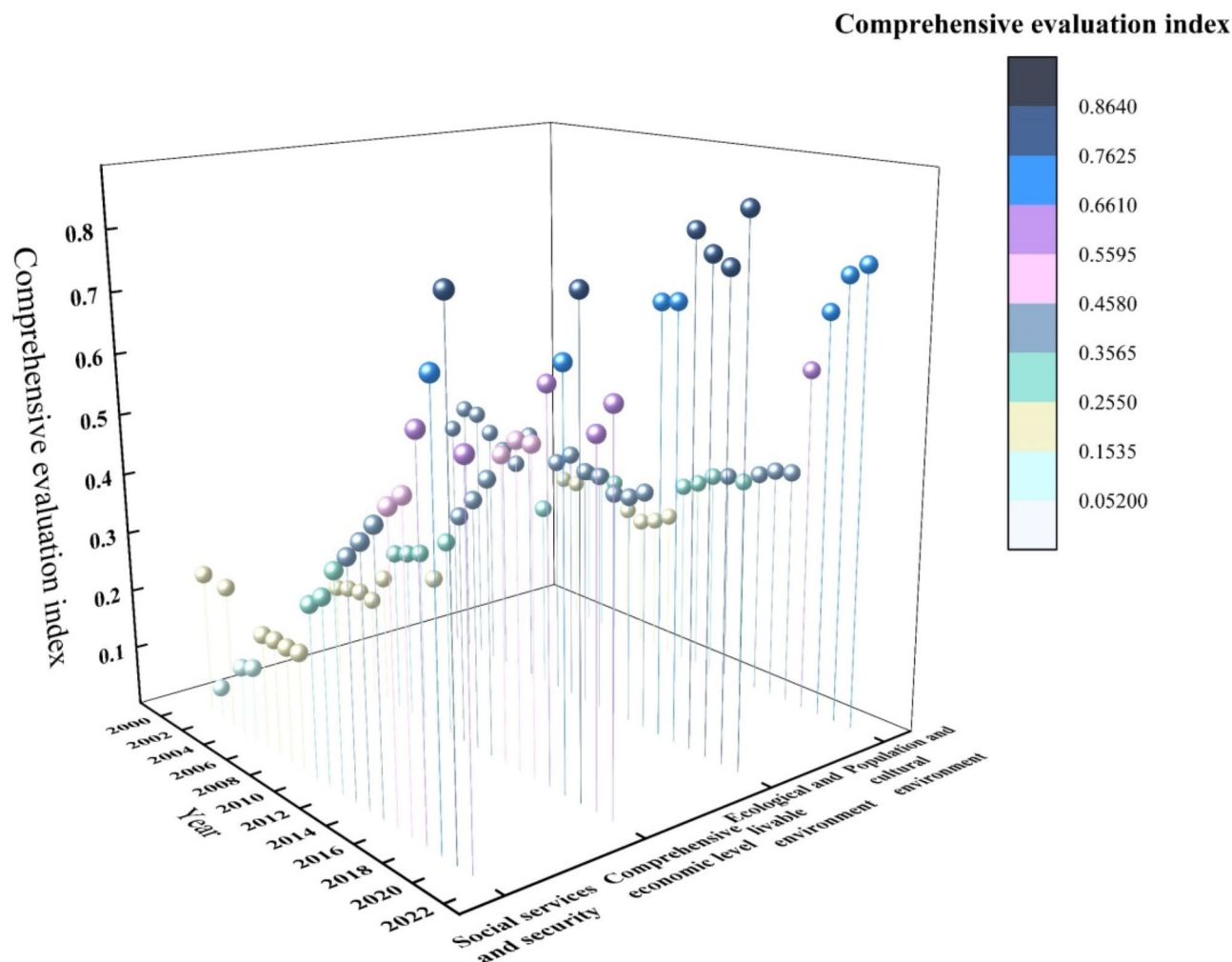


Fig. 4. Human settlement environment subsystem valuation.

- People,” “Settling and Developing Pastoralism,” and “Guaranteed Housing.” The objective of these initiatives is to ensure the protection of residents’ livelihoods, housing, and employment.
- (2) The comprehensive economic level subsystem has exhibited a persistent upward trajectory, with only minor fluctuations influenced by factors such as population dynamics, cultural environment, and ecological livability. From 2001 to 2004, there was a gradual improvement in the comprehensive economic level, with the evaluation value fluctuating between 0.157 4 and 0.170 1. The period between 2005 and 2007 saw a modest surge in development, with the evaluation value increasing from 0.213 4 to 0.275 8, representing a 29.24% growth. The period between 2008 and 2010 exhibited a “V”-shaped trend, characterised by an initial decline followed by an increase. From 2011 to 2018, a more pronounced increase was observed, with the appraisal value rising from 0.374 8 to 0.662 3. From 2019 to 2021, a “V” trend was identified. In 2014, the Xinjiang region initiated twelve key talent projects with the objective of attracting high-level expertise and stimulating economic growth. With the backing of the national government, nascent industries such as new energy, biomedicine, and new materials are experiencing growth, leading high-tech enterprises to spearhead Xinjiang’s economic advancement.
 - (3) The ecologically liveable environment subsystem demonstrates fluctuations in both directions. Specifically, the period from 2001 to 2006 is characterised by an inverted “V”-shaped trend of “increasing-decreasing”. The evaluation value decreased from 0.395 9 to 0.371 2, representing a 6.24% reduction. Subsequently, between 2007 and 2009, a “V” trend of “decreasing-increasing” is evident. Subsequently, there was a slight decline from 2010 to 2014, with a reduction of 9.1% from 0.417 8 to 0.379 8. It is noteworthy that a considerable increase is observed from 2015 to 2018, with the value rising from 0.396 0 to 0.820 7. From 2019 to 2021, a comparable “decreasing-increasing” pattern is observed. In 2016, Xinjiang introduced the *Xinjiang Uygur Autonomous Region Implementation Programme for the National Carbon Emission Trading Market*. The programme effectively regulates industrial production gas emissions by establishing a greenhouse gas emission monitoring body and then allocating carbon emission quotas to key enterprises and industries. It also aims to enhance energy efficiency, drive industrial transformation, and develop a low-carbon industrial system.

- (4) The Population and Cultural Environment subsystem demonstrates an overall inverted V-shaped trend of “increasing-declining” from 2001 to 2009. This is evidenced by a notable increase in the rating value from 0.252 9 to 0.250 6, representing a 0.91% decline. From 2010 to 2018, this subsystem demonstrated a gradual upward trajectory, with the evaluation value increasing from 0.313 4 to 0.753 1. In 2008, the Xinjiang government initiated a series of cultural activities in communities, enterprises, rural areas, schools, military barracks, and other key locations with the objective of addressing the population's spiritual and cultural requirements through the advancement of cultural and artistic pursuits. The objective of these initiatives was to guarantee the effective protection of the cultural rights and interests of residents. As living standards have improved, residents have become increasingly focused on pursuing their own cultural development and education. The implementation of favourable policies, including bilingual education, special education, and 12-year free compulsory education, has served to further ensure the right to education of the population in question.

Characteristics of the Spatial evolution of the quality of human settlement environment

In order to evaluate the quality of the human environment in 14 prefectural and municipal cities in Xinjiang, five time points were selected based on the characteristics of time-series changes. The selected nodes were 2001 (a), 2006 (b), 2012 (c), 2018 (d), and 2021 (e). The TOPSIS model was adapted to facilitate the processing of data, thereby enabling a comprehensive evaluation of the quality of the human habitat in each area. Subsequently, the cold spot analyses of habitat quality were conducted using ArcGIS 10.1 in each location, and the spatial evolution trends regarding habitat quality in different regions were analysed (Fig. 5).

From 2001 to 2006, a discernible deterioration in the quality of the habitat environment was observed, predominantly within the sub-cold spot zone. In 2006, Hami City (Hami) and Aksu region (Aksu) exhibited a transition from the sub-hot spot to the sub-cold spot zone, while Bortala Mongolian Autonomous Prefecture (Bo Prefecture) shifted from the sub-cold spot to the cold spot zone. Conversely, Kashi region (Kashi) and Altay region (Altay) transitioned from the cold spot to the sub-cold spot zone. From 2006 to 2012, there was an observable improvement in the quality of the habitat environment, predominantly within the sub-hot spot zone. In 2012, Changji Hui Autonomous Prefecture (Changji), Turpan City, Aksu, and Hetian region (Hetian) transitioned from the sub-cold spot to the sub-hot spot zone, while Yili Kazakh Autonomous Prefecture (Yili) advanced from the cold spot to the sub-hot spot zone. In addition, Bo Prefecture shifted from the cold spot to the sub-cold spot zone, while Karamay City decreased from the hot spot to the sub-hot spot zone, and Altay declined from the sub-cold spot to the cold spot zone. From 2012 to 2018, there was an upward trajectory in the quality of the human habitat environment, with the majority of regions falling within the sub-hot spot and sub-cold spot zone. In 2018, the Kizilsu Kirgiz Autonomous Prefecture (Ke Prefecture) experienced a transition from the cold spot to the sub-cold spot zone, while Kashi shifted from the sub-cold spot to the sub-hot spot zone. Changji experienced a transition from the sub-hot spot to the hot spot zone, Altay underwent a transition from the cold spot to the sub-cold spot zone, Bo Prefecture regressed from the sub-cold spot to the cold spot spot

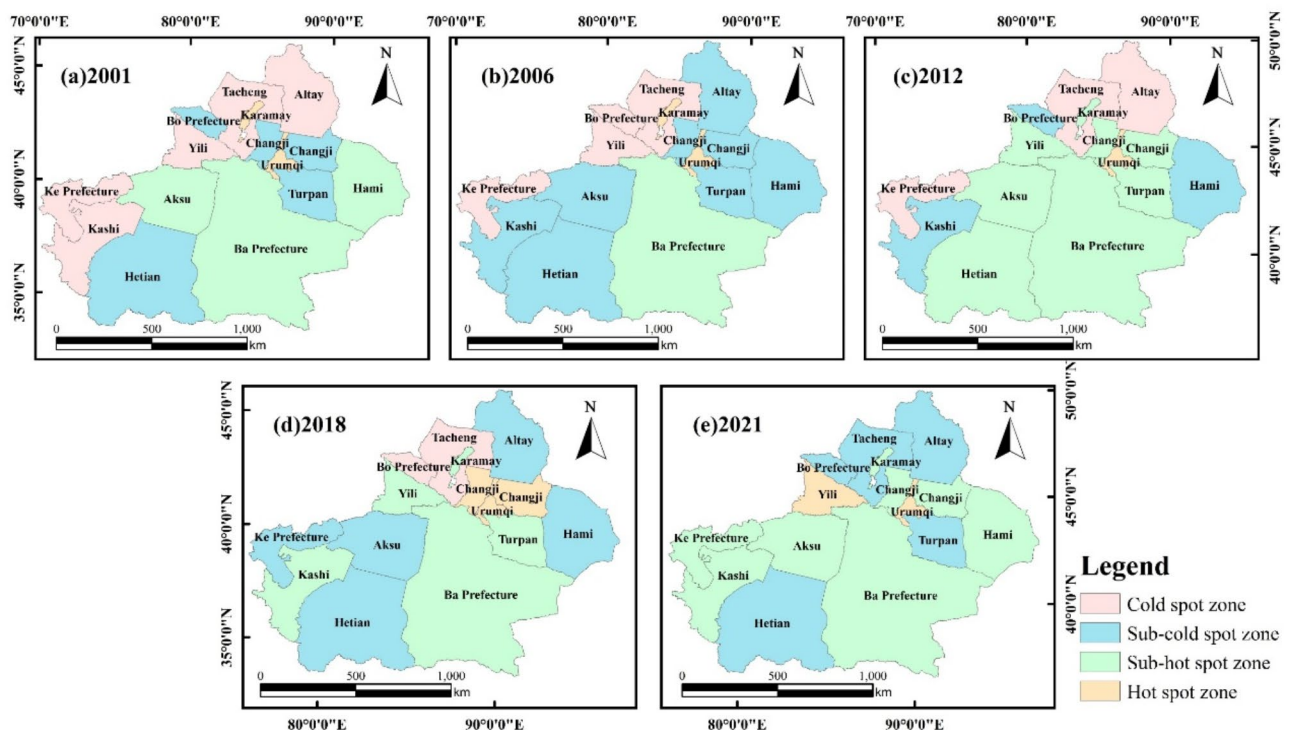


Fig. 5. Patterns of spatial distribution of human settlement environment quality.

zone, and Aksu and Hetian declined from the sub-hot spot to the sub-cold spot zone. By 2021, the quality of the human habitat had exhibited an upward trajectory and was primarily situated within the sub-hot spot zone. Ke Prefecture, Aksu, and Hami exhibited an ascent from the sub-cold spot to the sub-hot spot zone, whereas Bo Prefecture and Tacheng region (Tacheng) demonstrated advancement from the cold spot to the sub-cold spot zone. Yili transitioned from the sub-hot spot to the hot spot zone, while Changji experienced a decline from the hot spot to the sub-hot spot zone, and Turpan City experienced a decline, moving from the sub-hot spot to the sub-cold spot zone.

The study period was characterised by the presence of both sub-cold and sub-hot spot areas in the human settlement environment of Xinjiang. This variation can be attributed to significant disparities in economic development, geographical conditions and resource endowments, leading to differing qualities of the human settlement environment. Notably advantageous growth areas, such as Urumqi City and Changji, have emerged due to a diversified economic development system that capitalises on the strengths of both secondary and tertiary industries. The enhancement of urbanisation construction, infrastructure and public services has attracted increased investment, leading to enhanced medical services and educational quality, and consequently improving the overall quality of the human settlement environment. Regions such as Yili and Altay possess rich historical and cultural heritage, and unique natural landscapes, such as Kanas Lake, Baihaba and Hemu Village, which are utilised for the promotion of eco-tourism and cultural tourism. This has not only deepened the development of tourism products but also increased infrastructure investment, thereby laying the foundation for sustainable regional development. Resource-rich areas such as Aksu and Hetian have heavily depended on natural resource extraction to fuel economic growth. However, the lack of effective resource management and ecological protection measures has led to the overexploitation of mineral resources, including coal, oil and natural gas, resulting in ecological degradation and heightened tensions between economic development and environmental protection.

The spatial development of human settlement quality in Xinjiang demonstrates considerable inter-regional variation, yet a discernible trend towards convergence is observable over time. In general, the distribution of the quality of the human settlement environment in Xinjiang was found to be in a cluster shape, with the geospatial proximity effect being more pronounced, forming a “gradient” with Urumqi City at the centre of the development characteristics of the decreasing gradient. The initial tier, comprising Karamay City, Changji, and Yili, exhibits a robust economy, superior public infrastructure, and an array of recreational facilities. Additionally, its well-established “residence-industry-tourism” system is a consequence of its distinctive geographic location. The second tier, comprising Altay, Tacheng, Bo Prefecture, Turpan City, and Hami, is confronted with considerable constraints in economic, social, and cultural development, which can be attributed to specific geographical characteristics, vulnerable ecosystems, inadequate transportation infrastructure, limited educational resources, and a dispersed population. The third tier, comprising Ke Prefecture, Kashi, Hetian, Aksu, and Bayingolin Mongolian Autonomous Prefecture (Ba Prefecture), is characterised by a wealth of agricultural, mineral, and port resources. However, the livestock and plantation industries, along with mineral extraction, have caused irreparable damage to the region’s ecological balance.

Spatial correlation of human settlement environment quality in Xinjiang

Global Spatial correlation analysis

In this study, the global *Moran's I* index (Fig. 6) was calculated with the objective of evaluating the quality of the human settlement environment across Xinjiang. This entailed the selection of data samples for a comprehensive evaluation of the human settlement environment, the creation of a weight matrix, the evaluation of the similarity

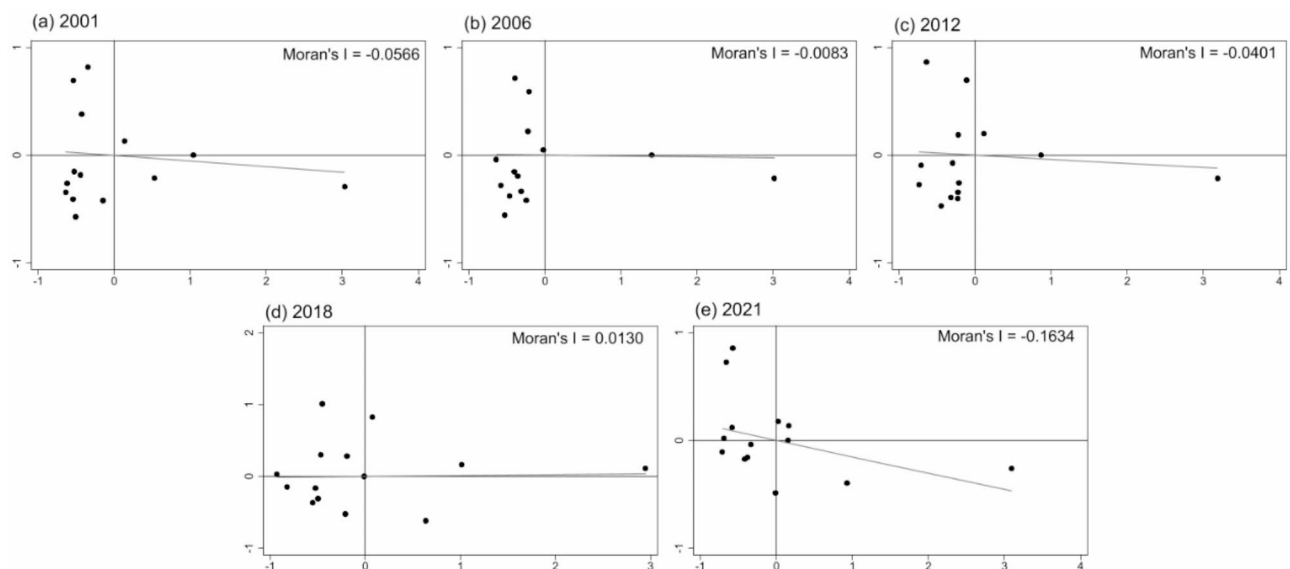


Fig. 6. Moran's scatter plot of spatial correlation of human settlement environment quality.

of attribute values among neighbouring evaluation units, and the identification of spatial clusters. The objective was to ascertain whether there was any spatial correlation in the quality of the human settlement environment in Xinjiang.

The quality of human settlement environment in the Xinjiang region was evaluated through the utilisation of Moran scatter plots, which identified four distinct spatial patterns corresponding to quadrants one, two, three, and four. In the initial quadrant, regions exhibiting high human settlement environment quality are situated in proximity to other areas of high value, thereby forming a high-high (H-H) agglomeration. The second quadrant demonstrates regions exhibiting low human settlement environment quality, situated in proximity to high-value zones, thereby constituting a low-high (L-H) agglomeration. The third quadrant represents areas with low human settlement environment quality surrounded by low-value zones, resulting in a low-low (L-L) agglomeration. Lastly, the fourth quadrant indicates areas with high human settlement environment quality surrounded by low-value zones, thereby creating a high-low (H-L) agglomeration.

Moran's I values for regional habitat quality in Xinjiang were -0.0566 in 2001, -0.0083 in 2006, -0.0401 in 2012, and -0.1634 in 2021, all of which were below 0. This indicates a negative correlation in the spatial distribution of human habitat quality in Xinjiang. In 2018, *Moran's I* was 0.0130 , indicating a positive correlation between the spatial patterns of human habitat quality in Xinjiang's, with evidence of clustering. In total, it is recommended that the L-L agglomeration area intensify its efforts to enhance the living environment, pursue uninterrupted improvements to the human habitat environmental protection system, and, as a consequence, elevate the quality of life for residents.

Local Spatial correlation analysis

The global *Moran's I* index is limited to analyzing the overall spatial autocorrelation of human habitats in Xinjiang and is not able to characterize the local spatial clustering features. To further investigate the spatial correlation of human settlements in Xinjiang across different years, a LISA clustering map of human settlements was created using the localised *Moran's I* index (Fig. 7). The map illustrates three principal distribution categories. The H-H, H-L, and L-H categories indicate the presence of both positive and negative spatial correlations in the human habitat in Xinjiang.

In 2001, 2006, 2012, 2018 and 2021, the Xinjiang Habitat is observed to have a more pronounced presence in the H-H and H-L regions. In 2001, Turpan City was situated within the L-H region. In comparison, the data sets from 2006 to 2012 indicate that Karamay City is situated within the H-L agglomeration area, which represents a region of low growth. Furthermore, Turpan City is located within the H-H region. In 2018, the spatial clustering of Xinjiang Habitat became more pronounced, with Karamay City situated within the H-L cluster, Altay within the L-H cluster, and Turpan City and Ba Prefecture located in the H-H cluster. In 2021, Karamay City was classified within the H-L cluster, while Turpan City was classified within the L-H cluster. The two are situated in a region exhibiting a transitional spatial correlation. From 2006 to 2021, Karamay City has consistently been situated within the H-L agglomeration area, which is characterised by a relatively high quality human settlements

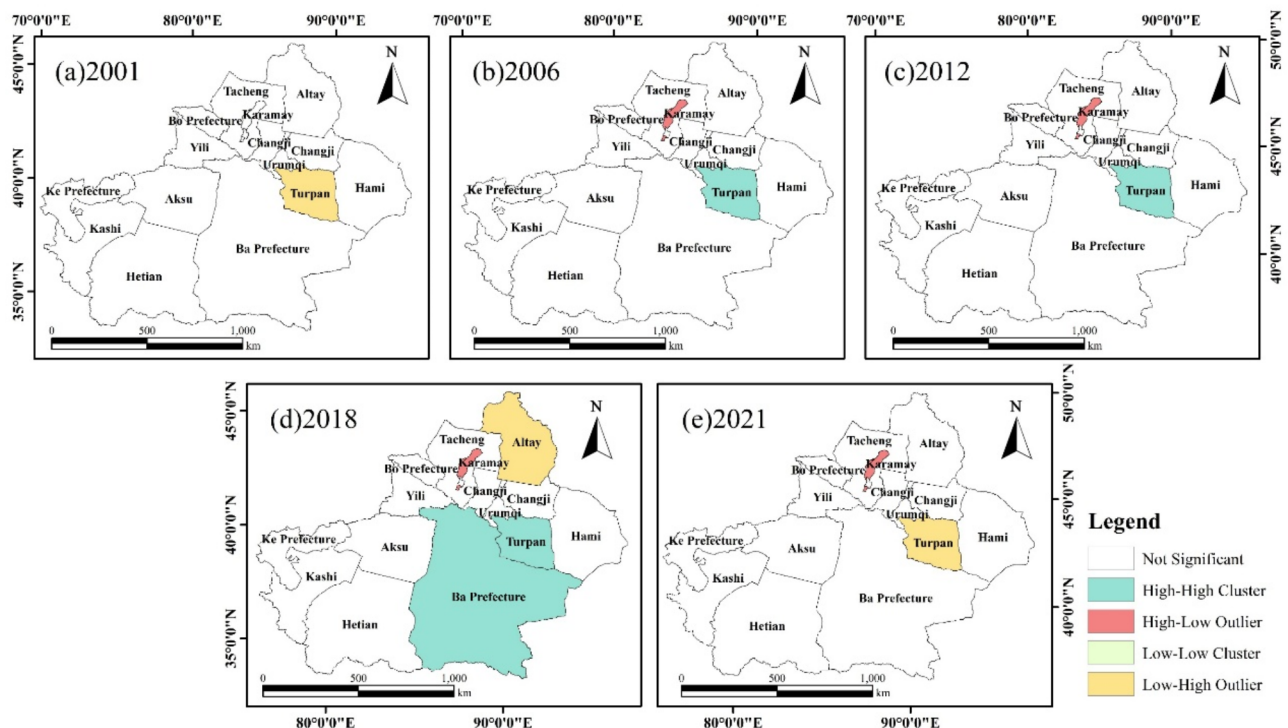


Fig. 7. LISA diagram of local spatial correlation of human settlement environment quality.

environment. This renders it a high-value agglomeration zone. The number of areas classified as H-H increased markedly from 2006 to 2018, particularly in Ba Prefecture and Turpan City. From 2001 to 2021, the distribution of L-H cluster areas remained relatively limited. The results provide substantial evidence of significant spatial interdependency among human settlements in Xinjiang over the course of the research period. However, the lack of a regional cooperation mechanism and a well-structured industrial chain layout has resulted in a limited impact on neighbouring regions, leading to a notable spatial polarization effect on the regional habitat.

Detection of factors affecting the quality of human settlement environment in Xinjiang

In the study of influential factors, the evolutionary dynamics of the regional habitat environment were taken into account, with consideration of existing studies and the actual development situation in Xinjiang^{50,51}. Twelve indicator factors were selected to detect the factors influencing the quality of the habitat environment, with a focus on social security, economic development, residents’ quality of life, and ecological security. The GeoDetector tool was employed to ascertain the intensity of the role of the selected indicator factors in influencing the quality of Xinjiang’s habitat environment and to identify the main influencing factors and the types of interactions between them. The dependent variable was the comprehensive evaluation value of the spatial quality of Xinjiang’s habitat environment, while the independent variables were the aforementioned indicator factors.

The geodetector model was utilized to assess the influence of the explanatory factors, and the q-value obtained from the factor detector was used to determine the explanatory power of the independent variable X on the dependent variable Y, within the range of [0,1], with a higher q-value indicating a stronger influence of X on Y (Table 3). Over the time series analyzed for the indicator factors, the q-value displays a pattern of increase followed by decrease between 2001 and 2021. The construction of human settlements environment in Xinjiang varies across different time periods, driven by a combination of internal and external factors including policy, economy, society, and environment. In the year 2001, the primary influencing factors were identified as per capita local fiscal revenue (X_5), energy consumption per unit of GDP (X_{10}), and expenditure on education in various types of schools (X_3). By 2006, the dominant influencing factors had shifted to total retail sales of consumer goods per capita (X_7), expenditure on education in various types of schools (X_3), and the amount of domestic waste removal (X_{11}). In the year 2012, the primary factors were per capita local fiscal revenue (X_5), domestic waste removal (X_{11}), and the number of hospital doctors per 10,000 people (X_1). By 2018, total retail sales of consumer goods per capita (X_7), per capita local fiscal revenue (X_5), and the number of hospital doctors per 10,000 people (X_1) had become the dominant influencing factors. In 2021, the primary influencing factors were identified as the amount of domestic waste removal (X_{11}), the number of hospital doctors per 10,000 people (X_1), and energy consumption per unit of GDP (X_{10}). The values pertaining to economic development and social security exhibited a gradual decline, whereas those pertaining to resident life and ecological security initially declined before showing an increase. From 2001 to 2021, the most significant influence on the habitat environment of Xinjiang was that of ecological security. The eight major industrial clusters in Xinjiang are highly energy-intensive, resulting in elevated energy consumption and increased pollution emissions within the sector. The combined pressures of environmental vulnerability and industrial transformation have considerably heightened the vulnerability of the human environment in the region, thereby posing substantial challenges for achieving high-quality development.

The “interaction detector” was employed to ascertain the explanatory power of interactions between influencing factors on the quality of the human environment. As illustrated in Fig. 8, the selected index factors demonstrate that two-factor interactions exceed the q value of a single factor. Furthermore, the two-by-two interaction type is distinguished by two-factor enhancement and nonlinear enhancement, with no instances of independent or weakened situations. This indicates that the quality of the human environment in Xinjiang is the result of a combined effect, whereby the interaction of various influencing factors is responsible for its overall character. In particular, the two-factor sets that exhibited strong explanatory power in 2001 were X_{10} - X_6 , X_{10} - X_3 ,

Impact factors	Specific indicator	2001	2006	2012	2018	2021
Social Security	Number of hospital doctors per 10,000 people X_1	0.308	0.525	0.740	0.722	0.499
	Average wage of employed workers X_2	0.406	0.584	0.149	0.232	0.164
	Expenditure on education in various types of schools X_3	0.792	0.797	0.132	0.522	0.345
Economic Development	GDP per capita X_4	0.006	0.483	0.155	0.148	0.178
	Per capita local fiscal revenue X_5	0.897	0.483	0.945	0.742	0.073
	The proportion of output value of tertiary industry in GDP X_6	0.072	0.050	0.145	0.273	0.255
	Total retail sales of consumer goods per capita X_7	0.749	0.874	0.738	0.780	0.473
Resident Life	Urban road area per capita X_8	0.047	0.160	0.110	0.015	0.155
	Per capita disposable income X_9	0.219	0.629	0.195	0.429	0.477
Ecological Security	Energy consumption per unit of GDP X_{10}	0.798	0.560	0.315	0.183	0.480
	Domestic waste removal X_{11}	0.767	0.753	0.890	0.719	0.794
	Public green space per capita X_{12}	0.065	0.292	0.079	0.037	0.326

Table 3. Indicator system and q-value for detecting factors affecting the quality of the human settlement environment.

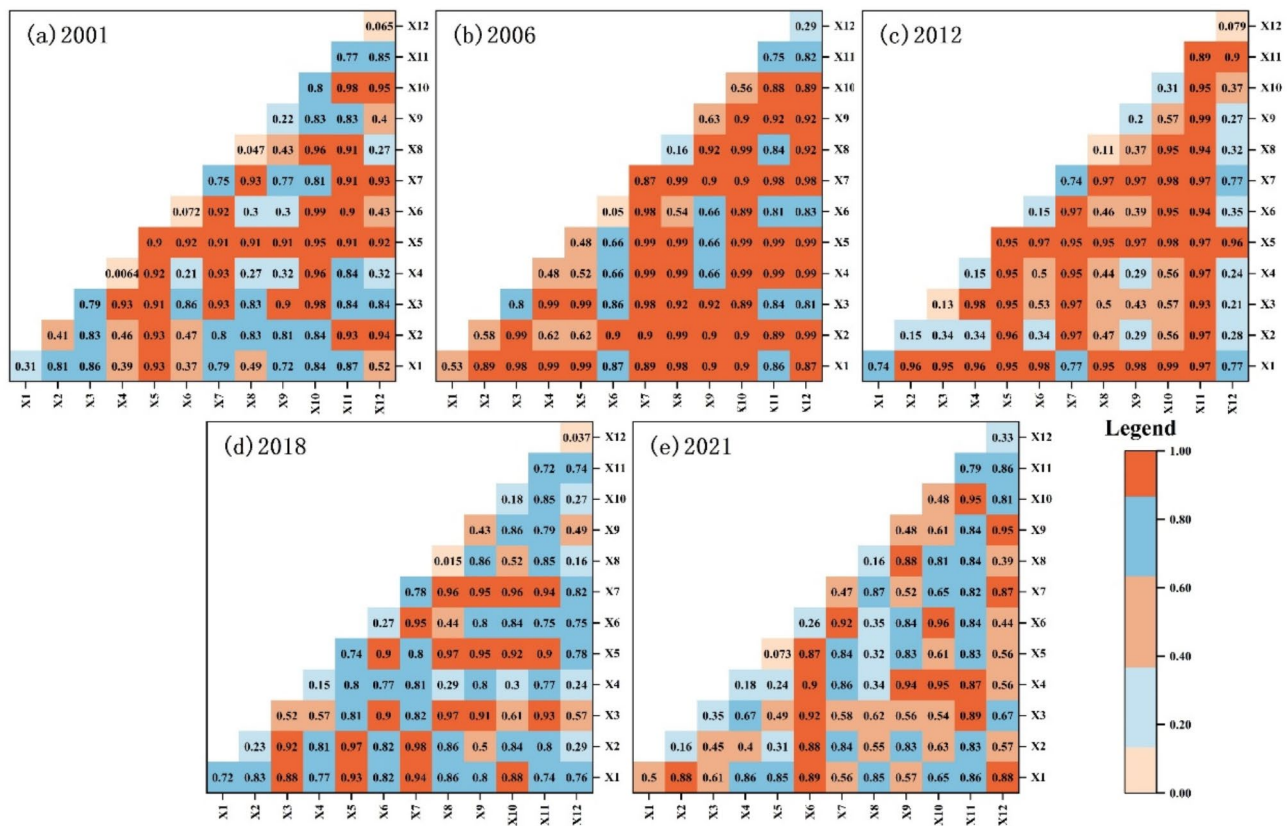


Fig. 8. Results of the interaction of factors influencing the quality of the human settlement environment.

X_{10} - X_{11} , and X_{10} - X_4 . In 2006, the combination factors that exhibited the greatest explanatory power were X_{12} - X_4 , X_{12} - X_5 , X_4 - X_3 , and X_5 - X_3 . In the case of 2012, the combination factors with significant explanatory power were X_{10} - X_1 , X_{11} - X_9 , X_{10} - X_7 , and X_6 - X_1 . In the year 2018, the combination factors with significant explanatory power were identified as X_7 - X_2 , X_8 - X_3 , X_8 - X_5 , and X_5 - X_2 . In 2021, the combination factors with the greatest explanatory power were identified as X_{10} - X_6 , X_{12} - X_9 , X_{10} - X_{11} , and X_{10} - X_4 . Among the two-by-two interaction factors for each period, the following showed interaction explanations greater than 0.990: X_4 - X_{12} (0.995), X_5 - X_{12} (0.995), X_4 - X_3 (0.994), X_5 - X_3 (0.994), and X_2 - X_3 (0.992). Moreover, the two-factor interactions significantly augmented the aforementioned interaction types. However, the individual explanatory power of these factors is relatively weak, indicating that the regional infrastructure, social development, quality of life of residents, and economic conditions they represent are indirect factors influencing the quality of the human environment in Xinjiang. It is therefore imperative that these factors continue to receive sustained attention if the sustainable development of the arid zone habitat is to be achieved.

Discussion and conclusions

Discussion

Human settlement environment sustainable development strategy options

The interconnectedness and synergistic development within the habitat system can be attributed to the interaction of various elements influencing the habitat system from different perspectives⁵². The population in arid regions is predominantly concentrated in oasis areas, where the ecological carrying capacity and ecological security of the oasis system represent significant factors influencing the region's overall livability⁵³. A slow rate of population growth has a detrimental impact on the availability of labour and market demand, which subsequently affects the disposable income and consumption levels of residents, thereby constraining regional economic development. It can thus be argued that the sustainable development of the regional habitat can be promoted by focusing on the following key areas: public services, industrial development, ecological protection and the well-being of the population.

- (1) Strengthening the active participation of multiple actors, including residents and the Government: It is recommended that the government implement measures designed to enhance residents' sense of ownership and involvement in the development process. It is recommended that priority be accorded to the maintenance and improvement of public infrastructure, with a particular focus on healthcare, education, and public safety. It is of the utmost importance to reinforce the social security service system, in addition to developing a comprehensive infrastructure that enables residents to access essential services within a "15-minute living area". This should include the expansion of commercial convenience services, the provi-

- sion of primary healthcare, and the guarantee of convenient access to essential services for all residents. It is of the utmost importance to enhance the accessibility and quality of social services on the Xinjiang.
- (2) Promoting the diversified development of industries in Xinjiang by giving full play to the advantages of latecomers: The industrial development model of the eastern region will be emulated, and the advantages of latecomers will be fully exploited. Local industries with advantages, such as coal, agriculture and animal husbandry, will undergo a transformation from sloppy development to high-quality development. It is essential to actively introduce both human capital and financial resources, diversifying industrial sectors through the innovative development of the digital economy. This will facilitate the acceleration of the development of new productive forces, enhancing the productivity and competitiveness of emerging science and technology industries, thereby promoting sustainable economic development.
 - (3) Strictly enforcing ecological regulation and promoting green development: It is of the utmost importance that the “double random, one open” supervision requirements are rigorously enforced and that comprehensive monitoring is conducted over the implementation of ecological environment laws. Furthermore, the implementation of rigorous ecological zoning and protection measures, the maintenance of natural landscapes and biodiversity, the assurance of the sharing of ecological dividends, and the establishment of ecological firewalls are of the utmost importance. The objective is to facilitate the advancement of recycled agriculture, enhance the efficiency of green spaces, preserve ecosystem stability, and guarantee a favourable ecological environment as the foundation for community well-being.
 - (4) Promoting the integration and development of projects for the benefit of the people and cultural heritage: The implementation of the people-benefit project is designed to foster social cohesion and harmony. The government has effectively promoted cultural embellishment in a tangible and sensible manner, strengthened the protection and utilisation of cultural relics and cultural heritage, integrated cultural and tourism resources to create cultural and creative industries, promoted the diversity and inclusiveness of cultural industries, and protected and inherited the rich cultural heritage of Xinjiang.

Spatial heterogeneity of human settlement environment

In this study, the distribution of the quality of the human settlement environment in Xinjiang was found to be in a cluster shape, with the geospatial proximity effect being more pronounced, forming a “gradient” with Urumqi City at the centre of the development characteristics of the decreasing gradient. Pang et al. utilised multi-source data to confirm that the overall development level of the human habitat in Xinjiang is low, with obvious spatial differentiation, showing a spatial differentiation pattern of local circling decreasing centred on the cities of Urumqi City and Changji⁵⁴. Yan et al. explored the quality of human habitats in 30 provinces and regions in China from a strong sustainability perspective, and revealed that differences in human habitats quality did not significantly change over time, but instead exhibited significant spatial clustering and distinct characteristics⁵⁵. This phenomenon can be attributed to an imbalance in economic development between the northern and southern regions, which has resulted in a widening of regional economic disparities. In order to address this issue, it is imperative to enhance the free movement of resources and elements, establish a dual-core multilateral integration that fosters economic supply and demand cycles, and overcome regional barriers. The overarching objective is to establish a synergistic regional development model and accelerate the emergence of new economic growth centres in Xinjiang. This transition will result in a shift from Xinjiang’s current passive reliance on external resources to a more active and self-sufficient stance. Moreover, the study proposes a multi-center synergistic development model to examine the evolution of human-environment interactions within complex systems. This model introduces novel perspectives to the research paradigm concerning the human settlement environment relationship.

The human habitat environment is of vital importance in supporting human life and development. However, the excessive exploitation of natural resources resulting from economic, social, and industrial growth, when considered alongside the constraints of fragile regional ecological environments, has had a significant impact and posed substantial challenges to the human habitat environment in Xinjiang. As a result, in arid and semi-arid regions, the constraints imposed by factors such as the geographic environment, living conditions, and economic status are particularly evident, thereby exacerbating the vulnerability of the habitat system. It is thus imperative to consider the specificities and constraints of the geographic environment, living conditions, and economic status in order to achieve the coordinated development of humans, nature, and society in the evolution of the regional habitat environment.

Interactive detection of human settlement environment impact factors

The term “human settlement environment” is defined as a complex system comprising the built environment, social and natural surroundings, and the supporting infrastructure. This study employs a multi-disciplinary approach, integrating a range of social, economic, ecological, cultural and related indicators, with the objective of investigating the influencing factors and interaction types within the habitat environment. This approach serves to enhance the research framework of the habitat environment at the meso-micro scale in arid regions. The analysis of the factors influencing the human habitat environment in Xinjiang demonstrates that the combined effect of any two factors is greater than the impact of a single factor on habitat quality. It is observed that there are synergistic effects, with two-factor enhancement and non-linear enhancement representing the primary interaction types. Although energy consumption per unit of GDP has a relatively minor direct impact on the quality of the human environment, its interaction with other factors significantly amplifies its overall effect in Xinjiang. Therefore, the disparate quality of human settlements in Xinjiang can be attributed to the cumulative interactions of multiple factors. In the context of the dynamic evolution of socio-economic and ecological environments, human settlement environment systems in arid zones have undergone significant changes. Local residents have frequently engaged in over-exploitation and inefficient resource use in pursuit of short-term

economic gains. This persistent “ecological plunder” has had a direct and indirect effect on the growth potential of secondary and tertiary industries, resulting in an ecological environment that cannot sustain long-term socio-economic development. This has, in turn, led to an exacerbation of ecological vulnerability. Consequently, a comprehensive analysis of the unique social structures, economic patterns, and ecological conditions in arid zones is essential to elucidate sustainable development pathways for regional human settlement environment under resource and environmental constraints.

Limitations and perspectives

Specific geographic regions, including arid zones, areas where agriculture and pastoralism overlap, and alpine regions, are prone to significant human-land conflicts. These conflicts impede the sustainable development of regional human-land systems and increase the vulnerability of the human-land environment⁵⁶. Arid regions, in particular, experience various disruptions from both natural ecosystems and human activities, adding complexity and vulnerability of the human settlement environment system. However, the current coupled human-earth system models do not account for the indirect impacts of human factors under the cascading effects of disruptions. Human activities are typically represented as external scenarios, which do not fully capture the dynamic processes of human-earth systems. The present study constructs an evaluation index system for assessing the quality of human habitats, based on the dimensions of “society, economy, ecology and culture”. Theories of polycentric governance and synergy form the basis of the polycentric synergistic development model that is proposed. An in-depth analysis of the spatial differentiation pattern and influence mechanism of the quality of human settlements in Xinjiang is conducted to promote the organic link between the theory of polycentric synergy and the governance of human settlements, with a view to solving the complex problem of assessing the quality of human settlements. Future research should aim to integrate diverse data from multiple sources, considering various perspectives, including economic, social, ecological, cultural, educational, medical, and more. Conducting horizontal and vertical comparisons at the village or meso-micro scale and exploring the spatial organisational structure of the human settlement environment are further recommendations. A detailed examination of the dynamic relationship between human activities and environmental changes is also necessary. Through the lens of interactive human-earth relationships, our focus will be on assessing the sustainable development potential of the human habitat. We will strive to enhance governance of the human habitat in arid regions, promote regional synergistic development, and provide theoretical support and scientific foundations for modelling the future trends of the human habitat in the area.

Conclusions

In this study, the enhanced TOPSIS model is employed for the evaluation of the quality of the human habitat across all 14 prefectural and municipal cities in Xinjiang. Furthermore, a cold hotspot analysis is conducted, and the spatial autocorrelation model is employed to analyse the *Moran's I* index and the clustering characteristics of spatial units with regard to the quality of the human settlement environment in Xinjiang. Furthermore, the geodetector model is utilised to ascertain the influencing factors of the human habitat and their interactions. The principal findings are as follows: (1) The quality of the human habitat in Xinjiang demonstrates a general upward trend, with minor fluctuations observed in all subsystems except for the population and cultural environment subsystem. (2) The distribution of the quality of the human settlement environment in Xinjiang was found to be in a cluster shape, with the geospatial proximity effect being more pronounced, forming a “gradient” with Urumqi City at the centre of the development characteristics of the decreasing gradient. (3) The spatial correlation of the quality of human settlements in Xinjiang was negative in 2001, 2006, 2012 and 2021, indicating significant spatial variations. However, in 2018, the spatial correlation became positive. Areas exhibiting significant spatial agglomeration display a relatively stable distribution pattern, with a discernible dependence effect. (4) Ecological security elements exert a dominant influence on the regional habitat. The interaction detection results indicate two-factor enhancement and non-linear enhancement, with no instances of independence, weakening, or opposition. The Xinjiang habitat can be characterised as a combined effect resulting from the interaction of multiple factors.

Data availability

The datasets used and analysed during the current study available from the corresponding author on reasonable request.

Received: 30 September 2024; Accepted: 11 March 2025

Published online: 13 May 2025

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Author contributions

Haijun Liu and Qingyuan Yang designed the study and wrote the manuscript. Beizi Chen, Lulu Zhou and Wenxin Wang put forward important opinions and suggestions on the manuscript. All authors participated in data collection and processing, contributed results and related discussions.

Funding

This research was supported by National Social Science Foundation West project (grant number 23XMZ068) and National Natural Science Foundation of China (grant number 42471290). We want to thank the editor and anonymous reviewers for their valuable comments and suggestions to this paper.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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