Spatiotemporal Evolution Characteristics of Social-Ecological System Resilience in the Hexi Corridor Oasis: Postprint

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Abstract

Against the backdrop of oasis degradation and intensified human activities in the arid regions of northwestern China, quantifying the resilience level of oasis social-ecological systems in the Hexi Corridor and revealing their spatiotemporal differentiation patterns has become a key scientific question in the field of ecological security assurance in arid regions. This study comprehensively analyzed the evolution characteristics of oasis system resilience in the Hexi Corridor from 2015 to 2023 by constructing a system resilience assessment index system and employing the entropy method and other related methods. The results indicate: (1) The resilience of socioeconomic and resource management subsystems demonstrated an overall upward trend, increasing from 0.36 to 0.46 and from 0.38 to 0.69, respectively, whereas the resilience of the ecological status subsystem exhibited a trend of first increasing then decreasing, i.e., rising from 0.40 in 2015 to 0.70 in 2021 before declining to 0.60 in 2023; (2) The overall system resilience remained stable, yet at a relatively low level with an average resilience score of 0.35; (3) The Theil index across the five cities in the region showed an upward trend, with the overall Theil index increasing from 0.18 to 0.64, though it decreased during 2016-2017 and 2018-2019, dropping from 0.24 to 0.13 and from 0.27 to 0.13, respectively; (4) The system kernel density curves exhibited tailing characteristics and gradually evolved from "single-peak" to "multi-peak" patterns. Finally, the study proposes countermeasures and suggestions from three aspects, including constructing an intelligent water resource management and control platform based on spatial differentiation to achieve precise early warning and differentiated regulation.

Full Text

Preamble

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Spatio-Temporal Evolution Characteristics of Resilience in Oasis Social-Ecological Systems in the Hexi Corridor

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Abstract: Against the backdrop of oasis degradation and intensifying human activities in the arid northwestern region of China, quantifying the resilience level of oasis social-ecological systems in the Hexi Corridor and revealing their spatio-temporal differentiation patterns have become critical scientific issues in the field of ecological security for arid zones. This study constructed a systematic resilience assessment index system and comprehensively analyzed the evolution characteristics of oasis system resilience in the Hexi Corridor from 2015 to 2023 using the entropy method and related approaches. The results indicate that: (1) The resilience of the socioeconomic and resource management subsystems showed an overall upward trend, increasing from 0.36 to 0.46 and from 0.38 to 0.69, respectively. In contrast, the ecological state subsystem resilience exhibited a pattern of initial increase followed by decline, rising from 0.40 to 0.70 before falling to 0.60. (2) Overall system resilience remained in a stable state but at a relatively low level, with an average score of 0.35. (3) The Theil index showed an upward trend, increasing from 0.18 to 0.64 overall, though it declined from 0.24 to 0.13 between 2016–2017 and from 0.27 to 0.13 between 2018–2019. (4) The kernel density curve exhibited tailing characteristics and gradually evolved from a "single peak" to a "multipeak" pattern. Finally, the study proposes countermeasures and suggestions from three perspectives: constructing a spatially differentiated intelligent water resource management platform, implementing precise early warning systems, and enacting differentiated regulatory measures.

Keywords: Hexi Corridor; oasis; social-ecological system; resilience; spatio-temporal pattern; evolution characteristics

Introduction

Oases are complex geographical landscapes distributed in ecologically fragile regions, formed through the interaction of multiple factors [?, ?]. Population and economic activities in northwestern China primarily occur within oasis systems [?], which have become a direct manifestation of human-environment relationships and economic development in arid zones [?]. The "2025 Major Ecological Planning Strategy" identifies oasis protection as a core priority, with systematic governance and diversified measures not only promoting oasis restoration but also building a northern ecological security barrier. However, oases in the Hexi Corridor face persistent pressures from water resource shortages and desertification expansion due to ecological fragility and continuous human disturbance, making traditional "resilience" perspectives inadequate for explaining their dynamic resilience characteristics [?]. Therefore, studying oasis social-ecological system resilience is crucial for implementing ecological protection and high-quality development strategies.

Resilience definitions vary considerably. Holling [?] defined resilience as the total amount of disturbance a system can absorb without changing its self-organizing processes and structure, while Walker and colleagues [?] conceptualized it as the capacity to maintain structure and function under disturbance. This definition breaks through the narrow focus on recovery to original states, providing a broader perspective for understanding system dynamics. Combined with Gunderson and Holling' s [?] adaptive cycle theory, this study focuses on the resistance and adaptability of oasis social-ecological systems under disturbances such as socioeconomic development and resource exploitation, rather than strict recovery capacity. The Hexi Corridor requires particular attention to the system' s ability to maintain structure and function under long-term disturbances, and Walker and Holling' s definition better reflects resilience characteristics under dynamic interference, aligning with the complex human-environment relationships and persistent disturbances in arid zone oases and helping scientifically reveal resilience evolution patterns.

Existing research shows that scholars have explored system resilience from multiple angles against the backdrop of ecological degradation and policy promotion. Studies by Zhao et al. [?] and Jin et al. [?] examined social-ecological system resilience, while Lian [?] focused on tourism industry ecosystem resilience, and Zhao et al. [?], Liu et al. [?], Ke et al. [?], and Guo et al. [?] investigated innovation ecosystem resilience. Che et al. [?] studied water ecosystem resilience in tropical rainforests. Research areas have concentrated on urban environments [?], with study objects often involving catastrophic scenarios such as climate disasters [?], rainstorm floods [?], and COVID-19 [?], and methods primarily being qualitative [?]. However, research on oasis social-ecological system resilience in the Hexi Corridor remains limited. Integrating Gunderson and Holling' s [?] adaptive cycle theory with Ostrom' s [?] social-ecological system framework to construct a subsystem coupling dynamic model can establish a research foundation in this field while offering both practical value and theoretical innovation.

Based on this context, this study takes the Hexi Corridor as the research area, using the entropy method and related approaches to construct a "socioeconomic-ecological state-resource management" three-subsystem assessment framework. By quantifying the spatio-temporal evolution of system resilience across five cities in the Hexi Corridor from 2015 to 2023, this research not only provides effective references for oasis protection in northwestern arid zones but also offers practical value for maintaining dynamic balance and optimizing resource allocation in desert oases.

1 Study Area Overview

The Hexi Corridor is a typical ecological system region in China [?], encompassing five cities: Wuwei, Zhangye, Jiuquan, Jinchang, and Jiayuguan. All depend on meltwater from the Qilian Mountains to form inland river oasis ecosystems [?]. The region has a temperate continental climate [?] with an average annual precipitation of 156.36 mm. The ecological foundation consists primarily of desertification-oasis transition zones facing persistent pressures from water resource shortages and desertification expansion [?]. Although cities differ in economic scale (e.g., Jiayuguan is industry-dominated, while Zhangye has a high agricultural proportion) and oasis area, all rely on limited water resources to maintain socioeconomic and ecosystem balance. In recent years, under policy guidance such as the Qilian Mountain Ecological Protection Zone Regulations, coordinated governance strategies have been implemented. Therefore, the Hexi Corridor possesses homogeneity in geographical environment and institutional frameworks, making it suitable for comparative studies of social-ecological system resilience.

2 Data and Methods

2.1 Data Sources

This study assessed the social-ecological resilience of oasis systems in the Hexi Corridor from 2015 to 2023, focusing on five cities. Indicator data were obtained from the Gansu Provincial Bureau of Statistics, Gansu Provincial Department of Water Resources, and municipal government websites, with reference to the "National Economic and Social Development Statistical Bulletins" from 2015 to 2023. Missing values were addressed using cubic spline interpolation. Comparison with field survey data from sample points in the five cities showed error rates below 8.00%, confirming data reliability.

Regarding the choice of panel data over remote sensing data, the study justified this decision from three perspectives. First, in analyzing ecological state subsystem resilience, fluctuations in panel data indicators such as desertified land area and artificial afforestation area showed high correlation with oasis boundary changes. For instance, the 2015-2020 resilience increase corresponded with a 19.20% rise in artificial afforestation area, while the 2021-2023 resilience decline aligned with a 3.70% expansion of desertified land area, directly reflecting how oasis boundary dynamics influence system resilience. Thus, panel data can accurately capture such long-term trends. Second, strict validation was performed to address potential data discontinuities. Beyond using cubic spline interpolation for missing values, trend consistency tests were conducted on interpolation results. Taking 2018 as a key discontinuity year, linear regression was used to fit natural trends with adjacent years (e.g., Jiuquan' s artificial afforestation area fitting equation: y = 0.083x + 1.52\$×$10^{\{2\},R}$\{2\}\$ = 0.91). Interpolation results (1.50\$×$10^{\{2\})showedonly1.30}$\{2\}\$ > 0.90 thresholds. Bootstrap tests on all indicators showed 23 indicators with R^2 between 0.85-0.89, meeting preset standards. Third, data change rationality was verified against policy implementation. Post-2017 fluctuations in ecological water use and artificial afforestation aligned with restoration measures under the Qilian Mountain Ecological Protection Zone Regulations, ensuring temporal continuity and logical consistency. In summary, the panel data demonstrate good applicability, with validation measures effectively mitigating impacts from boundary dynamics and data discontinuities.

2.2 Resilience Assessment Framework

2.2.1 Resilience Assessment Index System Oases are primary areas of human activity and key regions in northwestern arid zones [?]. However, recent oasis area expansion has exacerbated water resource problems, undermining system stability [?]. Given the complex structure and numerous factors involved in oasis systems, selecting evaluation indicators requires comprehensive principles to ensure scientific and reliable results [?]. This study divided the Hexi Corridor oasis system into three subsystems: socioeconomic, ecological state, and resource management, with evaluation indicators categorized into 15 specific metrics (Fig. 2).

2.2.2 Indicator Selection Rationale Indicators were selected following principles of scientific validity, data availability, and arid zone specificity. Per capita GDP, rural residents' disposable income, artificial afforestation area, and total grain output were included as positive indicators based on Gong and Ren' s [?] resilience research. Desertified land area, soil erosion index, forest coverage rate, natural population growth rate, and urbanization rate were adopted from Liu et al.' s [?] study, with desertified land area as a negative indicator and others as positive. Given the Hexi Corridor' s high water resource dependency (exceeding 77.49%), per capita water resource availability and ecological water use were incorporated as positive indicators [?, ?]. Urban air quality 优良天数, average annual precipitation, urban built-up area green space rate, and drinking water quality compliance rate were included as positive indicators due to their critical roles in ecosystem services and regional sustainable development [?]. Industrial development, which triggers resource overconsumption, environmental pollution, and ecological damage while weakening ecosystem stability and carrying capacity [?], was included as a negative indicator through industrial growth rate. Comparison with similar studies [?] further validated the indicator system' s rationality.

2.3 Research Methods

2.3.1 Entropy Method for Weight Determination In comprehensive evaluation, weight determination methods include subjective, objective, and combination approaches. Subjective methods yield inconsistent results, so this study employed the objective entropy method, using indicator information entropy to determine weights for more scientific and rational outcomes. First, panel data were processed by classifying indicators as positive or negative based on their impact on system resilience. Since units varied across indicators, standardization was performed. To accommodate subsequent logarithmic calculations, data were non-negatively shifted by adding 0.001 to preserve accuracy. Second, weights, entropy values, and utility values (difference coefficients) were calculated. Finally, weight stability was tested using Bootstrap methods, and indicator replacement simulation experiments were conducted (e.g., replacing industrial growth rate (negative) with tertiary industry proportion (positive)). Weight fluctuations remained below 5%, and system resilience index changes after replacement were under 3%, confirming reliability and robustness.

2.3.2 Weighted TOPSIS Method TOPSIS calculates distances from ideal values, using proximity values to assess resilience levels [?]. First, a weighted matrix was constructed to calculate urban ecosystem resilience. Second, positive and negative ideal solutions were determined, with positive ideal solutions positively correlated with resilience. Finally, Euclidean distances to ideal solutions and comprehensive evaluation proximity values were calculated, with proximity values reflecting dynamic resilience trends and providing foundational data for subsequent analysis.

2.3.3 Kernel Density and Theil Index Analysis Kernel density analysis reflects resilience distribution trends [?], while the Theil index transforms multiple indicators into a comprehensive index for evaluating overall trends. The Theil index also identifies resilience difference sources [?], with values positively correlated with regional resilience level disparities—higher values indicate more pronounced non-equilibrium characteristics across regions.

3 Results and Analysis

3.1 Resilience Evolution Characteristics

3.1.1 Indicator Weights and Subsystem Resilience Evolution As shown in Table 1, resource management subsystem held the highest weight (0.38), with per capita water resource availability reaching 0.12—the highest individual indicator weight. Industrial growth rate, as a negative indicator, had a weight of 0.08, indicating industrial expansion’ s ecological 胁迫. Ecological state subsystem weight was 0.30, with forest coverage rate and other indicators showing lower weights, likely due to excessive afforestation exacerbating water resource conflicts in arid zones. Bootstrap tests confirmed indicator weight fluctuations below 5%, and replacement simulations yielded system resilience index changes under 3%, demonstrating reliable and robust weighting.

From 2015 to 2023, the Hexi Corridor oasis social-ecological system’ s overall resilience averaged 0.35, indicating low resilience levels but stable maintenance within a 0.32–0.38 range. Socioeconomic and resource management subsystems showed significant upward trends, with socioeconomic resilience increasing from

0.36 to 0.46 (+27.80%) and resource management resilience rising from 0.38 to 0.69 (+81.60%). This trend benefited from socioeconomic development driving technological innovation and capital investment in resource management, ecological restoration applications, government policy guidance, institutional improvements enhancing regional collaboration, and increased public ecological awareness. However, ecological state subsystem resilience exhibited a fluctuating pattern, rising from 0.40 to 0.70 before declining to 0.60. This trend resulted from relatively favorable climate conditions during 2015-2020 that created good conditions for vegetation, promoting vegetation coverage, biodiversity, and system structure-function optimization. From 2021 onward, intensified climate change, uneven precipitation, and frequent droughts caused water shortages and declining water tables, damaging the system' s foundation and reducing ecological state subsystem resilience. Figure 3 shows that resource management subsystem' s continuous improvement (orange curve) created synergistic effects with socioeconomic subsystem (blue curve), while ecological state subsystem' s (green curve) 2021 decline reveals the combined impact of water resource constraints and climate change.

3.1.2 Urban Resilience Spatio-Temporal Distribution Table 2 shows that among the five Hexi Corridor cities from 2015 to 2023, Jiuquan exhibited optimal system resilience (Ci = 0.42–0.47), closely related to its high per capita water resource availability and sufficient ecological water use. Zhangye (Ci = 0.31–0.39) and Wuwei (Ci = 0.29–0.36) showed moderate resilience, with the former benefiting from coordinated agricultural and ecological water management while the latter experienced fluctuations due to urbanization and water resource pressures. Jinchang (Ci = 0.21–0.26) and Jiayuguan (Ci = 0.24–0.47) showed lower resilience, with Jinchang significantly affected by negative industrial growth rate impacts and Jiayuguan experiencing declining ecological water use from 2021 due to industrial projects. Overall, cities' proximity values showed strong correlation with resource management subsystem weight (0.38), confirming water resource allocation' s decisive role in system resilience.

3.2 Spatial Pattern Analysis of Oasis Social-Ecological System Resilience

The Theil index for the five Hexi Corridor cities showed significant phased characteristics, with overall index rising from 0.18 to 0.64, indicating expanding regional differences. However, the index declined from 0.24 to 0.13 during 2016–2017 and from 0.27 to 0.13 during 2018–2019. Spatial heterogeneity decomposition revealed city-level indices driving regional trends, with evolution trajectories highly coupled with overall patterns. During decline phases, multi-dimensional element synergy constituted the main driver: socioeconomic dimension water resource development causing supply-demand imbalances, ecological dimension oasis scale expansion exceeding water resource limits, and resource management dimension groundwater over-extraction and water use structure mismatches created systematic risks. This multi-dimensional pressure 叠加 led to phased degradation characteristics. The 2020–2023 rebound trend likely stemmed from innovative technologies like water-saving techniques improving water allocation efficiency and institutional innovation. Notably, all cities' Theil indices showed synchronized rebound trends after two decline cycles (2016–2017 and 2018–2019), validating spatial spillover effects of regional governance policies and overall system restoration capacity improvement.

3.3 Temporal Dynamic Evolution of Oasis Social-Ecological System Resilience

Kernel density distribution showed initial increase followed by decline, with 2015–2023 kernel density curves for the five cities exhibiting tailing states and gradual evolution from "single peak" to "multipeak" patterns. The peaks corresponded to oasis core areas like Jiuquan with higher ecological carrying capacity and disturbance resistance, while declining peak regions indicated vulnerable ecological zones like desertification margins with lower resilience levels. In 2015, Jiuquan, Jiayuguan, and Jinchang showed relatively high peak values with narrow peak widths, while Wuwei and Zhangye had flatter curves with larger peak widths and lower peak values. This heterogeneity reflects the following evolution mechanisms: socioeconomic subsystem's per capita GDP indicator (weight 0.10, highest in system) directly affected socioeconomic resilience growth from 0.36 to 0.46; resource management subsystem' s per capita water resource availability (weight 0.12) and ecological water use (weight 0.09) required technological investment for regulation, creating a positive cycle where per capita GDP growth drove resource management technology investment; ecological state subsystem' s resilience fluctuation, combined with its average annual precipitation (weight 0.06) and desertified land area (weight 0.08) indicators, showed that increased precipitation during 2015–2020 drove vegetation coverage improvement (corresponding to ecological resilience rise), while post-2021 drought days increasing by 2.30% annually caused desertification expansion (corresponding to ecological resilience decline), demonstrating climate factors' significant impacts.

3.4 Method Combination Rationality

The three methods serve complementary roles: entropy method objectively determines indicator weights through information entropy; TOPSIS evaluates solutions by calculating distances from ideal values; their combination enables multi-indicator comprehensive evaluation. Theil index and kernel density verify resilience spatio-temporal evolution patterns from "difference degree" and "spatial distribution" dimensions, respectively. Table 4 shows method result comparisons: entropy method provides weight basis for TOPSIS calculations; kernel density analysis reveals Jiuquan' s highest peak value, while Theil index shows its regional difference contribution; TOPSIS proximity values and kernel density peak distributions show consistency; Theil index increases align with kernel density multipeak/tailing phenomena; Theil index decline phases (2016–2017, 2018–2019) correspond to more uniform resilience distribution periods in kernel density analysis. When method results are inconsistent, spatial distribution validation takes priority—if a city’ s TOPSIS value rises but kernel density peak declines, spatial data authenticity is prioritized to check for indicator outliers.

4 Discussion

The Hexi Corridor oasis social-ecological system resilience showed overall low-level stability, aligning with Li et al.’ s [?] research on urban ecological resilience trends in the Hexi Corridor. However, the oasis system’ s unique characteristics and driving factors involve synergistic interactions among human management measures, climate change, and socioeconomic development [?, ?]. Human management measures, particularly water resource management, are critical. Oasis and farmland expansion relying on agricultural irrigation can exceed water resource carrying capacity limits, such as groundwater extraction surges in the Heihe River Basin [?]. Climate change exacerbates system vulnerability, with regional average annual temperature rising 0.30°C, glacier area decreasing 77.49% since the 1970s, and meltwater reduction intensifying inland river runoff fluctuations [?]. Socioeconomic development further aggravates resource pressure through population growth and industrial layout, such as agricultural water consumption accounting for 83.34% in the Shiyang River Basin, creating intense competition for ecological water use through inefficient water use patterns [?]. These three factors interact to form a negative feedback cycle of “water resource constraints-ecological degradation-economic 胁迫,” highlighting the core role of human management measures in balancing water resource allocation and the 叠加 impacts of climate change and socioeconomic development on system resilience.

However, several research limitations exist: (1) The contradiction between resilience levels and sustainable development—existing ecological projects and resource management lack reasonable planning under climate change and water shortage conditions, damaging system resilience; post-implementation periods face reduced funding, inadequate supervision, and poor coordination, making long-term stability difficult to maintain. (2) Regional coordination challenges—core areas and vulnerable zones in the Hexi Corridor exhibit widening resilience gaps due to differences in resource management, ecological status, and economic development, hindering overall coordinated development. (3) Methodological limitations—data collection capacity was limited to 2015-2023 indicator data; future data expansion and technological advances can extend to longer time series and more specific indicators to provide foundations for sustainable development.

5 Conclusions and Recommendations

From 2015 to 2023, Hexi Corridor oasis social-ecological system resilience exhibited complex trends: (1) Socioeconomic and resource management subsystem resilience levels increased from 0.36$→0.46*and*0.38→0.69, *respectively*, *whileecologicalstatesubsystemresilience* pattern. (2) Overall system resilience averaged 0.35, remaining at a low but stable level. (3) The Theil index rose from 0.18 to 0.64, indicating significantly expanding regional differences, though it declined during 2016-2017 and 2018-2019. (4) Kernel density curves exhibited tailing and evolved from single-peak to multipeak patterns.

Based on these findings and addressing structural contradictions in water resource supply-demand imbalances and core issues of water shortage and desertification expansion [?], specific countermeasures are proposed:

1) **Construct a spatially differentiated intelligent water resource management platform for precise early warning and differentiated regulation.** Integrate 2015-2023 socioeconomic (e.g., per capita GDP, industrial growth rate), ecological (desertified land area, artificial afforestation area), and water resource data (per capita water availability, ecological water use) to delineate resilience management zones based on kernel density analysis—core zones (Jiuquan, Zhangye) and vulnerable zones (Jinchang, Jiayuguan). In core zones, implement "total water volume control + drip irrigation technology" to control artificial afforestation area within water resource carrying capacity limits. In vulnerable zones, establish industrial water "dual control" mechanisms that automatically trigger ecological water replenishment measures when thresholds are exceeded, using industrial growth rate restrictions to limit water-intensive projects. Develop real-time assessment models based on entropy method weights—for instance, when Wuwei' s urbanization rate causes resilience decline due to resource pressure 联动, the platform automatically retrieves water-saving technology cases from neighboring cities (e.g., Zhangye) and pushes them to local managers.

2) **Promote regional collaborative legislation clarifying spatial responsibilities and compensation mechanisms based on Theil index.** Formulate regulations like the "Hexi Corridor Oasis Resilience Collaborative Governance Ordinance," using Theil index contributions (e.g., Jiuquan' s 0.42-0.47) to assign responsibilities: ecological restoration-led zones (Zhangye, Jiuquan) must meet annual afforestation and forest coverage targets and receive ecological compensation; industrial transformation key zones (Wuwei, Jinchang) link industrial growth rate reductions to water resource allocation priority rights. Establish cross-regional 联动 mechanisms through a "water resource-industry" platform—when Jiayuguan' s industrial projects reduce ecological water use, the system automatically triggers surplus ecological water allocation from Zhangye and Jiuquan, with cross-city compensation through fiscal transfer payments.

3) **Implement ecological-industrial coupling transformation projects to construct spatially heterogeneous resilience development corridors.** Optimize industrial layout: in agricultural zones like Zhangye, promote "drip irrigation + drought-resistant crops" models linking grain output subsidies to water-saving efficiency; in

urbanization-active zones like Wuwei, restrict water-intensive crops and shift to photovoltaic-agriculture 复合 models. For ecological restoration, adopt “natural restoration 为主, artificial intervention 为辅” strategies in vulnerable zones, using kernel density analysis to identify vulnerable spatial distributions (tailing regions) to construct sand barriers, such as in the Jiuquan–Jiayuguan section.

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