Postprint: Spatiotemporal Differentiation of Resource and Environmental Carrying Capacity in Gansu Province

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Abstract

Twenty-four indicators were selected from four subsystems—economic, social, environmental, and resource—to construct a regional resource-environment carrying capacity evaluation system. The weighted TOPSIS model combined with GIS spatial analysis functionality was employed to analyze the comprehensive carrying capacity and the internal carrying capacity levels of the four subsystems for 14 prefecture-level cities and autonomous prefectures in Gansu Province from 2004 to 2013 across temporal and spatial dimensions. The research indicates: (1) Over the past decade, the resource-environment comprehensive carrying capacity index of various prefecture-level cities and autonomous prefectures in Gansu Province exhibited a stable trend at a low level, consistent with the economic development level; it displayed a spatial pattern of high in the northwest and low in the southeast, and a pyramid-shaped hierarchical structure. Jiayuguan City occupies the first tier; Jinchang City, Lanzhou City, and Jiuquan City occupy the second tier; other prefecture-level cities and autonomous prefectures occupy the third tier. (2) The impacts of different subsystems on the resource-environment comprehensive carrying capacity vary. The carrying capacity of the eco-environmental subsystem contributes the most to the resource-environment comprehensive carrying capacity, significantly higher than the other three systems, while the economic system contributes minimally. (3) The carrying capacity indices of various subsystems across different prefecture-level cities and autonomous prefectures exhibit obvious spatio-temporal differentiation. The economic support capacity index shows a spatial pattern of high in the Hexi region (except Wuwei) and Lanzhou, and low in the southeast and south, presenting a pyramid-shaped hierarchical structure that is generally low with minor changes. The social carrying capacity index is relatively stable across various cities, except for a significant abrupt change in Jinchang City; spatially, it shows a pattern of high in the Hexi region (except Wuwei) and Lanzhou, and low in the southeast and south; Jiayuguan City, Lanzhou, and Jiuquan have relatively high values, while other regions are relatively low. The environmental carrying capacity index changes frequently with small fluctuation amplitudes, spatially presenting a dumbbell-shaped pattern with high values at both ends and low values in the middle. The resource carrying capacity index is relatively low; the index curves of Wuwei, Qingyang, Dingxi, Gannan, Linxia, and Tianshui are stable, while the remaining eight prefecture-level cities and autonomous prefectures fluctuate frequently with large amplitudes; spatially, it shows a concentrated distribution pattern of high values in the Hexi region (except Wuwei) and Longnan City, and low values in other prefecture-level cities and autonomous prefectures.

Full Text

Preamble

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Spatiotemporal Variation in Resource Environmental Carrying Capacity in Gansu Province, China

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Abstract

Based on an evaluation index system for measuring resource environmental carrying capacity (RECC), this study measured the RECC of 14 cities in Gansu Province and analyzed their spatiotemporal variation. To comprehensively understand RECC and accurately identify its trends, 24 indicators from four subsystems—economic, social, resource, and ecological—were selected to build the RECC evaluation system. Index weights were calculated using the entropy weight method, and the TOPSIS model was applied for multi-criteria decision analysis. Furthermore, GIS spatial analysis was employed to examine the spatiotemporal variation in RECC across the 14 cities and the internal carrying capacity of the four subsystems from 2004 to 2013.

The results indicate that: (1) All 14 cities in Gansu Province exhibited low composite RECC indices with no significant variation from 2004 to 2013, showing a trend similar to economic development levels. The spatial pattern demonstrated higher RECC in the northwest than in the southeast, forming a pyramidal hierarchy with three distinct levels: Jiayuguan City at the top; Lanzhou, Jiuquan, and Jinchang cities in the middle; and other cities at the bottom. The difference between the first and second levels was significant, whereas the difference between the second and third levels was insignificant. (2) Considerable differences were observed among the effects of the four subsystems. The ecological subsystem had the largest effect, significantly higher than the other three subsystems, followed by the social and resource subsystems, while the economic subsystem had the smallest effect. (3) Distinct spatiotemporal variation exists across the subsystems. The economic support index and social carrying capacity were higher in the Hexi region (except Wuwei City) and Lanzhou region than in the southeast and southern regions. The economic support index showed a pyramidal hierarchical structure with low values and insignificant differences between levels. The social carrying capacity of all cities was similar except for Jinchang City, which showed a large change in 2009. Although environmental carrying capacities changed frequently, fluctuations were insignificant. The spatial pattern was dumbbell-shaped—low in the middle and high at both ends. Overall, resource carrying capacity indices were low; they remained constant in Wuwei, Qingyang, Dingxi, Gannan, Linxia, and Tianshui cities, but variable in the remaining eight cities. The Hexi region (except Wuwei) and Longnan region showed higher resource carrying capacity indices than other parts.

Keywords: resource environmental carrying capacity; evaluation index; entropy weight TOPSIS model; Gansu Province; spatiotemporal variation

1. Introduction

Resource environmental carrying capacity (RECC) is both a regional and global issue that has become an important indicator for measuring regional sustainable development. With industrialization and urbanization, RECC has attracted widespread attention as a critical criterion for evaluating coordinated human-land relationships. International research on comprehensive RECC originated in the early 1970s when researchers at MIT used system dynamics models to construct the famous "Limits to Growth" framework, after which RECC became a core focus of ecological and environmental research. Subsequent studies employed system dynamics models to examine population-earth carrying capacity relationships, introduced tourism carrying capacity concepts, and conducted environmental carrying capacity assessments for townships and lakes.

Domestic scholars have conducted extensive theoretical and empirical research by learning from international studies while adapting to China' s actual conditions. For example, Li Ming applied a supply-demand balance model to analyze and predict water resources carrying capacity in Chongqing's metropolitan area; Song Yanchun used the state space method to dissect RECC in the Poyang Lake Eco-economic Zone; Guo Ke analyzed RECC and dynamic mechanisms in the Beijing-Tianjin-Hebei region using state-space models and time series Tobit models; Dong Wen examined evaluation index systems for RECC in major function-oriented zones; Liu Xiaoli reviewed research on RECC in urban agglomerations; An Cuijuan conducted RECC evaluation research from an ecological civilization perspective in Guangxi' s Beibu Gulf Economic Zone; and Zhou Kan used GIS spatial analysis and simulation methods to study RECC characteristics and influencing factors in China' s underdeveloped regions.

Existing research has primarily employed multivariate statistical analysis methods, but several problems remain: (1) Subjective factors cannot be avoided in weight determination, leading to less objective weights; (2) The status of different indicators in the RECC evaluation system is often ignored, failing to reflect gaps between actual and ideal carrying capacity; (3) Some methods have high sample capacity requirements and cannot fully reflect differences among evaluation objects when sample sizes are small.

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method, proposed by Hwang in 1981, provides a feasible solution to these problems. This multi-criteria decision analysis method evaluates RECC levels by measuring the proximity to positive ideal solutions and distance from negative ideal solutions, offering objective and comprehensive reflection of dynamic changes. TOPSIS has no strict restrictions on sample size or data distribution and has been widely applied in ecological system evaluation, land use performance assessment, and other fields. Scholars have improved traditional TOPSIS by integrating entropy weight methods to calculate weights from original data, reflecting information implied in the data and avoiding analysis difficulties caused by minor indicator differences.

Driven by national land spatial planning needs, RECC research continues to emerge, particularly in underdeveloped regions. Gansu Province is a typical underdeveloped and ecologically fragile area where RECC evolution shows characteristics of rapid succession, large fluctuations, and long recovery cycles after overload. As an important ecological security barrier in northwestern and even national China, improving RECC is crucial. Drawing on existing analytical frameworks, this study constructs a RECC evaluation index system from four subsystems (economic, social, ecological, and environmental), applies an improved entropy-weighted TOPSIS model, and uses GIS spatial analysis to examine the spatiotemporal patterns of RECC in Gansu Province from 2004 to 2013, aiming to visually present evolution trends and provide references for sustainable development.

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2. Study Area

Gansu Province is located between 32°31 -42°57 N and 92°13 -108°46 E, controlling the upper reaches of the Yellow River at the intersection of the Loess Plateau, Qinghai-Tibet Plateau, and Inner Mongolia Plateau. The terrain and landforms are complex and diverse. Situated deep in China' s northwest interior, Gansu has low vegetation coverage, relatively scarce water resources, and belongs to a typical ecologically fragile zone with annual precipitation of 36.6–734.9 mm.

[Figure 2: see original paper] The generality of the study region

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3. Data Sources

All statistical data were obtained from the Gansu Statistical Yearbook, Gansu Development Yearbook, and development bulletins for each year from 2004 to 2013.

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4. Methodology

4.1 Evaluation Index System Selection

Many factors influence regional RECC. Research on RECC evaluation index systems has evolved from single-factor to comprehensive multi-factor, multi-objective studies. In recent years, domestic scholars have focused on water and land resources, ecology, and other aspects. There is consensus that RECC is a complex concept requiring comprehensive consideration of both carriers and carried objects.

Based on existing research and Pearson correlation analysis of indicators, 24 indicators with correlation coefficients greater than 0.5 were selected to build the RECC evaluation index system. The resource system provides essential resources for human survival and development, forming the foundation of environmental carrying capacity. The environmental system' s capacity to carry waste is limited. While supporting and constraining socio-economic development, these subsystems are also pressured by socio-economic activities. Factors such as population support capacity and tolerable socio-economic 总量 constitute constraints on RECC.

4.2 Indicator Orientation and Value Direction

All indicator definitions follow National Bureau of Statistics standards. Indicators are classified into two types: (1) Positive indicators, where higher values indicate better evaluation results; and (2) Negative indicators, where higher values indicate worse results. The evaluation system contains both positive and negative indicators.

Evaluation indexes of regional resources and environment carrying capacity and indicator value orientation

4.3 Regional RECC Evaluation Model Construction

4.3.1 TOPSIS Method TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is a comprehensive evaluation method that uses distance as an evaluation criterion to solve finite-scheme multi-objective decision problems. By defining a measure in target space and calculating the proximity to positive and negative ideal solutions, it can assess RECC and comprehensively reflect its dynamic changes and trends.

4.3.2 Entropy Weight Method Entropy is an ideal scale in multi-objective decision-making and evaluation. Weights determined from original indicator data can effectively reflect indicator variation and importance. The entropy weight calculation formula is:

Let y_{ij} represent the RECC evaluation decision matrix with m indicators and n years, where n is the number of evaluation years and m is the number of evaluation indicators. V_{ij} is the standardized data matrix of original indicator data, representing the data of year j under indicator i. P_{ij} is the proportion of the standardized value of indicator i in year j across the entire evaluation year sequence.

$V_{ij} = P_{ij} = V_{ij} / \sum_{j=1}^{n} V_{ij}$

$E_i = -k \sum_{j=1}^{n} P_{ij} \times \ln(P_{ij})$

where E_i is the entropy of indicator i, k is the Boltzmann constant, and when $P_{ij} = 0$, $P_{ij} \cdot \ln(P_{ij}) = 0$.

The weight of indicator i is: $w_i = (1 - E_i) / \sum_{i=1}^{m} (1 - E_i)$

4.3.3 Improved Entropy-Weighted TOPSIS Model RECC is determined by multiple subsystems with different indicator effects. The evaluation system is complex and multi-objective. The improved TOPSIS method can objectively and comprehensively reflect RECC dynamics. Due to indicator diversity and complexity, data standardization is required to eliminate dimensional effects.

Step 1: Construct Standardized Evaluation Matrix

For positive indicators: $V_{ij} = (y_{ij} - y_{ij}^{\min}) / (y_{ij}^{\max} - y_{ij}^{\min})$

For negative indicators: $V_{ij} = (y_{ij}^{\max} - y_{ij}) / (y_{ij}^{\max} - y_{ij}^{\min})$

where $y_{ij}^{\max}$ and $y_{ij}^{\min}$ are the maximum and minimum values of indicator i, and V_{ij} is the standardized indicator.

Step 2: Determine Positive and Negative Ideal Solutions

Let A^+ be the positive ideal solution (maximum value of each indicator across all years) and A^- be the negative ideal solution (minimum value).

$A^{+} = \{V_1^{\max}, V_2^{\max}, ..., V_m^{\max}\}$

$A^{-} = \{V_1^{\min}, V_2^{\min}, ..., V_m^{\min}\}$

Step 3: Calculate Distances

Calculate the distance between each evaluation object and the positive/negative ideal solutions:

$D_j^{+} = \sqrt{\sum_{i=1}^{m} w_i (V_{ij} - V_i^{\max})^2}$

$D_j^{-} = \sqrt{\sum_{i=1}^{m} w_i (V_{ij} - V_i^{\min})^2}$

Step 4: Calculate Closeness Coefficient

The closeness coefficient C_j represents the RECC index:

$C_j = D_j^{-} / (D_j^{+} + D_j^{-})$

where $C_j = 1$ indicates the highest RECC (closest to optimal) and $C_j = 0$ indicates the lowest.

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5. Results

5.1 Weight Calculation

Using the entropy weight method, the average weight of each indicator from 2004-2013 was calculated as the final weight. Weights were normalized for comparative analysis.

The weight of evaluation indexes

5.2 Analysis of RECC in Gansu Province Based on Weighted TOPSIS Model

Original data for 14 cities were processed using the weighted TOPSIS model in statistical software to obtain evaluation indices for comprehensive RECC and subsystem carrying capacity from 2004-2013. ArcGIS was used to map spatiotemporal distribution patterns.

The dynamic evaluation results of the synthetic carrying capacities in 2004–2013

The dynamic evaluation results of the subsystems carrying capacities in 2004–2013

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6. Discussion

6.1 Overall System Carrying Capacity Analysis

Careful analysis of Gansu' s comprehensive RECC evaluation reveals several key findings:

From 2004–2013, Gansu' s comprehensive RECC indices remained stable at low levels. The spatial pattern showed higher values in the northwest and lower values in the southeast, consistent with economic development patterns. The ranking hierarchy formed a pyramid structure: Jiayuguan City ranked first, Jinchang and Jiuquan cities ranked second, and other cities ranked third. The difference between the first and second levels was significant, while the difference between the second and third levels was insignificant.

In 2013, the highest comprehensive RECC index was Jiayuguan City (0.679), while the lowest was Pingliang City (0.114). The spatial layout clearly showed a northwest-southeast gradient.

The dynamic evaluation results of carrying capacities in 2004—2013

[Figure 3: see original paper] The change trend of the synthetic carrying capacities

[Figure 4: see original paper] The space-time pattern of the carrying capacities

Subsystem contributions to comprehensive RECC varied significantly. The ecological subsystem contributed most (0.25-0.27), far exceeding others, while the economic system contributed least. Resource supply support showed relatively large fluctuations, indicating economic development pressures. A mutation occurred in 2009, when resource supply was relatively low.

[Figure 5: see original paper] The average resource environmental carrying capacity index of Gansu Province in 2004—2013

6.2 Subsystem Carrying Capacity Analysis

Economic Subsystem: Economic support indices showed a pyramidal hierarchy and spatial pattern of high values in Hexi and low values in southeast/south regions. Overall levels were low with minimal change. Jiayuguan City ranked highest (0.832), followed by Jiuquan in the middle tier. Dingxi, with poor natural resources and fragile ecosystems, had the lowest index. The Hexi region' s abundant resources and high land use efficiency produced relatively high economic carrying capacity, while Wuwei' s proximity to desert edges and slow economic growth resulted in lower indices. Longnan' s ecological function zones also showed low economic carrying capacity.

[Figure 6: see original paper] The change trend of the economic carrying capacities

[Figure 7: see original paper] The space-time pattern of the economic carrying capacities

Social Subsystem: Social carrying capacity indices were stable across cities except for a major mutation in Jinchang City. Spatial patterns showed high values in Hexi and low values in southeast/south regions. The hierarchy featured Jiayuguan at the top, with other cities at lower levels. Before 2010, indices showed slow upward trends, but after 2010, rapid urbanization caused non-agricultural populations to surge, reducing social carrying capacity indices. Southern Gansu had the lowest social carrying capacity due to high population density, high natural growth rates, and low urbanization.

[Figure 8: see original paper] The change trend of the social carrying capacities

[Figure 9: see original paper] The space-time pattern of the social carrying capacities

Environmental Subsystem: Environmental carrying capacity indices varied little between cities but fluctuated frequently with small amplitudes, forming a dumbbell-shaped spatial pattern (high at both ends, low in the middle). Jiayuguan and Jinchang had relatively high indices, while Gannan also showed high values. Rapid secondary industry development in Jiayuguan caused more severe environmental system damage, with high per-unit industrial wastewater, solid waste, and exhaust emissions resulting in lower carrying capacity indices.

[Figure 10: see original paper] The trend of the environmental carrying capacities

[Figure 11: see original paper] The space-time pattern of the environmental carrying capacities

Resource Subsystem: Resource carrying capacity indices were generally low, fluctuating frequently with large amplitudes. The spatial pattern showed high values in Hexi, Linxia, Tianshui, and Longnan, with other cities showing low concentrated distribution. Longnan' s resource system index fluctuated substantially, while Gannan' s remained nearly unchanged. The overall pattern was high in the northwest and low in the southeast. Water resource shortages across the province exacerbated fluctuations.

[Figure 12: see original paper] The change trend of the resource carrying capacities

[Figure 13: see original paper] The space-time pattern of the resource carrying capacities

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7. Conclusions

Based on 24 carefully selected indicators from economic, environmental, and resource subsystems, this study constructed a RECC evaluation system for Gansu

Province. Using mathematical statistics and GIS spatial analysis, we examined the spatiotemporal dynamics of comprehensive RECC and subsystem carrying capacity from 2004–2013. Key conclusions include:

1. Gansu' s comprehensive RECC indices remained stable at low levels, consistent with economic development patterns. The spatial pattern showed high values in the northwest and low values in the southeast, forming a pyramidal hierarchy with significant gaps between the first and second tiers but small gaps between the second and third tiers.

2. Subsystem contributions varied significantly. The ecological subsystem contributed most to comprehensive RECC, while the economic system contributed least. The overall RECC index was low with minimal change.

3. Subsystem carrying capacities showed distinct spatiotemporal variation:

    - Economic support indices formed a pyramidal hierarchy with low overall values, showing a spatial pattern of high values in Hexi and low values in southeast/south regions.
    - Social carrying capacity indices were stable except for a major mutation in Jinchang, showing similar spatial patterns.
    - Environmental carrying capacity indices fluctuated frequently with small amplitudes, forming a dumbbell-shaped spatial pattern.
    - Resource carrying capacity indices were low with frequent fluctuations, showing a spatial pattern of high values in Hexi, Linxia, Tianshui, and Longnan.

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8. Policy Recommendations

Gansu' s comprehensive RECC is low, particularly economic subsystem support. To improve RECC:

1. **Accelerate economic development**: Introduce advanced technologies, develop characteristic industries, and adjust industrial structure. Reduce heavy-polluting enterprises and mineral resource development.

2. **Develop tourism**: Utilize natural landscapes like Danxia landforms, Maijishan, and Kongtong Mountain, as well as Gannan' s grasslands and characteristic agriculture to develop natural and ecological tourism.

3. **Promote circular economy**: Improve waste utilization efficiency, advance energy conservation and emission reduction, and achieve harmless, reduced, and resource-based treatment of agricultural solid waste.

4. **Optimize land use**: Advance new urbanization, improve land use efficiency, strengthen ecological migration, and promote intensive resource utilization.

5. **Enhance ecological protection**: Continue implementing returning farmland to forest and grassland strategies, increase vegetation coverage, and establish ecological barriers in desert-edge Hexi regions. Learn from developed regions' environmental governance experiences.
6. **Establish compensation mechanisms**: Create reasonable ecological compensation systems to coordinate society, economy, and environment, drawing on successful experiences such as Changsha County's development model.

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