Study on the Spatiotemporal Coupling Coordination and Driving Factors of Habitat Quality and Urbanization along the Great Wall

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Abstract

The coordinated development of habitat quality and urbanization is an important issue for sustainable development and an inevitable requirement of Chinese modernization. Taking 97 cities (leagues) along the Great Wall from 2000 to 2020 as research units, this study systematically analyzes the spatiotemporal characteristics and driving mechanisms of the coupling coordination between habitat quality and urbanization using the InVEST model, the coupling coordination model, and the spatiotemporal geographically weighted regression model. The results show that: (1) From 2000 to 2020, the overall pattern of habitat quality along the Great Wall remained relatively stable, exhibiting a gradient spatial distribution with higher values in the east and lower values in the west. Urbanization showed a spatial pattern characterized by polarized leadership in urban agglomeration areas such as Beijing-Tianjin and Zhengzhou, alongside coordinated development across the entire region. (2) From 2000 to 2020, the coupling coordination degree between habitat quality and urbanization along the Great Wall showed a slow growth trend, but the overall level remained low, highlighting the structural contradiction between urbanization expansion and insufficient ecological supply. In some areas along the Great Wall, the relative development degree shifted from a type in which urbanization lagged behind habitat quality to a synchronous type and even an advanced type. (3) The coupling coordination between habitat quality and urbanization exhibited spatial differentiation characterized by higher values in the east and lower values in the west. The regional imbalance structure of "high-high clustering and low-low clustering" was significant, the phenomenon of "central collapse" gradually eased, and system evolution showed path dependence. (4) The driving process of the coupling coordination between habitat quality and urbanization is complex. Precipitation, economic development, scientific and technological innovation, and transportation density are key positive factors, and the effects of various factors on the coupling coordination relationship exhibit spatiotemporal heterogeneity. It is recommended that different regions establish dynamic assessment and early-warning mechanisms and formulate differentiated strategies for coordinated system development according to their resource endowments and development stages, thereby promoting harmonious coexistence between humans and nature along the Great Wall.

Full Text

Study on the Spatiotemporal Coupling Coordination and Driving Factors of Habitat Quality and Urbanization along the Great Wall

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Abstract: The coordinated development of habitat quality and urbanization is an important issue for sustainable development and is also an inevitable requirement of Chinese-style modernization. Taking 97 cities (leagues) along the Great Wall from 2000 to 2020 as the research units, this study applies methods including the InVEST model, the coupling coordination model, and spatiotemporal geographically weighted regression to systematically analyze the spatiotemporal characteristics and driving mechanisms of the coupling coordination between habitat quality and urbanization. The results show that: (1) From 2000 to 2020, the overall pattern of habitat quality along the Great Wall remained relatively stable, showing a stepped spatial distribution of high values in the east and low values in the west. Urbanization exhibited a spatial pattern in which urban agglomeration areas such as Beijing-Tianjin and Zhengzhou showed polarization and leading development, while the entire region developed jointly. (2) From 2000 to 2020, the coupling coordination degree between habitat quality and urbanization along the Great Wall showed a slow growth trend, but the overall level remained low, highlighting the structural contradiction between urbanization expansion and insufficient ecological supply. In some areas along the Great Wall, the relative development degree shifted from the type in which urbanization lagged behind habitat quality to a synchronous type and even to an advanced type. (3) The coupling coordination between habitat quality and urbanization showed spatial differentiation characterized by high values in the east and low values in the west; the regional imbalance structure of "high-high clustering and low-low clustering" was prominent, the phenomenon of "central collapse" gradually eased, and systematic evolution displayed path dependence. (4) The driving process of the coupling coordination between habitat quality and urbanization is complex. Precipitation, economic development, technological innovation, and traffic density are key positive factors. The influence of each factor on the coupling coordination relationship shows spatiotemporal heterogeneity. It is recommended that different regions, according to their resource endowments and development stages, establish dynamic assessment and early-warning systems and formulate differentiated systematic coordinated-development strategies, so as to promote harmonious coexistence between people and nature along the Great Wall.

Keywords: habitat quality; urbanization; coupling coordination; the Great Wall

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Promoting the coordinated development of urbanization and habitat quality is an inevitable path for practicing modernization characterized by harmonious coexistence between humanity and nature[1]. As an important linear cultural heritage in northern China, the Great Wall and its surrounding areas are not only core carriers of regional civilizational integration, but also ecologically fragile zones and transition belts of different ecological functions in China. They have complex geographical connotations and systemic functions, and regional habitats are highly sensitive to disturbances caused by urbanization. An in-depth analysis of the coupling coordination relationship between habitat quality and urbanization and its driving mechanisms can provide theoretical support for scientifically understanding the disturbances of human activities to the ecological environment along the Great Wall and their feedback mechanisms.

At present, research on habitat quality and urbanization in different disciplines shows a multi-track and progressive trend. Ecology focuses on the structure, functions, and dynamic evolution of habitat quality, analyzing species survival conditions and mechanisms of action[2]. Geography, by means of models such as PLUS, CA-Markov, and SLEUTH[3], reveals the spatiotemporal pattern differentiation and evolution trends of habitat quality from perspectives such as land use and ecological landscape[4]. Environmental science, with the atmosphere, water bodies, and soil as the core, analyzes the spatial diffusion of environmental pollution and the stress effects of accumulation on habitats[5]. Urbanization encompasses the multidimensional process of human activities. Studies have mostly constructed evaluation systems from dimensions such as population, economy, society, and space[6], carried out single-index or multi-index assessments, and explored urbanization development patterns, dynamic mechanisms, and urban–rural spatial imbalance[7]. Research on the relationship between habitat quality and urbanization, based on an interdisciplinary perspective, has adopted quantitative methods such as linear correlation analysis, geographical detectors, and geographically weighted regression to explore the unidirectional stress effect of the urbanization process on habitat quality or the supporting role of habitat quality for urbanization[8].

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Luo Yao et al.[9] used a geographic detector to analyze and found that population conditions, economic performance, land use, and public services are important factors influencing spatial differences in the coupling coordination between urbanization and habitat governance.

A review of the literature on habitat quality and urbanization shows that, in terms of research content, most studies separately analyze habitat quality, characteristics of urbanization development, and the unidirectional impacts of urbanization on habitat quality, while systematic studies of the coupling and coordination relationship between the two remain relatively rare. From a disciplinary perspective, research on the relationship between habitat quality and urbanization mainly comes from the perspectives of ecology and environmental science; quantitative analytical tools that follow the geographical research paradigm to systematically explore the spatiotemporal characteristics and driving mechanisms of the coupling coordination between habitat quality and urbanization are urgently needed. Studies of driving mechanisms mostly examine the influencing factors of habitat quality and changes in urbanization separately, and lack in-depth analysis of the driving logic of their coupling coordination from a systematic perspective. In terms of study areas, the regions along the Great Wall are transition zones between monsoon and non-monsoon regions, as well as boundary lines and integration belts between farming civilization and nomadic civilization. They have distinctive characteristics in nature, ecology, transportation, culture, and economy; research on the relationship between habitat quality and urbanization along the Great Wall still needs to be enriched.

The innovations of this study are as follows. In terms of research perspective, based on a systems-coupling perspective, habitat quality and urbanization are placed within the same research framework to deconstruct the mechanism of their coupling coordination, which helps provide a comprehensive understanding of their coordinated relationship. In terms of research content, grounded in the geographical research paradigm of "pattern-process-mechanism," this study comprehensively examines the spatiotemporal characteristics and driving mechanisms of the coupling coordination between habitat quality and urbanization, enriching the geographical research scope of habitat quality and urbanization. In terms of research methods, a geographically and temporally weighted regression (GTWR) model is introduced to reveal the influencing factors of differences in the coupling coordination between habitat quality and urbanization systems, thereby enriching quantitative analytical tools.

1 Data and Methods

1.1 Overview of the Study Area

As a giant linear structure with historical military defense, cultural-symbolic, and natural-geographical boundary functions, the Great Wall (Fig. 1) remains across multiple historical periods, including the Warring States, Qin, Han, Sui, Liao, Jin, and Ming dynasties. Spatially, it is distributed across 15 provinces (autonomous regions), including Liaoning Province, Hebei Province, and the Inner Mongolia Autonomous Region. Referring to relevant literature and comprehensively considering principles such as the historical evolution characteristics of the Great Wall, spatial adjacency, and the integrity of administrative divisions, 97 prefecture-level administrative districts along the Great Wall were selected as the research samples[10]. The geographical background along the

Fig. 1 Schematic diagram of the study area

Figure 1: Fig. 1 Schematic diagram of the study area

Great Wall is characterized by complexity and transitionality, including multiple typical ecological units such as the western ecologically fragile zone, the northern sand-control belt, the loess hilly and gully region, and the northern agro-pastoral ecotone. The areas along the Great Wall transition from temperate monsoon climate to temperate continental climate, and its course roughly overlaps with the 400 mm equal-precipitation line; two types of eco-economic belts, agricultural and pastoral, are interlaced and distributed here.

1.2 Construction of the Urbanization Indicator System

Urbanization has multidimensional and complex characteristics, including population concentration, economic development, and increases and decreases in construction land. This study constructs a comprehensive evaluation system for urbanization along the Great Wall from three dimensions: population urbanization, economic urbanization, and spatial urbanization (Table 1). Population urbanization refers to the process by which rural populations transfer to cities and towns and the degree of aggregation of urban populations, characterized by population density; economic urbanization is the level of comprehensive economic benefits in the urbanization process, measured by the density of regional gross domestic product; spatial urbanization refers to changes in the allocation of construction land in urban and rural space, measured by the proportion of urban construction land. Indicator weights are determined using the entropy weight method.

Note: The map was prepared based on the standard map with approval number GS(2024)0650 from the standard map service website of the Ministry of Natural Resources; the boundaries of the base map were not modified. The same below.

图 1 研究区示意图

Fig. 1 Schematic diagram of the study area

Table 1 Urbanization indicator system

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Target layer	Criterion layer	Indicator layer	Weight
Urbanization	Population urbanization	Population density	0.2440
Urbanization	Economic urbanization	Gross regional product density	0.5049

Target layer	Criterion layer	Indicator layer	Weight
Urbanization	Spatial urbanization	Proportion of urban construction land	0.2511

1.3 Data sources and processing

The land-use data for the Great Wall area were obtained from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn); precipitation data were obtained from the National Meteorological Science Data Sharing Service Platform (https://data.cma.cn); climate data such as $PM_{2.5}$ were obtained from the National Tibetan Plateau Scientific Data Center (https://data.tpdc.ac.cn); nighttime light data were obtained from the U.S. Defense Meteorological Satellite Program. The DMSP/OLS data for 2000–2013 and NPP-VIIRS data for 2012–2020 were corrected and mask-extracted to obtain nighttime light data for the Great Wall area. Construction-land data were obtained from the *China Urban Construction Statistical Yearbook*; statistical data such as industrial structure and patents were obtained from the *China City Statistical Yearbook*, the *China Land and Resources Statistical Yearbook*, population census reports, and provincial statistical yearbooks or socioeconomic development statistical bulletins of prefecture-level cities.

1.4 Research methods

1.4.1 Habitat quality evaluation model Using the Habitat Quality module in the InVEST model, and taking land-use data of the Great Wall area as the basis, land-use types that pose ecological threats were identified as threat factors. The maximum impact distance and weight of each threat factor were set (Table 2), as were the habitat suitability of each land type and its sensitivity to disturbance from threat factors [11–14] (Table 3), in order to evaluate habitat quality in the Great Wall area.

Table 2 Stress factors and their stress magnitude

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Stress factor	Maximum stress distance/km	Influence weight	Spatial decay type
Cultivated land	4	0.6	Linear decay
Urban land	8	1.0	Exponential decay

Stress factor	Maximum stress distance/km	Influence weight	Spatial decay type
Rural residential sites	6	0.6	Exponential decay
Industrial and transportation land	9	0.8	Exponential decay
Unused land	4	0.5	Linear decay

1.4.2 Coupling coordination degree model Based on the principle of physical coupling, a coupling coordination degree model between habitat quality and urbanization was constructed [15]. The equal-interval method was used to classify coupling coordination types into five levels: imminent imbalance (0.00–0.20), barely coordinated (0.20–0.40), low coordination (0.40–0.60), moderate coordination (0.60–0.80), and high coordination (0.80–1.00).

Table 3 Habitat suitability and sensitivity of different land-use types

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Land-use type	Habitat suitability	Cultivated land	Urban land	Rural residential sites	Industrial and transportation land	Unused land
Paddy field	0.3	0.0	0.8	0.5	0.6	0.3
Dry land	0.5	0.0	0.8	0.5	0.7	0.4
Forested land	1.0	0.6	0.9	0.8	0.8	0.4
Shrubland	0.9	0.6	0.7	0.7	0.6	0.5
Sparse woodland	0.8	0.7	0.9	0.8	0.8	0.5
Other woodland	0.7	0.7	0.8	0.8	0.7	0.5
High-coverage grassland	0.9	0.6	0.7	0.6	0.6	0.7

Land-use type	Habitat suitability	Cultivated land	Urban land	Rural residential sites	Industrial and transportation land	Unused land
Medium-coverage grassland	0.8	0.7	0.8	0.7	0.7	0.7
Low-coverage grassland	0.7	0.7	0.8	0.8	0.7	0.7
River and canal	0.9	0.6	0.7	0.7	0.8	0.4
Lake	0.9	0.6	0.8	0.6	0.7	0.4
Reservoir/pond	0.8	0.5	0.8	0.7	0.7	0.4
Permanent glacier and snow	0.1	0.1	0.0	0.1	0.2	0.1
Beach	0.5	0.5	0.5	0.4	0.6	0.3
Wetland	0.5	0.5	0.5	0.4	0.6	0.3
Urban land	0.0	0.0	0.0	0.0	0.0	0.0
Rural residential sites	0.0	0.0	0.0	0.0	0.0	0.0
Industrial and transportation land	0.0	0.0	0.0	0.0	0.0	0.0
Sandy land	0.2	0.2	0.2	0.2	0.2	0.0
Gobi	0.1	0.1	0.1	0.1	0.1	0.0
Saline-alkali land	0.2	0.2	0.2	0.2	0.3	0.0
Marshland	0.2	0.2	0.3	0.3	0.3	0.0
Bare land	0.2	0.1	0.4	0.4	0.5	0.0

Land-use type	Habitat suitability	Cultivated land	Urban land	Rural residential sites	Industrial and transportation land	Unused land
Bare rocky gravel land	0.1	0.0	0.1	0.2	0.2	0.0
Other	0.1	0.1	0.1	0.1	0.1	0.0

1.4.3 Spatial variogram Based on the theory of regionalized variables in geostatistics, the spatial variogram function analyzes the structural, random, correlational, and spatial pattern variation characteristics of spatially distributed data [16]. The kriging spatial interpolation method was used to infer and estimate the spatial data of the coupling coordination degree between habitat quality and urbanization in the Great Wall area.

1.4.4 Geographically and temporally weighted regression model Based on the spatiotemporal non-stationarity integration function of the GTWR model [17], this study constructed a distance spatial matrix and adopted an adaptive bandwidth to conduct a spatiotemporal dynamic analysis of the driving mechanism of the coupling coordination between habitat quality and urbanization in the Great Wall area.

2 Results and analysis

2.1 Evolutionary characteristics of habitat quality and urbanization

Taking 2000, 2005, 2010, 2015, and 2020 as time sections, and based on the comprehensive urbanization evaluation indicator system and the InVEST model

…the model calculation was used to obtain the evolutionary characteristics of habitat quality and urbanization along the Great Wall (Fig. 2).

(1) From 2000 to 2020, the overall pattern of habitat quality along the Great Wall remained relatively stable, but spatial differences within the region were pronounced, showing an east–west gradient with high values in the east and low values in the west. In the western section of the Great Wall, there are extensive deserts and grasslands; the ecosystem structure is relatively simple, dominated by low and relatively low habitat quality. Typical areas are distributed in the Tarim Basin, the Qaidam Basin, the Alxa Plateau, and the Badain Jaran Desert. Relatively high-value and high-value areas in the east are mainly distributed in mountainous forest land and grassland, covering areas such as the Daxing' anling Mountains, Changbai Mountains, and Taihang Mountains. Because of high-intensity

development in the urban clusters of the North China Plain and the Northeast Plain, the patches show a fragmented trend.

(2) Urbanization has formed a spatial pattern of "polarized leadership and common development." Urban-cluster areas such as Beijing–Tianjin, Zhengzhou, and the Shandong Peninsula are high-level urbanization agglomeration areas. With high population density, favorable locational conditions, and well-developed infrastructure, regional growth poles have been continuously strengthened. Although the development level of the central and western regions is not high, it also shows an overall upward trend.

2.2 Spatiotemporal characteristics of coupled coordination between habitat quality and urbanization

2.2.1 Temporal characteristics of coupled coordination degree

As can be seen from Fig. 3, from 2000 to 2020 the coupled coordination degree between habitat quality and urbanization steadily increased, rising from 0.396 to 0.453. This indicates that, under the coordinated advancement of ecological protection and restoration projects and urbanization strategies along the Great Wall, the coordination relationship between the ecological-environmental system and the urban-development system has gradually strengthened. Although the trend of change was positive, the level of coupled coordination remained low. In terms of the coordination-degree hierarchy, cities at the two ends—on the verge of imbalance and highly coordinated—accounted for relatively small proportions, whereas cities at the intermediate levels of barely coordinated and low coordination dominated, showing a typical spindle-shaped distribution. Further analysis reveals that the rapid advance of urbanization and the lagging supply capacity of ecosystem services have produced functional mismatches between systems, constraining the improvement of overall coordination.

2.2.2 Spatial distribution characteristics of coupled coordination degree

From 2000 to 2020, the coupled coordination degree between habitat quality and urbanization along the Great Wall showed an east-high, west-low distribution. In the eastern region, a high-level coordinated agglomeration area formed in Beijing–Tianjin–Shandong Peninsula, where urbanization development and ecological protection achieved positive interaction. In the arid northwest, low-level agglomeration formed, where the fragile ecological environment and the urbanization process constrained each other. During the study period, habitat quality and the coupled coordination degree of urbanization along the Great Wall exhibited obvious spatial diffusion characteristics (Fig. 4). Relying on the capital's advantages in resource concentration and its forward-looking ecological-construction layout, Beijing occupied an obviously leading position in the coupled coordination level of habitat quality and urbanization; it radiated and drove

Fig. 3 Coupling coordination development process of urbanization and habitat quality along the Great Wall from 2000 to 2020

Figure 2: Fig. 3 Coupling coordination development process of urbanization and habitat quality along the Great Wall from 2000 to 2020

the expansion of moderately coordinated areas, and the spatial spillover effect of regional coordination level was evident. The areas on the verge of imbalance in the west shrank into scattered distributions in Jiuquan City, Hami City, and the Kizilsu Kirgiz Autonomous Prefecture. The gradient differences in coupled coordination degree among regions showed a converging trend, indicating that the spatial balance of human-land relations along the Great Wall had been strengthened.

Based on the relative development degree model[^18], the 2000-2020 Long ···

(a) Habitat quality in 2000

(b) Habitat quality in 2010

(c) Habitat quality in 2020

(d) Urbanization in 2000

(e) Urbanization in 2010

(f) Urbanization in 2020

Legend —National boundary —- Undetermined national boundary —Provincial boundary —Municipal boundary

Habitat quality index: low habitat quality; relatively low habitat quality; medium habitat quality; relatively high habitat quality; high habitat quality

Urbanization level: 0.00-0.05; 0.05-0.15; 0.15-0.25; 0.25-0.35; >0.35

Fig. 2 Spatial dynamics of habitat quality and urbanization along the Great Wall from 2000 to 2020

Fig. 3 Coupling coordination development process of urbanization and habitat quality along the Great Wall from 2000 to 2020

The relative development degree of habitat quality and urbanization along the Great Wall (Fig. 5) was divided into three types: the habitat-quality lagging behind urbanization type, the synchronous urbanization-habitat quality type, and the habitat-quality lagging ahead of urbanization type. The results show that in 2000, the relative development degree of most cities along the Great Wall was in the stage in which habitat quality lagged behind urbanization. The synergistic linkage between the two major systems of the urbanization process and habitat-quality conservation was relatively weak; the cross-system flow efficiency of various key elements was low; and some regions still had problems such as overlapping functional allocation or mismatch between supply and demand, constraining the enhancement of regional sustainable development capacity. By 2020, the North China Plain showed an obvious characteristic in which urbanization lagged ahead of habitat quality, while some areas in the central and western parts had shifted to a stage of synchronous development between urbanization and habitat quality.

2.2.3 Spatial heterogeneity trend of coupling coordination

The coupling coordination degree values of cities (leagues) along the Great Wall were assigned to geometric center points for spatial variogram analysis. The results show (Table 4) that the optimal fitted step length was 165.39 km; the optimal model in 2020 was the spherical model, while the Gaussian model was optimal for all other years. The coefficients of determination of the fitted models in all periods were greater than 0.84, indicating good model fit. The coordination relationship between habitat quality and urbanization had significant spatial self-organizing characteristics. Under a given step length, coordination continued to increase with increasing distance, indicating that the spatial influence range of urbanization and habitat-quality-system coupling coordination along the Great Wall continued to expand. Both the nugget value and the sill value showed declining trends, indicating that the degree of spatial variation in coordination level weakened. Although the nugget coefficient declined slightly, it remained greater than 0.80 throughout, showing that the spatial variation in coupling coordination degree was dominated by random factors and that spatial heterogeneity was strong.

According to the spatial interpolation results (Fig. 6), the coordination degree between habitat quality and urbanization systems along the Great Wall as a whole presented a gradient distribution pattern of higher values in the east and lower values in the west, with peak values undergoing an evolutionary process of first increasing and then decreasing. From 2000 to 2010, spatial clusters of high coordination levels were distributed in the southeastern plains, while low-value clusters were mainly in northwestern regions such as the Xinjiang Uygur Autonomous Region and Gansu Province. By 2015, the coordination level between habitat quality and urbanization decreased stepwise toward the northwest, forming a continuous low-value belt, and spatial gradient differences were alleviated to some extent. In 2020, the clustering effect of high-value areas in the east continued to strengthen, while low-value areas in the west remained concentrated; however, their coverage tended to shrink, showing a certain path dependence.

Fig. 4 Spatial evolution process of coupling coordination degree of urbanization and habitat quality along the Great Wall from 2000 to 2020

Figure 3: Fig. 4 Spatial evolution process of coupling coordination degree of urbanization and habitat quality along the Great Wall from 2000 to 2020

2.3 Analysis of driving factors of spatial differences in coupling coordination between habitat quality and urbanization

2.3.1 Selection of driving factors

To analyze the driving mechanism of the coupling coordination level between habitat quality and urbanization along the Great Wall, explanatory variables were selected—

Fig. 4 Spatial evolution process of coupling coordination degree of urbanization and habitat quality along the Great Wall from 2000 to 2020

(a) 2000 (b) 2005 (c) 2010

(b) 2015 (e) 2020

Legend:
National boundary; Undetermined national boundary; Provincial boundary; City boundary.
Relative development stage: Lagging stage; Synchronous stage; Leading stage.

Fig. 5 Spatial distributions of relative development type of urbanization and habitat quality along the Great Wall from 2000 to 2020

Table 4 Spatial semi-variogram fitting parameters along the Great Wall

Year	Range	Nugget	Sill	Nugget coefficient	Fitting model	Coefficient of determination	Residual
2000	3966	0.0232	0.2134	0.891	Gaussian model	0.904	1.08×10^{-3}
2005	4195	0.0200	0.1660	0.892	Gaussian model	0.888	8.19×10^{-4}
2010	3135	0.0200	0.1350	0.852	Gaussian model	0.896	8.56×10^{-4}
2015	7110	0.0181	0.1133	0.840	Gaussian model	0.892	4.47×10^{-4}
2020	7110	0.0105	0.0774	0.864	Spherical model	0.864	3.19×10^{-4}

(a) 2000 (b) 2005 (c) 2010

(b) 2015 (c) 2020

Axes: Longitude / °E; Latitude / °N; Kriging value.

Fig. 6 Spatial variogram Kriging interpolation evolution from 2000 to 2020

···variables, and variance inflation factor (VIF) diagnosis was adopted to avoid multicollinearity problems[^19]. All VIF values were less than 4, indicating that the model had no collinearity or redundant explanatory variables. As the core parameter of the natural environmental background, precipitation directly affects vegetation productivity and biodiversity[^11]; annual mean precipitation was selected as the quantitative indicator of the natural environmental background. Air quality is an important representation of the human settlement environment and the foundation for high-quality population urbanization[^12]; annual mean $PM_{2.5}$ concentration was selected as an indicator measuring ecological-environmental pressure. Economic development is a dynamic process of regional industrial-structure upgrading and improvement in factor-allocation efficiency[^13]; the study selected nighttime light average-intensity data as the quantitative representation of the intensity and level of economic activity. Industrial structure reflects the way humans develop and transform nature; the ratio of the added value of the tertiary industry to that of the secondary industry was used to explore the driving effect of industrial structure on system coordination. Scientific and technological innovation is the core driving force for overall coordinated development[^14], and can provide advanced technical means and solutions for ecological protection and urbanization construction. Drawing on the results of Chen Guifu et al.[^20], weighted patent data were used to measure the level of regional innovation development; that is, the weighted sum of the numbers of inventions, utility models, and designs obtained in that year, with weights of 0.5, 0.3, and 0.2, respectively. Human-capital stock provides intellectual support for coordinated development[^21]; average years of education were selected to measure human-capital stock. Traffic density promotes the flow of population and economic factors across different spaces and builds bridges of communication between regions[^22], but it is also a natural ecological barrier; road density was adopted as the measurement indicator. Government regulation plays a controlling role in coordinated development[^23]; the proportion of fiscal expenditure was selected as the proxy variable for policy intervention intensity.

2.3.2 Model testing and setting

(1) Spatial autocorrelation test

The global Moran' s I values for the coupling coordination between habitat quality and urbanization ranged from 0.380 to 0.480, with $Z > 0$, and all passed the 1% significance test (Table 5). This indicates significant positive spatial correlation. The coordinated evolution of the Great Wall Belt system is influenced by spatial association effects in neighboring regions. According to the LISA cluster maps (Fig. 7), high-high cluster areas are mainly distributed in the North China Plain, whereas low-low cluster areas are distributed in the west, showing relatively strong spatial stickiness. The time-series data show that in 2020 the global Moran' s I value decreased to 0.380, and the Z value also decreased but remained greater than 2.58, indicating that the spatial dependence of coupling coordination between habitat quality and urbanization tended to weaken, and the spatial network relationship of coordination changed. Therefore, analysis from a spatial perspective is more consistent with reality.

Table 5 Global Moran' s Index

Tab. 5 Global Moran' s I

Year	Global Moran' s I	Z statistic	P value
2000	0.456	11.280	0.000
2005	0.480	11.798	0.000
2010	0.452	11.138	0.000
2015	0.422	10.414	0.000
2020	0.380	9.424	0.000

(2) Spatial econometric test

A spatial Durbin model (SDM) was used to verify whether the influencing factors have spatial effects[^24], in order to test the robustness of the GTWR model estimation results. The regression results and the decomposition of direct, indirect, and total effects all demonstrate that there are certain spatial effects among the explanatory variables affecting coordination (Table 6). The goodness of fit (R^2) of the SDM is 0.324, and all explanatory variables are significant at different confidence levels. Specifically, precipitation, economic development, industrial structure, scientific and technological innovation, and human-capital stock all show significant positive effects on the coupling coordination between habitat quality and urbanization, whereas the direct effects of air quality, traffic density, and government regulation are significant···

Fig. 7 LISA cluster for coupling coordination from 2000 to 2020

Subfigures: (a) 2000; (b) 2005; (c) 2010; (d) 2015; (e) 2020.

Legend: national boundary; undetermined national boundary; provincial boundary; municipal boundary. Local spatial association types: not significant; low-low cluster; low-high cluster; high-low cluster; high-high cluster.

Table 6 Regression results of the SDM

Tab. 6 Regression results of the spatial Durbin model

Variable	Main effect	Direct effect	Indirect effect	Total effect
Precipitation	0.0158^{**}	0.0166^{**}	-0.0203	-0.0037
	(0.0072)	(0.0078)	(0.0182)	(0.0123)
Air quality	-0.0345^{*}	-0.0364^{**}	0.1515^{***}	0.1151^{***}
	(0.0182)	(0.0184)	(0.0509)	(0.0401)
Economic development	0.0064^{***}	0.0066^{***}	-0.0089^{***}	-0.0024
	(0.0007)	(0.0007)	(0.0022)	(0.0020)
Industrial structure	0.0084^{***}	0.0090^{***}	-0.0241^{*}	-0.0151
	(0.0026)	(0.0026)	(0.0143)	(0.0141)
Technological innovation	0.4914^{***}	0.5078^{***}	-0.7723	-0.2645
	(0.1362)	(0.1350)	(0.5611)	(0.5525)
Human capital stock	0.0134^{***}	0.0133^{***}	0.0144	0.0278
	(0.0050)	(0.0051)	(0.0209)	(0.0196)
Traffic density	-0.0126^{*}	-0.0131^{*}	0.0219	0.0088
	(0.0069)	(0.0069)	(0.0182)	(0.0150)
Government regulation	-0.0102^{*}	-0.0096^{*}	-0.0247	-0.0343
	(0.0053)	(0.0056)	(0.0250)	(0.0251)
Spatial autoregressive coefficient	-0.8542^{***}	–	–	–
	(0.3102)			
Log-likelihood	1307.4709	–	–	–
Sample size	485	–	–	–

Note: , , ***and*** indicate significance at the 10%, 5%, and 1% levels, respectively; values in parentheses are standard errors.

is negative, which is generally consistent with the directions of action of the variables obtained from the GTWR model below. From the perspective of indirect effects, economic development and industrial structure show negative spatial spillover effects. A possible reason is that, among neighboring regions with homogenized industrial structures, resource elements and market demand tend to be similar; limited resources cluster in specific areas, generating rivalry and competition, or large cities exert negative impacts on surrounding areas through the "siphon effect." The spatial autoregressive coefficient is significantly negative at the 1% level, indicating that there is obvious spatial dependence between habitat quality and urbanization coordination along the Great Wall, which is consistent with the global Moran' s I results above, but the spatial diffusion effect is slightly enhanced.

(3) Model goodness-of-fit test

Ordinary least squares (OLS), temporally weighted regression (TWR), geographically weighted regression (GWR), and the GTWR model were compared and tested. The results show (Table 7) that the residual sum of squares and regression standard error of the GTWR model are the smallest, indicating that its fitting error is significantly lower than that of the other models. After adjustment, the GTWR model has an R^2 of 0.7398, and the Akaike information criterion is -1251.58, indicating that this model has the best explanatory power and is more robust. Therefore, choosing the GTWR model can more accurately reveal the spatiotemporal differentiation characteristics of the mechanism by which habitat quality and urbanization coupling coordination are influenced.

2.3.3 Analysis of coupling-coordination driving factors Based on the GTWR model, the driving mechanisms of the coupling-coordination relationship between habitat quality and urbanization were analyzed through box plots (Fig. 8), and the effects of driving factors were classified into five grades by the natural breaks method to analyze their spatial heterogeneity characteristics (Fig. 9).

(1) Precipitation has a significant positive promoting effect on the coupling coordination between habitat quality and urbanization along the Great Wall (Fig. 8a), but the mean regression coefficient gradually decreases, indicating that the intensity of climate change' s effect on coordinated development is weakening. In the process of urbanization, hydraulic engineering gradually plays a regulatory role in water resources, and the influence of natural precipitation on the coordinated development of the system is relatively reduced. Spatially (Fig. 9a), precipitation has a positive impact on both habitat quality and urbanization coordination along the Great Wall. High-value areas are mainly concentrated in typical grassland areas, mountain forest areas, and western desert areas, whereas the impact is relatively weak in the central desert-steppe and desert areas. This indicates that the sensitivity of the coordination between habitat quality and urbanization to precipitation differs significantly in space. Especially in arid areas with poor ecological background conditions, extremely strong precipitation may lead to the degradation of species originally adapted to arid climates, thereby causing problems such as soil loss and land degradation. Increased intensity and frequency of heavy precipitation may also increase the risk of urban flooding, threatening infrastructure and residents' production and life[25].

Table 7 Model selection and testing

Tab. 7 Model selection and testing

Model parameter	OLS	TWR	GWR	GTWR
Bandwidth	-	0.3284	0.2513	0.2209

Fig. 8 Temporal evolution trend of regression coefficients of driving factors along the Great Wall from 2000 to 2020

Figure 4: Fig. 8 Temporal evolution trend of regression coefficients of driving factors along the Great Wall from 2000 to 2020

Model parameter	OLS	TWR	GWR	GTWR
Residual sum of squares	–	2.0048	2.0251	1.7930
Regression standard error	–	0.0643	0.0646	0.0608
Akaike information criterion	−1214.45	−1241.44	−1230.25	−1251.58
R^2	0.6800	0.7138	0.7109	0.7441
Adjusted R^2	–	0.7090	0.7061	0.7398

Note: OLS is ordinary least squares; TWR is temporally weighted regression; GWR is geographically weighted regression; GTWR is geographically and temporally weighted regression; R^2 is goodness of fit.

(2) Economic development has a positive driving effect on the coupling coordination between habitat quality and urbanization along the Great Wall, but the marginal effect shows a decreasing trend (Figs. 8c, 9c). The regression coefficients in the central and western regions are significantly higher than those in the eastern region, indicating that the promoting effect of economic development on the coordinated development of habitat quality and urbanization is stronger in less-developed regions, showing a "catch-up" effect.

Legend: 25%–75%; range within 1.5IQR; median line; mean; median.

(a) Precipitation

(b) Air quality

(c) Economic development

(d) Industrial structure

(e) Scientific and technological innovation

(f) Human-resource stock

(g) Transportation density

(h) Government regulation

Note: 1.5IQR indicates outliers within 1.5 times the interquartile range.

Fig. 8 Temporal evolution trend of regression coefficients of driving factors along the Great Wall from 2000 to 2020

The reason is that, in the early stage of the study period, the central and western sections along the Great Wall were dominated by traditional agriculture. Their locational disadvantages led to insufficient market accessibility, and excessive resource exploitation caused deterioration of the fragile ecological environment. The lag in economic development further weakened ecological-environment governance capacity, forming a development predicament in which the economy and the environment constrained each other. However, with the sustained advancement of urbanization, the state strengthened policy support for the western region, continuously improved infrastructure construction, and raised resource-allocation efficiency[^26]. The steady improvement of the level of economic development gradually alleviated the contradiction between ecological and economic development, exerting a positive driving effect on the coupled coordination between habitat quality and urbanization.

(3) The influence of scientific and technological innovation on the coupled coordination between habitat quality and urbanization along the Great Wall shows a V-shaped evolutionary pattern (Fig. 8e). From 2000 to 2010, the regression coefficient of scientific and technological innovation was positive but showed a decreasing trend, indicating that technological development promoted the coupled coordination of habitat quality and urbanization; however, the negative ecological externalities generated by urbanization may have offset part of the improvement in urbanization quality and ecological-environment amelioration brought about by scientific and technological innovation. After 2015, its positive influence gradually strengthened, and the regional development model shifted from factor-accumulation and capital-driven modes toward an innovation-driven mode. Empowering ecological-governance technological iteration through scientific and technological innovation effectively improved the restoration capacity of regional habitat quality, and the positive regulatory effect on the coordinated development of the human–land system was significantly enhanced. The spatial pattern shows (Fig. 9e) that, in the central-western and northeastern parts of the Great Wall region, scientific and technological innovation has a positive promoting effect on system coupled coordination. Scientific and technological innovation can promote industrial transformation, improve resource-use efficiency, reduce the ecological-environmental sensitivity of resource demand in ecologically fragile areas, and mitigate ecological-environment constraint effects. In ad-

dition, scientific and technological innovation can also promote the deep integration of industrial ecologization and ecological industrialization[^27], thereby promoting the coordinated development of habitat quality and urbanization.

(4) The influence of transportation density on the coupled coordination relationship between habitat quality and urbanization along the Great Wall is mainly positive (Fig. 8g). In the eastern section along the Great Wall, the transportation network system is highly matched with the population and economic distribution, promoting the flow of production factors, optimizing spatial functions, improving resource-allocation efficiency, and, to a certain extent, reducing the disorderly occupation of ecological resources, thereby realizing spatial compatibility between development and protection. In the western region, transportation infrastructure construction and ecological protection and restoration projects have been implemented simultaneously, promoting the development of emerging industries such as ecotourism and the digital economy, and realizing a virtuous cycle of protection amid development and development amid protection[^28]. The western parts of Gansu Province and Shaanxi Province, as well as the western part of Inner Mongolia Autonomous Region, have benefited markedly from the large-scale construction of transportation facilities in China (Fig. 9g). The promoting effect of transportation density on the coordinated development of the habitat-quality and urbanization systems is significant, showing a certain latecomer advantage.

(a) Precipitation

(b) Air quality

(c) Economic development

(d) Industrial structure

(e) Scientific and technological innovation

(f) Human capital stock

(g) Transportation density

(h) Government regulation

Legend: national boundary; undetermined national boundary; provincial boundary; municipal boundary.
Regression coefficient.

For panel (a): 0.2246–0.2291; 0.2292–0.2321; 0.2322–0.2345; 0.2346–0.2414; 0.2415–0.2741.
For panel (b): −0.0525–−0.0260; −0.0259–−0.0040; −0.0039–0.0016; 0.0017–

0.0075; 0.0076–0.0137.
For panel (c): 0.3073–0.3241; 0.3242–0.3491; 0.3492–0.3702; 0.3703–0.3916; 0.3917–0.4326.
For panel (d): −0.0132–0.0046; 0.0047–0.0177; 0.0178–0.0299; 0.0300–0.0483; 0.0484–0.0898.
For panel (e): −0.1350–−0.0879; −0.0878–0.0261; 0.0262–0.0567; 0.0568–0.0761; 0.0762–0.1043.
For panel (f): −0.0096–−0.0030; −0.0029–0.0073; 0.0074–0.0215; 0.0216–0.0428; 0.0429–0.1894.
For panel (g): 0.0742–0.0944; 0.0945–0.1067; 0.1068–0.1156; 0.1157–0.1293; 0.1294–0.1418.
For panel (h): −0.0999–−0.0648; −0.0647–−0.0185; −0.0184–0.0125; 0.0126–0.0442; 0.0443–0.1734.

Fig. 9 Spatial distributions of regression coefficients of driving factors of coupling coordination along the Great Wall from 2000 to 2020

3 Discussion

3.1 Mechanisms by which urbanization coerces and transforms habitat quality

From the perspective of geographical spatial interaction processes, urbanization exerts a systematic influence on habitat quality along the Great Wall through pathways such as land-use transformation, resource-consumption agglomeration, and changes in ecological connectivity (Fig. 10). This is mainly manifested in the following aspects. (1) The spatial restructuring effect of land-use transformation. The expansion of construction land not only directly encroaches on ecological land such as forestland, grassland, and wetlands along the Great Wall[^29], squeezing the rotational grazing space of traditional nomadic husbandry and the production space of dryland agriculture; at the same time, the gradual and uneven nature of regional policies causes some ecological buffer zones around the Great Wall to become functional marginal zones. Ecological supporting projects for the protection of Great Wall cultural heritage become mismatched, producing problems such as spatial separation and imbalance in spatial order. (2) The ecological coercion effect of resource consumption and environmental pollution. Against the inherently fragile natural environmental background along the Great Wall, population and economic activities agglomerate toward towns and cities. The extensive development model leads to the spatial concentration of resource consumption and pollution emissions, triggering compound ecological problems such as heavy-metal soil pollution and eutrophication of water bodies. Meanwhile, the scaled expansion of traditional agriculture and animal husbandry leads to grassland degradation and intensified soil erosion, forming a compound coercion of point-source pollution and non-point-source pollution. (3) The ecological connectivity barrier effect of infrastructure construction. According to ecological-corridor theory, the Great Wall, as a physical barrier superimposed with the spatial expansion of transportation networks and building clusters, intensifies the fragmentation of habitat patches; species migration is impeded, which may further lead to the degradation of local ecosystem service functions.

3.2 Constraint and feedback mechanisms of habitat quality on urbanization

The ecological environment along the Great Wall, through the service functions it provides to regional ecosystems, reshapes spatial attractiveness and influences industrial development by promoting or constraining it, thereby affecting urban spatial expansion, the flow of production factors, and the transformation of economic development models (Fig. 10). Specifically, this is manifested as follows. (1) Habitat quality is the ⋯

Fig. 10 Coupling coordination mechanism between habitat quality and urbanization

Main labels in the figure include: habitat degradation; habitat carrying; habitat restoration; habitat quality; ecosystem-service supply; spatial attraction regulation and control; industrial development upgrading; sustainable support; spatial regulation effect; industrial transformation and upgrading; coupling feedback; ecological-space restructuring; ecological coercion effect; ecological barrier effect; mutually complementary, mutually reinforcing, and mutually coercive; land-use transition; resource consumption agglomeration; infrastructure construction; urbanization; population urbanization; economic urbanization; spatial urbanization; coordinated development; resource supply and threshold management; and provision of funds and technical support.

The illustrative contents include: "provide ecological services, build ecological barriers ⋯⋯" ; "attract high-end talent and innovation factors to agglomerate ⋯⋯" ; "reverse the transformation of traditional industries and activate the inheritance of cultural heritage ⋯⋯" ; "expansion of construction land, failure of ecological protection projects, reduction of biological habitat area ⋯⋯" ; "resource-space pressure, concentrated and extensive development model, expansion of traditional agriculture and animal husbandry models ⋯⋯" ; and "spatial expansion of transportation networks, building clusters, and other artificial facilities ⋯⋯" .

镇 economic, social, and cultural development provides sustainable support. The ecological environmental carrying capacity of a region determines the foundation and potential of urban-system development. Good habitat quality can reduce the risk of encroachment on Great Wall cultural heritage and lower protection costs, whereas habitat degradation weakens the stability of urban production and living activities. For example, the ecological barrier of the Three-North Shelterbelt has laid a foundation for the revitalization and utilization of Great Wall cultural heritage. (2) Habitat quality has a regulatory effect on regional spatial patterns. Good habitat quality and distinctive Great Wall cultural landscapes jointly constitute the core attraction for regional development, promoting the agglomeration of innovative factors such as high-end talent, high-tech enterprises, and venture capital[30], and facilitating the evolution of industrial spatial patterns. For example, Hohhot gives full play to its advantages in ecology, green electricity, and computing power, promoting clustered development across the whole chain of "computing–electricity coordination." (3) Habitat quality constrains and guides industrial transformation and upgrading. Ecological endowments and environmental capacity, as rigid constraints on the selection and development of urban industries, can force the transformation of industrial structures, promote the shift of traditional agriculture and animal husbandry toward organic agriculture and circular agriculture, and drive resource-based industries toward green and low-carbon transformation. Habitat quality can also serve as an important asset for the revitalization and utilization of Great Wall culture, promoting the coordinated development of cultural tourism and other industries with ecological environmental protection, and realizing the transformation of the urban industrial system from outward expansion to endogenous improvement.

4 Conclusions and Countermeasures

4.1 Conclusions

(1) From 2000 to 2020, the overall spatial pattern of habitat quality along the Great Wall remained relatively stable, but internal regional spatial differentiation was evident, showing an "east-high, west-low" gradient distribution. Urbanization showed a spatial pattern of "polarized leadership and common development" ; urban agglomeration areas such as Beijing-Tianjin, Zhengzhou, and the Shandong Peninsula were the main regions where high urbanization levels were concentrated.

(2) From 2000 to 2020, the coupling coordination relationship between habitat quality and urbanization along the Great Wall continuously strengthened, and the coupling coordination degree increased from 0.396 to 0.453. However, the overall coordination level remained low; most cities were in a state of barely coordinated or low-level coordination, and structural contradictions between rapid urbanization and ecological-system carrying capacity still existed. The evolution of the coupling coordination relationship between habitat quality and urbanization had significant path-dependence characteristics, and inertia intensity showed a decreasing trend over time.

(3) The coupling coordination degree between habitat quality and urbanization along the Great Wall presented a distribution pattern of high in the east and low in the west: the eastern region formed a high-level coordinated agglomeration area in Beijing–Tianjin–Shandong Peninsula, where urbanization development and ecological protection achieved benign interaction; the northwest arid region formed "low–low agglomeration,"

where the fragile ecological environment and the urbanization process constrained each other. The phenomenon of "central depression" has gradually been alleviated, while the western region mostly showed gentle spatial characteristics. In the early study period, urbanization development in most cities along the Great Wall lagged behind habitat quality; by the end of the study period, the North China Plain showed obvious characteristics in which urbanization was ahead of habitat quality.

(4) The interaction process between habitat quality and urbanization is jointly influenced by internal characteristics and external driving factors, presenting dynamic and nonlinear features. Among them, precipitation, economic development, scientific and technological innovation, and traffic density are key positive factors for the coordinated development of habitat quality and urbanization. Because the factors have spatiotemporal heterogeneity, their direction and intensity of effect on the coupling coordination between habitat quality and urbanization in different regions and at different periods are also different.

strengths differ.

4.2 Policy Recommendations

Based on the findings of this study, it is recommended that spatially adaptive strategies be implemented to promote ecological security and high-quality urbanization along the Great Wall. These mainly include: (1) building a cross-regional and cross-departmental "Digital Great Wall" platform for sharing ecological resources and economic data. Integrate information such as the regional ecological background, resource data, and engineering benefits, and implement precise management and control by segment, category, and grade. In cultural core areas and highly ecologically sensitive areas, strictly implement a negative-list system for urban development, and guide the orderly withdrawal or transformation of population and industries; in ecological restoration areas, promote nature-based solutions for ecological restoration and enhance ecological resilience; in urban development areas, strictly define growth boundaries, and improve construction density and land-use efficiency within towns through internal potential tapping. (2) Combine the cultural brand value of the Great Wall with its unique ecological resources, cultivate green economic growth poles with regional characteristics, tap the cultural connotations of local agricultural products, integrate business forms such as study tours, outdoor exploration, and digital cultural museums, and link characteristic agriculture and animal husbandry along the route to develop high-end business forms such as ecological health and wellness, nature education, and heritage study tours; strengthen infrastructure construction such as transportation, so as to use economic development to promote the coordinated development of habitat quality and urbanization. In addition, strengthen overall coordination among areas along the Great Wall, give full play to the radiating and driving role of advantaged areas, and promote the formation of a regional high-quality development pattern featuring complementary advantages.

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Spatiotemporal coupling coordination and driving factors of habitat quality and urbanization along the Great Wall

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Abstract: The coordinated development of urbanization and habitat quality is crucial for sustainable development, representing a core requirement for Chinese-style modernization. Focusing on 97 cities along the Great Wall from 2000 to 2020, this study integrates the InVEST model, coupling coordination model, and a spatiotemporal geographically weighted regression model to systematically analyze the spatiotemporal dynamics and driving mechanisms of the coupling and coordination between habitat quality and urbanization. The results reveal the following: (1) Throughout the study period (2000–2020), the macropattern of habitat quality along the region remained relatively stable, exhibiting a "high in the east, low in the west" gradient distribution. Concurrently, urbanization presented a polarized spatial pattern, facilitating development within core urban agglomerations, such as Beijing-Tianjin and Zhengzhou, while driving broader regional development. (2) Temporally, the coupling and coordination degrees between habitat quality and urbanization exhibited a slow upward trend, although the overall level remained low. The relative development level of certain subregions progressed from a lagging phase to a synchronized or advanced stage. (3) Spatially, the coupling and coordination degree between habitat quality and urbanization manifested a distinct "high in the east, low in the west" differentiation, characterized by a significant regional imbalance of "high-high and low-low agglomerations". Over time, the "middle collapse" phenomenon gradually eased, although the broader system evolution continued to exhibit pronounced path dependency. (4) The driving mechanisms of the established coupling and coordination were complex. Precipitation, economic development, technological innovation, and traffic density were key positive factors, with their marginal impacts exerting pronounced spatiotemporal heterogeneity across the region. Consequently, different regions must establish dynamic assessment and early-warning systems, formulating differentiated coordinated development strategies based on their local resource endowments and development stages to promote harmonious human-nature coexistence along the Great Wall.

Keywords: habitat quality; urbanization; coupling coordination; along the Great Wall

Note: Figure translations are in progress. See original paper for figures.