Spatiotemporal Evolution and Mechanism of Coupling Coordination of Human Settlement Environment Systems in Arid Regions: A Case Study of Xinjiang (Postprint)

Authors: Yao Lanbo

Date: 2023-07-20T00:00:00+00:00

Abstract

Human settlements in arid regions are constrained by arid natural conditions, exhibiting a state of systematic imbalance. Promoting system coupling coordination is crucial for constructing human settlements in arid regions. To explore the spatio-temporal evolution mechanism of arid region human settlements from the perspective of system coupling coordination, this study takes the human settlements of 14 prefecture-level cities in Xinjiang as the research object, constructs an evaluation system for the coordinated development of arid region human settlement systems, and based on a coupling coordination degree model of five subsystems, comprehensively employs the entropy method, GIS spatial analysis, and structural equation modeling to investigate the spatio-temporal evolution patterns and coupling action mechanisms of the coupling coordination degree of Xinjiang's human settlement systems from 2003 to 2019. The research indicates: (1) In the temporal dimension, both the coupling degree and coupling coordination degree of Xinjiang's human settlement systems exhibited a fluctuating upward trend from 2003 to 2019, with uneven growth rates among the 14 prefecture-level cities. (2) In the spatial dimension, a spatial distribution pattern of "high in the middle, low on both sides, high in the north and low in the south" was formed, evolving from a "linear pattern" to an "inverted U-shaped pattern" in the east-west direction, and from a "linear pattern" to a "U-shaped pattern" and then to an "oblique linear pattern" in the north-south direction. (3) In terms of action mechanisms, the main action paths formed were "human system → social system → residential system → support system" and "social system → natural system", with their effect values being 0.570, 0.972, 0.953, and -1.189, respectively. Among them, the human system is the fundamental driving force for the coordinated development of arid region human settlements,

indirectly acting on other systems through the social system in a positive or negative manner.

Full Text

Spatiotemporal Evolution and Mechanism of Coupling Coordination of Human Settlements System in Arid Areas: A Case Study of Xinjiang

YAO Lanbo[1,2], YE Jianming[1,3], WANG Yun[1], ZHU Xianwei[1] [1] Agricultural College, Shihezi University, Shihezi, Xinjiang 832003, China [2] School of Urban Design, Wuhan University, Wuhan, Hubei 430062, China [3] School of Architecture and Urban Planning, Tongji University, Shanghai 200092, China

Abstract: Human settlements in arid areas are constrained by natural drought conditions, presenting a trend of systematic imbalance. Promoting system coupling coordination is crucial for human settlements construction in these regions. To explore the spatiotemporal evolution mechanism of human settlements in arid areas from a system coupling coordination perspective, this study examines 14 prefecture-level administrative regions in Xinjiang as research objects. An evaluation system for coordinated development of human settlements systems in arid areas is constructed. Based on the coupling coordination degree model of five subsystems, this study comprehensively employs the entropy method, GIS spatial analysis, and structural equation model to explore the spatiotemporal evolution patterns and coupling mechanisms of the human settlements system coupling coordination degree in Xinjiang from 2003 to 2019.

The research reveals three key findings. First, from a temporal perspective, both the coupling degree and coupling coordination degree of Xinjiang's human settlements system exhibited fluctuating upward trends from 2003 to 2019. The coupling coordination degree increased from 0.370 to 0.603, with an average annual growth rate of 3.05%, evolving from a barely coordinated type to a well-coordinated type. The growth rates were uneven among the 14 prefecture-level administrative regions. Second, spatially, a distribution pattern of "high in the middle, low on both sides, high in the north and low in the south" emerged. In the east-west direction, the pattern evolved from a "linear type" to an "inverted U-shaped type," while in the north-south direction, it transformed from a "linear type" to a "U-shaped type" and then to an "oblique line type." Third, regarding the mechanism of action, the primary pathways formed were "natural system → human system → social system → residential system → support system" and "social system → natural system." The effect magnitudes were 0.570, 0.972, 0.953, and -1.189, respectively. Among these, the human system serves as the fundamental driving force for coordinated development of human settlements in arid areas, influencing other systems either positively or negatively through the social system.

Keywords: human settlements in arid areas; system coupling; spatial analysis;

structural equation model; Xinjiang

Introduction

The report of the 19th National Congress of the Communist Party of China explicitly proposed the basic strategy of “upholding harmonious coexistence between humanity and nature” for socialism with Chinese characteristics. As an intermediary and link connecting humanity and nature and their interactions, the ideal state of human settlements is achieving harmony and unity between humans and nature. However, human settlements construction in arid areas often faces contradictions between the arid natural environment and ecological livability. Due to limitations imposed by climatic conditions, uneven water resource distribution, and fragile ecological foundations, economic development levels in arid area human settlements lag relatively behind, and infrastructure construction remains inadequate. These factors constrain internal coordination and sustainable development within the human settlements system. Therefore, coordinating the relationship between arid environments and ecological livability, and promoting synergistic development among various systems of human settlements in arid areas, have become critical issues urgently requiring solutions in current research.

Existing domestic and international research on human settlements primarily focuses on quality evaluation, suitability assessment, spatiotemporal patterns, evolution mechanisms, planning and design, and environmental governance, demonstrating interdisciplinary integration characteristics. Human settlements science emphasizes treating human habitats (cities or villages) as a whole, yet holistic research from a system coupling coordination perspective remains relatively weak. Most coupling analyses focus on new urbanization, ecological environment, regional economy, and tourism industries, with few studies examining internal coupling coordination within human settlements systems. Research on coupling mechanisms among multiple systems is particularly scarce, failing to deeply analyze the intrinsic interaction relationships under spatiotemporal coupling of human settlements.

Consequently, this study distills the scientific question as “the spatiotemporal evolution mechanism of human settlements in arid areas from a system coupling coordination perspective.” Xinjiang represents a typical arid area human settlement in northwestern China, characterized by arid climate, fragile ecology, desertification, and scarce water, land, and building material resources. These special natural conditions pose severe challenges to human settlements construction. Therefore, this research takes the 14 prefecture-level administrative regions in Xinjiang as study objects, establishes a comprehensive evaluation system for human settlements systems in arid areas, and employs coupling coordination degree models, GIS spatial analysis, and structural equation models to explore spatiotemporal evolution patterns and coupling mechanisms. The findings aim to provide theoretical support and scientific basis for human settlements construction and sustainable development in arid areas.

1 Study Area Overview

This study takes Xinjiang (34°25 ~48°10 N, 73°40 ~96°18 E) as the research region, with its 14 prefecture-level cities, prefectures, and autonomous regions as research units [Figure 73: see original paper]. Xinjiang is located in China's arid and extremely arid zones, with average precipitation less than 147 mm, only one-quarter of the national average. Additionally, Xinjiang experiences high sunshine intensity, with water evaporation far exceeding precipitation. In summary, Xinjiang's low precipitation and uneven distribution make it a typical representative of arid areas with unique research value. The research unit is Xinjiang's prefecture-level administrative regions. Considering data scale gaps between prefecture-level and county-level cities, county-level administrative regions directly under the autonomous region are not included.

2 Methodology

2.1 Indicator System and Data Sources

Based on Academician Wu Liangyong's human settlements science theory, this study constructs a "natural-human-social-residential-support" comprehensive evaluation indicator system for human settlements. Human settlements construction in arid areas must satisfy human survival and development needs for "water," so indicators with arid area characteristics are added, including total water resources and soil erosion control area . Original indicator data are sourced from the *Xinjiang Statistical Yearbook* and *China Urban Construction Statistical Yearbook* from 2003 to 2019. Missing data are assigned values based on average annual growth rates, and the entropy method is used to determine weights for each observation indicator.

2.2.1 Entropy Method for Comprehensive Evaluation

Data preprocessing employs the range standardization method. Based on the objective dispersion degree of indicator data, weights are determined, and the comprehensive evaluation index for each subsystem of Xinjiang's human settlements is calculated through weighted summation.

The formulas are as follows:

$$p_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{m} x'_{ij}}$$

$$e_j = -k \sum_{i=1}^{m} p_{ij} \ln(p_{ij})$$

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}$$

$$U_i = \sum_{j=1}^{5} w_j x'_{ij}$$

Where: p_{ij} is the normalized value of indicator j for research unit i; x_{ij} is the yearbook data for research unit i and indicator j, with x'_{ij} being its standardized value; m is the total number of research units; k is a coefficient; e_j is the entropy value of indicator j; d_j is the entropy redundancy of indicator j; w_j is the weight of indicator j; n is the total number of indicators; and U_i is the comprehensive evaluation index of the system.

2.2.2 Coupling Coordination Degree Model

The coupling coordination degree model quantifies the interaction degree and coordinated development level among the five subsystems of human settlements. The specific formulas are:

$$C = 5\left\{\left[\prod_{i=1}^{5} U_i\right] / \left[\prod_{i=1}^{5} (U_i + C)\right]\right\}^{1/5}$$

$$T = \alpha U_{\text{natural}} + \beta U_{\text{human}} + \delta U_{\text{social}} + \lambda U_{\text{residential}} + \mu U_{\text{support}}$$

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

Where: C is the coupling degree; T is the comprehensive coordination index; D is the coupling coordination degree; U_{natural}, U_{human}, U_{social}, $U_{\text{residential}}$, and U_{support} are the comprehensive evaluation indices of the natural, human, social, residential, and support systems, respectively. Higher C values indicate stronger mutual influence among subsystems; higher D values indicate stronger coupling coordination. The parameters α, β, δ, λ, and μ are undetermined coefficients. Referring to previous studies [13,18], this research considers the five subsystems equally important in human settlements spatiotemporal evolution, thus all are set to 0.2. The classification criteria for coupling coordination degrees are shown in .

2.2.3 ArcGIS Spatial Analysis

Four time-section coupling coordination degrees are selected as geographic data. First, ArcGIS software's natural breaks method characterizes spatial distribution maps. Second, spatial autocorrelation analysis explores distribution patterns. Finally, trend analysis fits spatial data into mathematical surfaces to reveal variation trends at larger spatial scales [19], uncovering spatial differentiation patterns and evolution trends of Xinjiang's human settlements system coupling coordination degree.

2.2.4 Structural Equation Model

Structural Equation Modeling (SEM) is essentially a multivariate statistical method using covariance structures for confirmatory analysis. It can analyze measurement model consistency and structural model causal relationships. This study treats the five human settlements subsystems as latent variables, continuously adjusts causal relationships based on model estimation results to find the optimal model, and clarifies action paths and effects between latent variables according to path coefficients [20], thereby revealing the human settlements system spatiotemporal coupling mechanism.

3 Results

3.1 Temporal Changes in Coupling Degree and Coupling Coordination Degree

Based on calculations of Xinjiang's human settlements system coupling degree and coupling coordination degree from 2003 to 2019, this study analyzes temporal evolution patterns through comparisons between the five subsystems and among the 14 prefecture-level administrative regions.

3.1.1 Overall Development Stage Differences Overall, from 2003 to 2019, Xinjiang's human settlements system coupling degree and coupling coordination degree showed fluctuating upward trends [Figure 2: see original paper]. The coupling degree ranged between 0.8-1.0, with a minimum value in 2009 but generally maintained within the 0.9-1.0 interval. The coupling coordination degree increased from 0.370 to 0.603, with an average annual growth rate of 3.05%, evolving from barely coordinated to well-coordinated. This comprehensively indicates that the interaction degree among the five subsystems and overall system coordination continuously strengthened.

According to coupling coordination degree changes, the evolution is divided into four stages [Figure 3: see original paper]. The barely coordinated stage (2003-2006) featured extremely lagging social and residential systems, primarily due to low economic development levels. The primary coordination stage (2007-2011) showed stable upward trends, with substantial improvements in social and residential systems, though the human system remained far ahead. The intermediate coordination stage (2012-2015) experienced a decline in 2012 followed by recovery, mainly because the natural system evaluation hit its lowest point in 2012. The good coordination stage (2016-2019) saw both coupling degree and coordination degree reach their highest values, with Xinjiang's human settlements system coordination jumping to the good coordination stage.

3.1.2 Differences Among Prefecture-Level Regions Examining differences among Xinjiang's 14 prefecture-level regions [Figure 4: see original paper], the largest gap appeared in 2003, with Karamay City (highest) and Turpan City (lowest) differing by 0.314. Overall, all 14 regions showed fluctuating upward trends, with some regions having standard deviations greater than 0.1 (e.g., Urumqi City, Turpan City, Karamay City), indicating high volatility. Others showed similar, smaller fluctuations (e.g., Hami City, Hotan Prefecture, Ili Kazakh Autonomous Prefecture Direct-Controlled Counties). Urumqi City had the highest average growth rate at 5.21%, while Turpan City had the lowest at 2.24%, demonstrating uneven growth rates and significant regional disparities.

3.2 Spatial Differentiation Characteristics of Coupling Coordination Degree

To further explore spatial differentiation characteristics, four time sections were selected to map spatial distributions [Figure 5: see original paper] and trend evolution.

3.2.1 Spatial Distribution Patterns As shown in [Figure 5: see original paper], Xinjiang's 14 prefecture-level regions exhibited gradually increasing coupling coordination degrees with significant spatial differentiation. Some regions experienced fluctuations, such as Turpan City, which ranked highest in 2003 and 2019 but lowest in 2011. Others showed spatial synchronization, such as eight regions (Urumqi, Turpan, Hami, Aksu, Altay, Changji Hui Autonomous Prefecture, Ili Direct-Controlled Counties, and Bortala Mongol Autonomous Prefecture) sharing the same coordination grade in 2019, indicating certain spatial consistency in internal forces.

Spatial distribution differences relate to uncoordinated development constraints: social system lag was the primary constraint in most regions; residential system lag constrained Kashgar, Hotan, Tacheng, Bayingolin Mongol Autonomous Prefecture, and Kizilsu Kirghiz Autonomous Prefecture; natural system lag constrained Karamay City.

3.2.2 Spatial Evolution Trends ArcGIS-based global spatial autocorrelation analysis calculated Moran's I indices for Xinjiang's human settlements system coupling coordination degree, with all estimates below 0.1 and Z-scores and P-values failing significance tests . This indicates no spatial dependency, presenting a dispersed pattern.

From fitted curve spatial evolution trends [Figure 6: see original paper], Xinjiang's coupling coordination degree showed significant trend effects from 2003 to 2019. In the east-west direction, the trend evolved from "linear type" to "inverted U-shaped type," with increasing differences between central and eastern/western regions, indicating expanding interaction intensity disparities. In the north-south direction, the trend evolved from "linear type" to "U-shaped type" then to "oblique line type," with changes first intensifying, then moderating, then intensifying again, showing higher coordination in northern regions and increasing north-south disparities.

3.3 Human Settlements System Coupling Mechanism

While coupling coordination degree evaluation reveals external spatiotemporal evolution characteristics, it cannot uncover intrinsic interaction mechanisms among system components. Therefore, this study employs SEM to quantitatively analyze Xinjiang's human settlements system coupling mechanism.

3.3.1 Theoretical Framework Based on SEM Grounded in Wu Liangyong's human settlements science [1], this study proposes a theoretical framework for coupling mechanisms in arid area human settlements systems. The natural system forms the foundation, as all human production and life rely on ecological carrying capacity. The system's core is "human," with research aiming to satisfy human settlement needs. Humans form societies through interconnections, permeating economic, cultural, educational, and health domains, creating livable residences and forming larger, more complex support networks. Social development also consumes natural resources and damages ecology. Therefore, the following hypotheses are proposed: H1—natural system positively affects human system; H2—residential system positively affects human system; H3—social system positively affects residential system; H4—residential system positively affects support system; H5—human system positively affects social system; H6—support system negatively affects natural system.

3.3.2 Model Results Analysis Using panel data of coupling coordination degrees for 14 prefecture-level regions from 2003 to 2019, with 238 samples (14 regions × 17 years), standardized data were imported into AMOS 26.0 software for maximum likelihood estimation. Model fit indices show: chi-square/df = 1.832, IFI, TLI, and CFI > 0.9, and PGFI > 0.5, indicating good overall model fit. SEM analysis results show that hypotheses H1, H2, H3, H4, and H6 are significant, while H5 is not, indicating human system does not directly affect social system.

3.3.3 Coupling Mechanism Analysis Based on Xinjiang's human settlements system action paths and intensities [Figure 7: see original paper], three key conclusions emerge. First, the human system is the fundamental driving force for coordinated development. It directly affects the social system (effect = 0.570), and indirectly affects residential and support systems through the social system (effects = 0.570$×0.972*and*0.554×$0.953), demonstrating that human needs, population structure, and scale influence other systems.

Second, the social system serves as an important hub with dual effects. Positively, it directly affects residential systems (0.972) and indirectly affects support systems (0.972$×$0.953), showing economic and cultural development promotes infrastructure. Negatively, it affects natural systems (-1.189), indicating Xinjiang's social development model damages ecological environments.

Third, the residential system is a core factor. It directly promotes support systems (0.953), as livable environment development is crucial for ecological suitability evaluation in arid areas. Support system indicators like urban water access and daily water consumption per capita significantly influence ecological livability.

4 Discussion

Human settlements in arid areas are complex dynamic evolution systems. This study reveals significant spatiotemporal heterogeneity in system coupling coordination, where realization depends on leveraging human system dynamics and social system hub value, consistent with previous research [13-14,20], demonstrating scientific validity.

The findings provide insights for arid area human settlements construction: prioritize natural base protection and restoration, rationally adjust socioeconomic industrial structures, and vigorously develop infrastructure. Addressing Xinjiang's unbalanced spatial development, the study suggests leveraging leading roles of well-coordinated regions like Urumqi and Karamay to promote regional coordinated development.

The coupling mechanism reveals that any practical problem involves multi-faceted changes in population, economy, and ecology, consistent with theoretical frameworks [1]. The five subsystems have interpenetrating, nested relationships. Therefore, Xinjiang should strengthen "multi-plan integration" top-level design, stimulating human system development momentum and regulating social system force directions to achieve sustainable development.

Limitations remain: (1) As spatiotemporal evolution patterns vary with research scales in temporal duration, spatial size, and complexity, the applicability across scales requires verification, suggesting future multi-level nested spatiotemporal coupling studies. (2) SEM analyzes linear relationships, yet human settlements systems have complex non-linear relationships. Overly complex paths (e.g., bidirectional human-nature mechanisms, support system feedback) cannot be calculated, suggesting future non-linear method optimization.

5 Conclusions

This study comprehensively analyzes Xinjiang's human settlements system coupling coordination from 2003 to 2019, revealing:

1) Overall, Xinjiang's human settlements system coupling coordination degree formed a "low-medium-high" spiral upward temporal pattern, a gradient-differentiated spatial distribution, and a multi-agent coupling mechanism combining single-chain and network structures.

2) Temporally, coupling degree and coordination degree showed upward trends, with coordination degree increasing from 0.370 to 0.603 (3.05% annual growth), evolving from barely coordinated to well-coordinated.

The 14 prefecture-level regions showed fluctuating growth with uneven growth rates.

3) Spatially, the east-west direction showed a "high middle, low sides" ridge pattern, evolving from "linear" to "inverted U-shaped." The north-south direction showed "high north, low south," evolving from "linear" to "U-shaped" to "oblique line." Lagging social, residential, and natural systems were key constraints.
4) Mechanistically, primary pathways formed were "natural system → human system → social system → residential system → support system" and "social system → natural system." The human system is the fundamental driving force, the social system is the crucial hub, and residential-to-support system evolution affects ecological livability.

References

[1] Wu Liangyong. Introduction to sciences of human settlements[M]. Beijing: China Building Industry Press, 2001: 37-99.

[2] Du Hongru, Tang Yuting, Zhang Ziyun. Regional characteristics and high-quality development path of urbanization in arid region of Xinjiang[J]. Economic Geography, 2021, 41(10): 200-206.

[3] Pang Ruiqiu, Hu Ning, Wei Ye. Evaluation of quality for human settlement in Xinjiang based on multi-source data[J]. Scientia Geographica Sinica, 2021, 41(12): 2127-2137.

[4] Guan Y Y, Li X M, Yang J, et al. Spatial differentiation of comprehensive suitability of urban human settlements based on GIS: A case study of Liaoning Province, China[J]. Environment, Development and Sustainability, 2021, 24: 4150-4174.

[5] Li Su, Liu Haonan. Spatio-temporal pattern evolution of coupling coordination between urbanization and ecological resilience in arid region: A case of Ningxia Hui Autonomous Region[J]. Arid Land Geography, 2022, 45(4): 1281-1290.

[6] Tang Jianxiong, Liu Yujing. The evolutionary process and driving mechanism of human settlement environment in typical tourism cities based on living-production-ecological system: A case study of Zhangjiajie City[J]. Geographical Research, 2021, 40(6): 1803-1822.

[7] Xie Jin, Quan Minghui, Xie Enli. Research on health-oriented human settlements planning in the context of healthy China: A case study of Hangzhou[J]. City Planning Review, 2020, 44(9): 48-54.

[8] Li Yurui, Cao Lizhe, Wang Pengyan, et al. Rural living environment improvement and rural revitalization[J]. Journal of Natural Resources, 2022, 37(1): 96-109.

[9] Wu Liangyong. The research progress of the sciences of human settlements (2002—2010)[M]. Beijing: China Building Industry Press, 2011: 11-24.

[10] Zhao Hulan, Yang Zhaoping, Han Fang, et al. Analysis and forecast of coupling situation among tourism industry, economic development, and ecological environment in Xinjiang[J]. Arid Land Geography, 2020, 43(4): 1146-1154.

[11] Weng Gangmin, Tang Yibo, Pan Yue, et al. Spatio-temporal evolution and spatial difference of tourism-ecology-urbanization coupling coordination in Beijing-Tianjin-Hebei urban agglomeration[J]. Economic Geography, 2021, 41(12): 196-204.

[12] Cai Wenjing, Xia Yong, Zhao Xianghao. Analysis of coupled coordinated development and forecast of ecological environment-economic development-urbanization in five provinces of northwest China[J]. Chinese Journal of Agricultural Resources and Regional Planning, 2020, 41(12): 219-227.

[13] Liu Binyi. Research methodology and application of human settlements[M]. Beijing: China Building Industry Press, 2016: 391-408.

[14] Wang Yong, Sun Ruixin. Impact of land use change on coupling coordination degree of regional water-food system: A case study of Beijing-Tianjin-Hebei urban agglomeration[J]. Journal of Natural Resources, 2022, 37(3): 582-599.

[15] Li Xueming, Guo Yujie, Tian Shenzhen, et al. The spatio-temporal pattern evolution and driving force of the coupling coordination degree of urban human settlements system in Liaoning Province[J]. Scientia Geographica Sinica, 2019, 39(8): 1208-1218.

[16] Ji Xiaofeng, Xie Shikun. Coupling mechanism of URTT composite system in Yunnan Province based on structural equation model[J]. Economic Geography, 2019, 39(6): 46-57.

[17] Tian Shenzhen, Li Xueming, Yang Jun, et al. Spatio-temporal coupling coordination and driving mechanism of urban pseudo- and reality human settlements in the three provinces of northeast China[J]. Acta Geographica Sinica, 2021, 76(4): 781-798.

[18] Wang Jiankang, Han Qian. Spatial-temporal pattern of the coupling coordination of urban economy-society-environment in China[J]. Economic Geography, 2021, 41(5): 193-203.

[19] Tian S Z, Qi A, Li Z H, et al. Urban Three states human settlements high quality coordinated development[J]. Buildings, 2022, 12(2): 178, doi: 10.3390/BUILDINGS12020178.

[20] Yang Shengsu, Zhang Liguo, Yu Ling, et al. The coordinated development and evolution of social economy and water resources utilization in Hunan Province[J]. Economic Geography, 2020, 40(11): 86-94.

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