Dominant Factor Identification and Type Classification of County-Level Resource and Environmental Carrying Capacity in the Yinshan North Slope Region

Manao [a], Aruhan [b]

College of Desert Governance, Inner Mongolia Agricultural University, Hohhot 010018, China;

[a]manao@emails.imau.edu.cn, [b]aruhan@imau.edu.cn

Abstract

Resource and environmental carrying capacity (RECC) provides an important basis for evaluating the coordination between resource support, environmental constraints, and socioeconomic development. Taking the Yinshan North Slope region as the study area, this study assessed the county-level RECC of 12 counties for 2005, 2010, 2015, 2020, and 2024 by constructing a resource-environment-socioeconomic indicator system and applying the dynamic entropy weighting method. Random forest, Lasso regression, and K-means clustering were further used to identify dominant factors and classify county types. The results show that county-level RECC in the region is jointly shaped by multidimensional factors, among which grassland area per capita, cultivated land area per capita, built-up land proportion, GDP per capita, urban disposable income, vegetation cover, water supply per unit cultivated land, ecological land proportion, aridity index, and water yield per unit area are the main dominant factors. In 2024, the counties were classified into three types: comprehensively advantaged, moderately balanced, and socioeconomically advantaged but resource-environment constrained. From 2005 to 2024, the spatial pattern was characterized mainly by stability, with limited local fluctuation and transformation. The results provide a basis for differentiated regulation of county-level RECC in the Yinshan North Slope region.

Keywords

Resource and environmental carrying capacity; Dominant factor; Type classification; county-level differentiation; Yinshan North Slope region.

1. Introduction

Resource and environmental carrying capacity (RECC) are an important tool for evaluating the coordination among regional resource supply, environmental assimilative capacity, and human development, and has significant application value in territorial spatial optimization, ecological restoration, and sustainable development research [1-2]. In recent years, RECC research has gradually expanded from conceptual discussions to multiple directions, including comprehensive evaluation, spatial disparity analysis, early warning, and territorial spatial planning [2-3,5]. Meanwhile, the analytical framework has shifted from single resource- or environment-oriented analysis to a composite resource-environment-socioeconomic system perspective [3-4,6]. This suggests that regional differences in RECC are shaped not only by resource endowments and eco-environmental constraints, but also by development intensity, industrial structure, and socioeconomic development levels[4,6]. In the northern slope of the Yinshan Mountains (hereafter, the Yinshan North Slope region), substantial differences in resource conditions, ecological settings, and development levels exist among counties, making it difficult for a single comprehensive evaluation to reveal the deeper causes of such disparities or to provide a sufficiently targeted basis for differentiated governance [1,3].

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Existing studies have generated substantial findings in terms of theoretical frameworks, indicator systems, and methodological approaches [7-8]. Empirical studies at different scales have developed multidimensional evaluation systems incorporating resource, environmental, and socioeconomic factors to identify regional carrying-capacity levels and spatial disparities. The scope of research has also gradually expanded from cities and towns to counties and special functional zones, indicating the strong scale adaptability and broad applicability of RECC evaluation[9-14]. At the same time, increasing attention has been paid to the key constraints underlying carrying-capacity formation, with methods such as obstacle diagnosis, the pressure-support-adjustment framework, and coupling-coordination analysis being used to reveal the major factors affecting improvements in regional carrying capacity[15-18]. International studies have also increasingly linked RECC evaluation with the Sustainable Development Goals, regional transformation, and governance responses, thereby enhancing the diagnostic and decision-support value of evaluation results[13,15,17-18]. Nevertheless, studies on dominant factor identification and type classification at the county scale remain relatively limited, particularly in ecologically fragile areas and agro-pastoral ecotones, where explanatory research aimed at supporting differentiated governance still needs to be strengthened [10-13,16].

Although substantial progress has been made in comprehensive evaluation, spatial disparity identification, and obstacle-factor diagnosis[8,15-18], further improvement is still needed. First, existing studies have mainly focused on cities, prefecture-level cities, resource-based regions, or specific functional zones, while relatively less attention has been paid to the county scale, especially in ecologically fragile and agro-pastoral transitional regions[11-13]. Second, most studies emphasize the measurement of overall carrying-capacity levels and the identification of obstacle factors, but have not sufficiently revealed the dominant roles of different indicators in shaping county-level RECC disparities[15-18]. In addition, although some studies have examined regional differences and corresponding governance responses, research integrating dominant factor identification, type classification, and differentiated regulation remains limited, thereby constraining the deeper application of RECC evaluation in county-level differentiated governance[7,12-13,16].

Therefore, this study selects 12 county-level administrative units in the Yinshan North Slope region and measures county-level RECC using data from 2005, 2010, 2015, 2020, and 2024. Random forest is employed to identify dominant factors, with Lasso regression used for robustness testing. K-means clustering is further conducted based on the indices of the three subsystems to classify county types and perform a comprehensive diagnosis. The aim is to reveal the key factors underlying county-level RECC disparities in the Yinshan North Slope region and to provide a reference for regional differentiated regulation and governance.

2. Study Area and Methods

2.1. Study Area and Data Sources

As shown in Fig. 1,the northern slope of the Yinshan Mountains is located in central Inner Mongolia Autonomous Region and forms an important part of the agro-pastoral ecotone in northern China. The study area covers 12 county-level administrative units, including Guyang County, Bayan Obo Mining District, and Darhan Muminggan Joint Banner in Baotou; Siziwang Banner, Chahar Right Middle Banner, Chahar Right Back Banner, Shangdu County, Huade County, and Wuchuan County in Ulanqab; Taibus Banner and Duolun County in Xilin Gol League; and Urad Middle Banner in Bayannur. The regional landscape transitions from hills to high plains and grassland tablelands. It is characterized by a temperate continental arid to semiarid climate, low and highly variable precipitation, uneven spatial and temporal distribution of water resources, and generally fragile ecological conditions.

The Yinshan region simultaneously performs multiple functions, including agricultural and pastoral production, ecological protection, and resource exploitation, and marked inter-county differences exist in resource endowment, ecological conditions, and socioeconomic development. The southern and areas generally have a relatively stronger foundation for agriculture and urban development, whereas the central and northern pastoral areas depend more heavily on grassland resources and the ecological environment. Some resource-development-oriented counties exhibit the coexistence of economic agglomeration and environmental constraints. Overall, the study area is characterized by a typical arid-semiarid transitional setting, a pronounced agro-pastoral ecotone, and substantial county-level heterogeneity, making it well suited for comprehensive evaluation of county-level RECC, dominant factor identification, and type classification.

The data used in this study mainly include statistical data and remote-sensing raster data. Statistical data were primarily obtained from the Inner Mongolia Statistical Yearbook, statistical materials of relevant leagues, cities, and counties, and the Inner Mongolia Water Resources Bulletin. Remote-sensing and raster datasets mainly included land use, fractional vegetation cover (FVC), net primary productivity (NPP), the aridity index (AI), nighttime light intensity, annual mean $PM_{2.5}$ concentration, and water yield per unit area. Five benchmark years, namely 2005, 2010, 2015, 2020, and 2024, were selected. Using the 12 county-level administrative units in the Yinshan region as the basic evaluation units, a multi-temporal comparative dataset for county-level RECC was constructed.

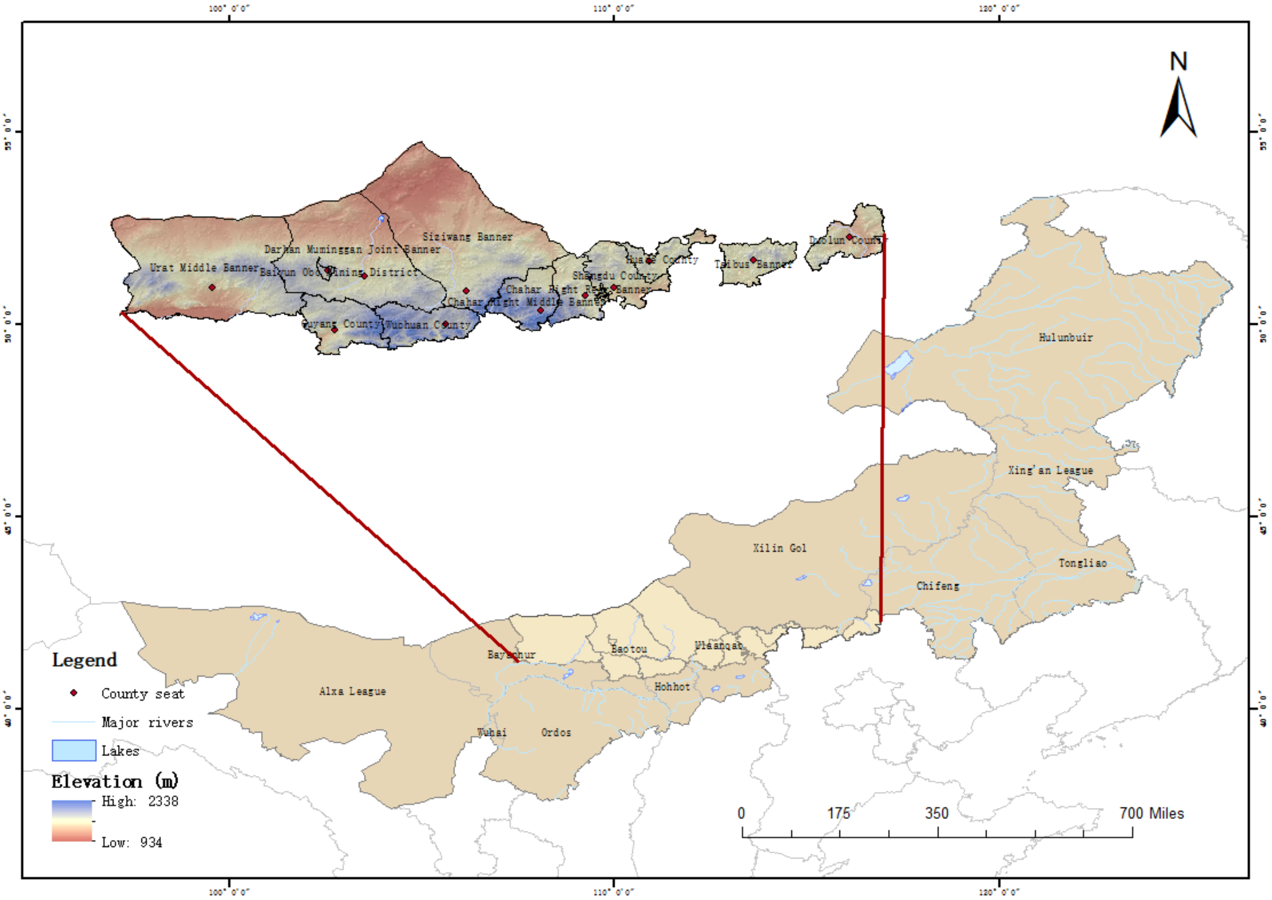

Fig. 1 Overview of the study area

For indicator-system construction, considering the regional characteristics of the Yinshan region as an arid-semiarid transitional zone, an agro-pastoral ecotone, and an area with pronounced county-level heterogeneity, the principles of scientific validity, representativeness, data availability, and county-level comparability were followed. Indicators were selected from three subsystems—resources, environment, and socioeconomic development—to construct

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the county-level RECC evaluation system. Specifically, the resource subsystem mainly reflects basic support conditions such as cultivated land, grassland, and water resources; the environmental subsystem mainly reflects ecological quality, environmental pressure, and the degree of development disturbance; and the socioeconomic subsystem mainly reflects population pressure, industrial structure, and development support capacity. A total of 20 formal evaluation indicators were finally included. The specific indicators, directional attributes, and data sources are listed in Table 1.

Table 1 Evaluation indicator system and data sources for county-level RECC in the Yinshan region.

Subsystem	Indicator	Direction	Data source	Description
Resource	Cultivated land area per capita	+	Land-use data; resident population statistics	Agricultural resource base
Resource	Proportion of cultivated land	+	Land-use data; administrative area data	Agricultural land-use structure
Resource	Grassland area per capita	+	Land-use data; resident population statistics	Grassland support for pastoral development
Resource	Water yield per unit area	+	China Ecosystem Service Dataset; administrative area data	Water resource endowment
Environment	Water supply per unit cultivated land	+	Water resources bulletins; cultivated land area data	Agricultural water-supply security
Environment	Proportion of ecological land	+	Land-use data; administrative area data	Ecological space protection
Environment	Proportion of built-up land	−	Land-use data; administrative area data	Ecological disturbance from development
Environment	Fractional vegetation cover (FVC)	+	National FVC dataset	Vegetation condition and ecological resilience
Environment	Annual mean NPP	+	National NPP dataset	Ecosystem productivity and material supply
Environment	Aridity index (AI)	−	Global aridity dataset	Regional aridity level
Environment	Nighttime light intensity	−	Corrected DMSP/OLS and NPP/VIIRS nighttime light dataset	Intensity of development and energy consumption
Environment	Annual mean $PM_{2.5}$ concentration	−	Annual mean $PM_{2.5}$ raster data	Atmospheric environmental pressure
Socioeconomic	Population density	−	Resident population statistics; administrative area data	Overall population pressure
Socioeconomic	Built-up land area per capita	−	Built-up land area data; resident population statistics	Intensity of built-up land occupation
Socioeconomic	Economic density	−	GDP statistics; administrative area data	Spatial concentration of economic activities
Socioeconomic	GDP per capita	+	Statistical yearbooks	Economic development and investment capacity

Socioeconomic	Share of secondary industry	−	Statistical yearbooks	Dependence on resource-based industries
Socioeconomic	Share of tertiary industry	+	Statistical yearbooks	Service-sector development and industrial upgrading
Socioeconomic	Share of agriculture, forestry, animal husbandry, and fishery output	+	Statistical yearbooks	Agricultural and pastoral development base
Socioeconomic	Per capita disposable income of urban residents	+	Statistical yearbooks	Living standard and socioeconomic development capacity

Note: All indicators were compiled for five benchmark years: 2005, 2010, 2015, 2020, and 2024. "+" and "−" denote positive and negative indicators, respectively.

To ensure comparability among multi-source data, datasets from different sources were uniformly processed and spatially matched. Statistical data were organized by study year and county-level unit, while remote-sensing and raster data were clipped, extracted, and summarized zonally under a unified projection and spatial extent, and then converted into county-level attribute values. Through these procedures, a basic database was established under a two-dimensional analytical framework of "year-county," providing data support for subsequent comprehensive evaluation, dominant factor identification, and type classification.

2.2. RECC Evaluation Method

Under the three-subsystem framework of resources, environment, and socioeconomic development, this study comprehensively evaluates the RECC of 12 county-level administrative units in the Yinshan region for 2005, 2010, 2015, 2020, and 2024. To eliminate the effects of differences in indicator dimensions and magnitudes, all original indicators were first standardized. Specifically, positive indicators were standardized using Eq. (1), whereas negative indicators were standardized using Eq. (2):

$$X_{ij} = \frac{x_{ij} - \min(x)}{\max(x_j) - \min(x_j)} \tag{1}$$

$$X'_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \tag{2}$$

where X_{ij} denotes the original value of the j-th indicator for the i-th sample, X'_{ij} denotes the standardized indicator value, and $\max(x_j)$ and $\min(x_j)$ represent the maximum and minimum values of the j-th indicator across all samples, respectively.

For weight determination, the dynamic entropy weighting method was used to calculate indicator weights for each year. Compared with fixed-weight approaches, the dynamic entropy weighting method determines indicator weights according to temporal variations in the information content of samples and can better reflect the stage-specific differences in indicator importance over the study period. On this basis, the RECC composite index was calculated using a weighted summation method:

$$RECC_i = \sum_{j=1}^{n} w_j X'_{ij} \tag{3}$$

where $RECC_i$ denotes the RECC composite index of the i-th county-level sample, w_j is the weight of the j-th indicator, n is the number of indicators, and X'_{ij} is the standardized value of the indicator.

Based on the above method, the resource subsystem index, environmental subsystem index, socioeconomic subsystem index, and the RECC composite index were calculated for each county in each study year. As the dynamic entropy weighting method can better capture interannual variations in indicators and their contribution levels, the subsequent analyses of dominant factor identification, type classification, and evolutionary diagnosis in this study were all conducted on the basis of the results derived from this method.

2.3. Dominant Factor Identification and Type Classification

To identify the key factors shaping county-level RECC disparities, this study used the RECC composite index calculated by the dynamic entropy weighting method as the response variable and the indicator-level standardized variables as explanatory variables, and employed a random forest model to assess the relative importance of individual indicators to overall carrying capacity [20]. Random forest is well suited for handling complex nonlinear relationships under multivariate conditions and can identify key influencing factors through variable-importance ranking; it is therefore appropriate for dominant factor identification in RECC, which is a multifactor-coupled system. Considering that the proportion of irrigated cultivated land was mainly treated as a reference indicator in the preliminary analysis and showed relatively limited stability, it was not included in the formal dominant factor identification process.

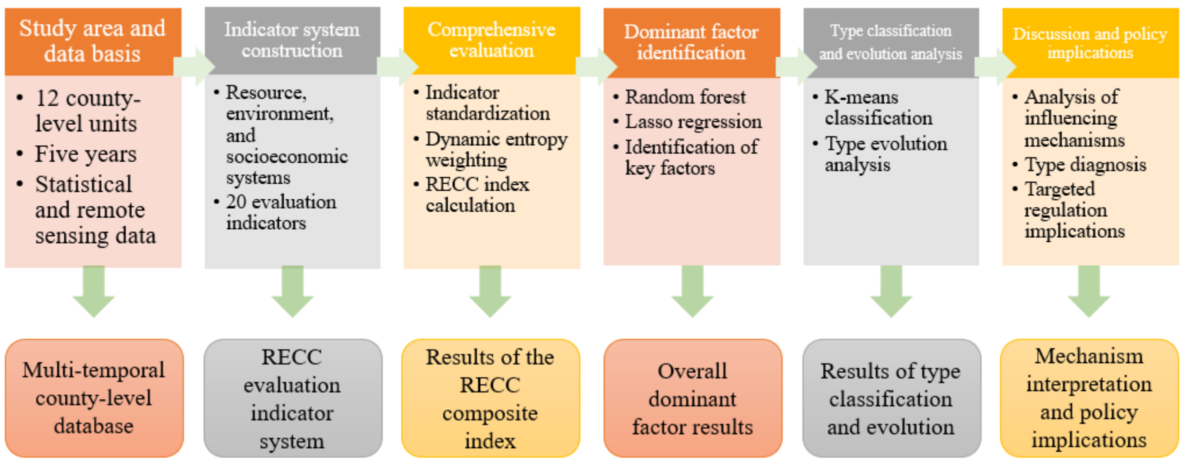

Fig. 2 Overall technical framework for RECC evaluation, dominant factor identification and type classification

On the basis of random forest identification, Lasso regression was further introduced as an auxiliary test to enhance the robustness of dominant-factor screening results. By imposing a penalty constraint on regression coefficients, Lasso regression performs variable shrinkage and selection, thereby reducing the interference of redundant variables and improving the stability of key-factor identification results [21]. By comprehensively comparing the results of the random forest and Lasso regression, indicators jointly highlighted by both methods and showing relatively high contributions were identified as the key dominant factors.

To reveal structural differences in county-level RECC, K-means clustering was applied to classify the 2024 county samples based on the indices of the three subsystems, namely resources, environment, and socioeconomic development. K-means clustering can automatically classify samples according to their similarity in multidimensional feature space and is suitable for identifying the intrinsic structural differentiation of county-level RECC [22]. Considering the sample size of the study area, the interpretability of clustering results, and the needs of type diagnosis, the counties were classified into three types, which were then named according to their relative advantages and constraints across the three subsystems.

Using the three-type framework identified for 2024 as an analytical reference, this study further examined county-type changes from 2005 to 2024 based on the structural combinations of the three subsystem indices, and then summarized the evolutionary trajectories of different counties. Based on the above data, indicator system, and analytical methods, an overall technical framework for RECC evaluation, dominant factor identification, type classification, and evolutionary analysis was established, as shown in Fig. 2.

3. Results

3.1. Dominant Factors of County-level RECC Differentiation

To identify the key factors shaping county-level RECC disparities in the Yinshan region, this study used the RECC composite index derived from the dynamic entropy weighting method, applied random forest to identify the importance of indicator-level variables, and combined the results with Lasso regression for robustness testing. The comprehensive screening results are presented in Table 2, and the random-forest importance ranking is shown in Fig. 3.

Judging from the random-forest importance ranking, the dominant factors of county-level RECC in the Yinshan region are not concentrated in a single subsystem, but instead reflect the joint effects of resource, environmental, and socioeconomic dimensions. Among them, grassland area per capita showed the highest importance (0.426), substantially exceeding that of the other indicators, and was identified as the primary dominant factor shaping county-level RECC disparities in the study area. It was followed by the proportion of built-up land (0.157) and cultivated land area per capita (0.115), indicating that the land-resource base and development intensity jointly constitute the core factors influencing county-level carrying-capacity levels. Meanwhile, per capita disposable income of urban residents, GDP per capita, fractional vegetation cover, and water supply per unit cultivated land also showed relatively high importance, suggesting that socioeconomic development capacity, eco-environmental quality, and water-resource security likewise exert significant effects on county-level RECC. Although the proportion of ecological land, aridity index, and water yield per unit area had relatively lower importance, they still ranked among the top 10 indicators, reflecting their persistent structural constraints on the formation of county-level carrying capacity.

Further analysis based on Table 2 shows that grassland area per capita, cultivated land area per capita, and water yield per unit area from the resource subsystem ranked among the top 10, indicating that resource endowment constitutes the basic support for the formation of county-level RECC in the study area. Within the environmental subsystem, the proportion of built-up land, fractional vegetation cover, water supply per unit cultivated land, the proportion of ecological land, and the aridity index entered the dominant-factor sequence, indicating that eco-environmental quality, land-use structure, and water-resource conditions impose clear constraints on county-level carrying capacity. Within the socioeconomic subsystem, per capita disposable income of urban residents and GDP per capita ranked among the top five, indicating that socioeconomic development level not only reflects the development foundation of counties, but also to some extent represents their capacity for resource integration, infrastructure provision, and environmental governance. Overall, the formation of county-level RECC in the study area is jointly shaped by resource foundations, environmental constraints, and socioeconomic regulatory capacity.

Table 2 Dominant factors of county-level RECC in the Yinshan region

Rank	Indicator	Subsystem	RF importance	Lasso coefficient	Interpretation
1	Grassland area per capita	Resource	0.426	0.064	Core resource factor
2	Proportion of	Environment	0.157	-0.009	Key development-

	built-up land				pressure factor
3	Cultivated land area per capita	Resource	0.115	0.013	Important resource-support factor
4	Per capita disposable income of urban residents	Socioeconomic	0.05	0.018	Important socioeconomic driver
5	GDP per capita	Socioeconomic	0.047	0.022	Important socioeconomic driver
6	Fractional vegetation cover (FVC)	Environment	0.04	0.05	Important ecological-support factor
7	Water supply per unit cultivated land	Environment	0.035	0.04	Important water-security factor
8	Proportion of ecological land	Environment	0.018	-0.013	Structural ecological-constraint factor
9	Aridity index (AI)	Environment	0.017	0.008	Important environmental-constraint factor
10	Water yield per unit area	Resource	0.014	0.03	Basic resource-support factor

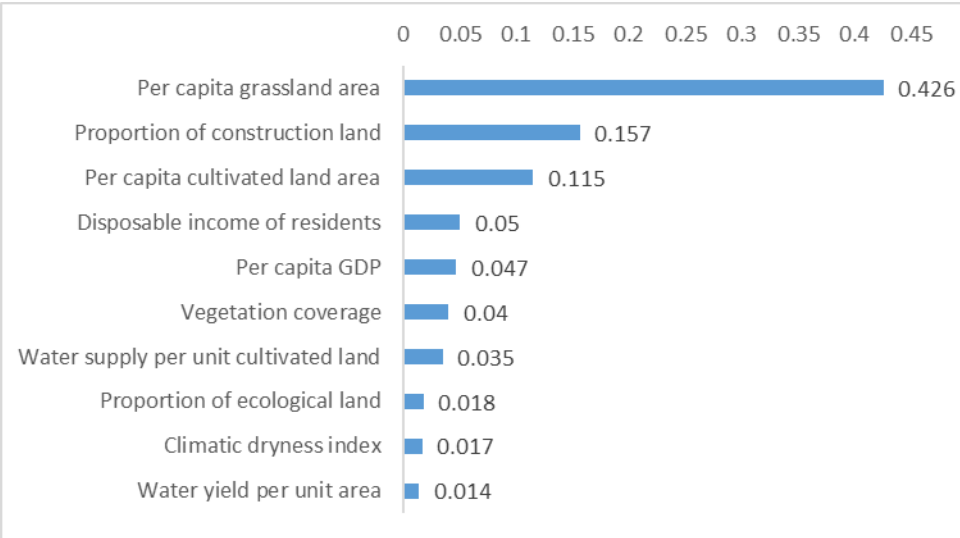

Fig. 3 Ranking of dominant factors by random forest importance for county-level resource and environmental carrying capacity in the Yinshan North Slope region.

According to the Lasso regression results, most indicators with high importance were retained, and a relatively high consistency with the random-forest results was observed for indicators such as grassland area per capita, cultivated land area per capita, resident income, GDP per capita, fractional vegetation cover, and water supply per unit cultivated land. This indicates that these indicators are highly robust and should be regarded as the key dominant factors shaping county-level RECC disparities in the study area. It should be noted that the coefficient directions of some indicators in the Lasso regression were not entirely consistent with their designed

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directional attributes, suggesting that the direction of variable effects at the county scale may be jointly influenced by sample size, variable correlation, and multifactor coupling. Therefore, this study primarily relies on the random-forest importance ranking, with the Lasso results used as auxiliary validation, to summarize the dominant-factor characteristics of county-level RECC in the study area. Overall, the dominant factors of county-level RECC in the Yinshan region exhibit clear characteristics of a composite system, indicating that ranking counties solely by the composite index is insufficient to reveal the structural differences underlying carrying-capacity formation. Further type-classification analysis based on the characteristics of the three subsystems is therefore required.

3.2. County Type Classification and Structural Characteristics in 2024

Building on the identification of dominant factors, this study further applied K-means clustering to the 12 county-level administrative units in the Yinshan region in 2024 based on the indices of the three subsystems—resources, environment, and socioeconomic development—to reveal the structural differentiation characteristics of county-level RECC. The clustering results indicate that the counties in the study area can be classified into three types: moderately balanced, socioeconomic-advantaged but resource- and environment-constrained, and comprehensively advantaged. The classification results are presented in , and the spatial distribution pattern is shown in Fig. 4. Overall, these types differ markedly in resource support, environmental constraints, and socioeconomic development level, indicating that county-level RECC varies not only in overall level but also in internal structural heterogeneity.

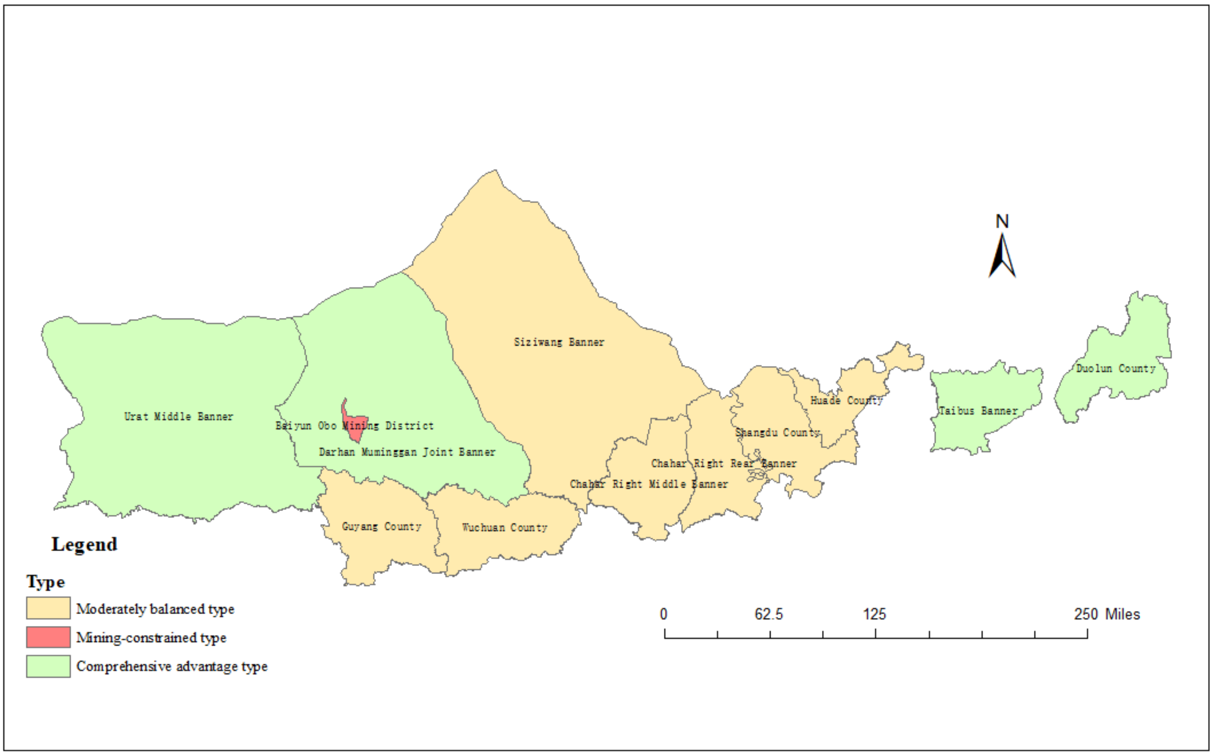

Fig. 4 Spatial distribution of county-level RECC types in the Yinshan region in 2024

The first type is the moderately balanced type, including Huade County, Shangdu County, Siziwang Banner, Guyang County, Chahar Right Middle Banner, Chahar Right Back Banner, and Wuchuan County, comprising seven counties and representing the largest share in the study area. This type is mainly characterized by RECC levels II and III, with an overall medium-low to medium level. It is marked by relatively stable environmental support, whereas its resource and socioeconomic advantages are less prominent. Spatially, this type is mainly distributed in the central and eastern contiguous parts of the study area, showing a certain degree of spatial continuity and suggesting that it is broadly representative in the Yinshan region.

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The second type is the socioeconomic-advantaged but resource- and environment-constrained type, represented solely by Bayan Obo Mining District. This type generally falls within the lower level of RECC level II. It exhibits relatively weak resource support and environmental carrying capacity, whereas its socioeconomic development level is clearly higher than those of the resource and environmental subsystems, forming a typical structure of "strong socioeconomic development but weak resource and environmental support." Spatially, it is located in the central-western part of the study area and shows strong independence in the regional pattern, reflecting the particularity of mining-based counties in terms of RECC structure.

The third type is the comprehensively advantaged type, including Urad Middle Banner, Duolun County, Taibus Banner, and Darhan Muminggan Joint Banner, comprising four counties. This type is dominated by RECC levels IV and V and generally exhibits a medium-high to high overall carrying-capacity level. It is characterized by strong resource support and environmental carrying capacity, while its socioeconomic development level is well matched with resource and environmental conditions, thereby forming a comprehensive advantage structure supported by the coordinated functioning of the three subsystems. In terms of spatial distribution, this type is mainly located along the western and eastern margins of the study area, showing a certain degree of concentration at both ends, and represents the areas with relatively high RECC in the study area.

Taken together, Table 3 and indicate that the differences in county-level RECC types in the Yinshan region in 2024 are not merely differences in composite index values, but essentially reflect different combinations of resource foundations, environmental conditions, and socioeconomic development. The moderately balanced type reflects a relatively stable structure with limited advantages; the socioeconomic-advantaged but resource- and environment-constrained type reflects structural imbalance under development-driven conditions; and the comprehensively advantaged type represents the coordinated support of resources, environment, and socioeconomic development. Therefore, type classification helps reveal the formation mechanism of county-level RECC from the perspective of structural differences rather than index values alone, and also provides a basis for subsequent analysis of type evolution and differentiated regulation.

Table 3 County-level RECC type classification results and main characteristics in the Yinshan region in 2024

Type	Included Counties	RECC Level	Resource Characteristics	Environmental Characteristics	Socioeconomic Characteristics	Summary
Moderately Balanced Type	Huade County, Shangdu County, Siziwang Banner, Guyang County, Chahar Right Middle Banner, Chahar Right Back Banner, Wuchuan County	Level II-III	Moderate resource support	Stable ecological conditions	Moderate socioeconomic support	Balanced development but not significant advantages
Socioeconomic-Advantaged but Resource- and Environment-Constrained	Bayan Obo Mining District	Level II	Weak resource support	Strong development pressure	Strong socioeconomic support	Mining-driven with high economic growth but

Type						weak resource-environment foundation
Comprehensively Advantaged Type	Urad Middle Banner, Duolun County, Taibus Banner, Darhan Muminggan Joint Banner	Level IV-V	Strong resource support	Coordinated ecological management	High socioeconomic support	High RECC, strong support from all subsystems

3.3. Evolution and Comprehensive Diagnosis of County Types from 2005 to 2024

Using the three-type framework identified for 2024 as an analytical reference, this study further examined county-level type changes across 2005, 2010, 2015, 2020, and 2024 based on the structural combinations of the three subsystem indices, and summarized the evolutionary trajectories of different counties. Overall, county-level RECC types in the study area remained highly stable from 2005 to 2024, although certain stage-specific adjustments and boundary fluctuations were also observed. As shown in Table 4, 10 of the 12 counties maintained stable types over the long term, accounting for 83.33% of the total, indicating that county-level RECC in the study area exhibits a clear path-dependent pattern, whereas only two counties showed evident stage-specific transformation or boundary fluctuation.

Table 4 Evolution patterns of county-level RECC types from 2005 to 2024

Evolution pattern	No. of counties	Counties
Long-term stable comprehensively advantaged type	4	Urad Middle Banner; Duolun County; Taibus Banner; Darhan Muminggan Joint Banner
Long-term stable moderately balanced type	5	Huade County; Shangdu County; Guyang County; Chahar Right Middle Banner; Chahar Right Back Banner
Long-term stable socioeconomic-advantaged but resource- and environment-constrained type	1	Bayan Obo Mining District
Boundary-fluctuation adjustment type	1	Wuchuan County
Stage-specific transformational evolution type	1	Siziwang Banner

The first category is the long-term stable comprehensively advantaged type, including Urad Middle Banner, Duolun County, Taibus Banner, and Darhan Muminggan Joint Banner. These counties consistently maintained a high-level comprehensive advantage, indicating that the three subsystems—resources, environment, and socioeconomic development—remained well coordinated over the long term and that their carrying-capacity structure was relatively stable. Combined with the 2024 results, this suggests a good match between resource-environmental conditions and socioeconomic development capacity, and indicates that their advantages stem from the long-term synergy of multidimensional supporting conditions.

The second category is the long-term stable moderately balanced type, including Huade County, Shangdu County, Guyang County, Chahar Right Middle Banner, and Chahar Right Back Banner. These counties remained in a moderately balanced state throughout 2005–2024, with a carrying-capacity structure that was generally stable over time. No marked leap or decline occurred in the resource, environmental, or socioeconomic subsystems, and the overall pattern was characterized by stability but limited improvement. Future optimization should therefore focus on strengthening weak links in resource support and socioeconomic development.

The third category is the long-term stable socioeconomic-advantaged but resource- and environment-constrained type, represented solely by Bayan Obo Mining District. This county consistently exhibited the coexistence of strong socioeconomic support and pronounced resource-environment constraints, reflecting the long-term influence of a mining-dominated development model. Although socioeconomic development remained relatively strong, weak resource foundations and prominent environmental constraints clearly limited further improvement in carrying capacity.

The fourth category is the boundary-fluctuation adjustment type, represented by Wuchuan County. This county fluctuated between the comprehensively advantaged type and the moderately balanced type, and changes in the relative status of the resource, environmental, and socioeconomic subsystems led to changes in its carrying-capacity type. It exhibited a relatively flexible structure, capable of reaching a higher carrying-capacity level when local conditions improved, but falling back to a lower level when supporting conditions weakened.

The fifth category is the stage-specific transformational evolution type, represented by Siziwang Banner. This county underwent marked type shifts at different stages, indicating that its carrying-capacity structure experienced a process of stage-specific adjustment and evolution. Compared with the long-term stable types, this category shows stronger dynamic characteristics, and relative changes in resources, environment, and socioeconomic development drove the transformation of its carrying-capacity type.

Overall, the evolution of county-level RECC types in the study area is characterized by “overall stability, local adjustment, and differentiated divergence.” The long-term stable comprehensively advantaged type and the long-term stable moderately balanced type constitute the main body, with the former reflecting high-level coordination and the latter representing a stable transitional pattern. The long-term stable mining-area constrained type reflects the structural pressure faced by mining-dominated counties, whereas the boundary-fluctuation adjustment type and the stage-specific transformational evolution type indicate that some counties remain in the process of restructuring their carrying-capacity systems. Combined with the dominant factor identification results in Section 3.1, it can be inferred that county-type evolution is closely related to relative changes in the three subsystems of resources, environment, and socioeconomic development. Improvement in RECC in the study area therefore depends not merely on the enhancement of a single indicator, but on the coordinated support of all three subsystems. Accordingly, subsequent regulation should be based on the evolutionary trajectories, structural shortcomings, and type characteristics of different counties, so as to implement differentiated measures.

4. Discussion

4.1. Mechanisms of Dominant Factors and Regional Differentiation Logic

The foregoing results indicate that county-level RECC disparities in the Yinshan region are driven by a clear pattern of composite influences. The overall identification of dominant factors shows that resource, environmental, and socioeconomic elements jointly affect county-level carrying-capacity conditions. The results of type classification and evolutionary analysis further demonstrate that substantial differences exist among counties in the combinations of key factors and in the intensity of their effects, thereby forming a relatively stable pattern of spatial differentiation.

From the overall perspective of the underlying mechanism, resource factors constitute the basic support for the formation of carrying capacity, environmental factors define the carrying boundary and ecological constraints, and socioeconomic factors reflect development capacity and regulatory capacity. Indicators such as grassland, cultivated land, water yield, and water supply determine the basic conditions for agricultural and pastoral production as well as population support in the study area. Indicators such as the proportion of built-up land, the proportion of ecological land, fractional vegetation cover, and the aridity index reflect the occupation of ecological space, environmental quality, and the level of natural stress. Indicators such as GDP per capita and per capita disposable income of urban residents reflect county-level capacities in resource allocation, infrastructure provision, and environmental governance. These three categories of factors do not operate independently, but jointly shape county-level RECC disparities through their interactions.

Combined with the summary results of key factors for each county in 2024 (Table 5), it can be seen that inter-county differences are not mainly manifested in the absolute level of a single factor, but rather in differences in the combinations of key factors. For the comprehensively advantaged type, key factors are mainly concentrated in resource and environmental indicators such as grassland area per capita, water yield per unit area, annual mean NPP, and the proportion of ecological land, indicating that its relatively high carrying-capacity status is primarily built upon favorable resource-environmental conditions and strong coordination among the three subsystems. By contrast, the moderately balanced type relies more on the joint support of factors such as the proportion of cultivated land, cultivated land area per capita, grassland area per capita, annual mean NPP, and the proportion of ecological land, reflecting a structure with an adequate foundation but limited advantages, relative balance, and weak synergistic enhancement.

Table 5 Summary of key factors for each county in 2024

County	Type	Leading factor 1	Contribution	Leading factor 2	Contribution
Urad Middle Banner	Comprehensively advantaged type	Per capita grassland area	0.4512	Water supply per unit cultivated land	0.3142
Huade County	Moderately balanced type	Proportion of cultivated land area	0.1117	Annual mean NPP	0.094
Shangdu County	Moderately balanced type	Proportion of cultivated land area	0.1518	Annual mean NPP	0.0873
Siziwang Banner	Moderately balanced type	Per capita grassland area	0.2456	Proportion of ecological land	0.1194
Guyang County	Moderately balanced type	Proportion of cultivated land area	0.1438	Per capita cultivated land area	0.1162
Duolun County	Comprehensively advantaged type	Water yield per	0.1687	Annual mean NPP	0.1458

		unit area			
Taibus Banner	Comprehensively advantaged type	Water yield per unit area	0.1389	Annual mean NPP	0.1285
Chahar Right Middle Banner	Moderately balanced type	Annual mean NPP	0.0919	Proportion of cultivated land area	0.0905
Chahar Right Back Banner	Moderately balanced type	Annual mean NPP	0.0811	Proportion of cultivated land area	0.0734
Wuchuan County	Moderately balanced type	Proportion of cultivated land area	0.13	Per capita cultivated land area	0.1227
Bayan Obo Mining District	Socioeconomic-advantaged but resource- and environment-constrained type	GDP per capita	0.4219	Per capita disposable income of urban residents	0.1512
Darhan Muminggan Joint Banner	Comprehensively advantaged type	Per capita grassland area	0.5568	Proportion of ecological land	0.123

Table 5 summarizes the two leading factors and their contribution values for each county in 2024, providing a concise basis for interpreting county-type characteristics and differentiated regulation directions

The socioeconomic-advantaged but resource- and environment-constrained type, represented by Bayan Obo Mining District, reflects another typical mechanism. Its key factors are mainly concentrated in socioeconomic indicators such as GDP per capita and per capita disposable income of urban residents, indicating that the carrying-capacity structure of this type is more strongly driven by economic development and development activities. In light of its mining-based development background, this type of county has relatively strong socioeconomic support capacity, but comparatively weak resource foundations and eco-environmental support, together with high development intensity. It therefore exhibits a structural pattern characterized by prominent socioeconomic advantages but relatively strong resource-environmental constraints.

Further consideration of the type evolution results from 2005 to 2024 suggests that the above differences in key-factor combinations are not merely the result of short-term fluctuations, but instead show clear persistence. Overall, the formation mechanism of county-level RECC in the Yinshan region can be summarized as follows: resource factors determine the basic support, environmental factors delimit the carrying boundary, and socioeconomic factors provide development and regulatory capacity, while inter-county differences in the combinations of these three categories of factors further shape the three structural differentiation patterns, namely the comprehensively advantaged type, the moderately balanced type, and the socioeconomic-dominant constrained type. This indicates that the understanding of county-level RECC in the study area should not be limited to comparing composite index values alone, but should further focus on the combinations of dominant factors, differences in type structure, and the stability of their evolution, so as to better capture the internal logic underlying the formation of different county-level carrying-capacity conditions.

4.2. Diagnostic Significance of Type Classification and Implications for Differentiated Regulation

The foregoing analysis examined county-level RECC disparities in the Yinshan region from three perspectives: overall dominant factor identification, county-level combinations of key factors, and type evolution. The results indicate that county-level RECC disparities in the study area are not merely differences in composite index values, but structural differences jointly shaped by resource foundations, eco-environmental conditions, and socioeconomic development pathways. From this perspective, the significance of type classification lies not in simply categorizing counties, but in revealing the structural causes underlying differences in carrying capacity, thereby providing a more targeted analytical framework for differentiated governance.

Compared with composite-index ranking, type classification has stronger diagnostic and explanatory power. Although the composite index can reflect the overall level of county-level RECC, it is insufficient for further identifying inter-county differences in advantageous conditions, limiting constraints, and potential risks. Type classification, by contrast, transforms county-level RECC differences from “level differences” into “structural differences,” distinguishing whether a county’s carrying-capacity status is built on coordinated resource-environmental advantages, on balanced support from multiple factors but without prominent advantages, or on relatively strong socioeconomic development accompanied by pronounced resource-environmental constraints. Therefore, type classification not only deepens the interpretation of the results, but also improves the applicability of the findings to governance practice.

In terms of the major issues facing different types, the comprehensively advantaged type generally has a favorable resource-environmental foundation and a relatively high carrying-capacity level; its main challenge lies not in insufficient basic support, but in how to consolidate existing advantages and prevent them from weakening. The moderately balanced type does not exhibit obvious weaknesses in resources, environment, or socioeconomic development, but lacks prominent advantageous factors overall. Its core issue is that, although multiple factors provide support, they have not formed a strong synergistic enhancement effect, and this type therefore tends to remain at a medium level over the long term. The socioeconomic-dominant constrained type is characterized by relatively strong socioeconomic support capacity, but weak resource foundations and pronounced eco-environmental constraints, resulting in a clear mismatch between development intensity and resource-environmental carrying capacity. Its core problem lies in structural imbalance and risk accumulation. Based on the above type characteristics, combinations of key factors, and evolutionary differences, the diagnostic characteristics and regulatory directions of county-level RECC for different types can be summarized as shown in Table 6.

Table 6 Diagnostic characteristics and regulatory directions of different county-level RECC types

Type	Representative counties	Key characteristics	Diagnostic focus	Regulatory direction
Comprehensively advantaged type	Urad Middle Banner; Duolun County; Taibus Banner; Darhan Muminggan Joint Banner	Key factors are mainly resource-environmental, including grassland area per capita, water yield per	Clear coordinated advantages; high and relatively stable carrying-capacity level; priority should be	Consolidate existing resource-environmental advantages; promote ecological protection,

		unit area, annual mean NPP, and the proportion of ecological land; strong resource-environmental synergy	given to preventing disturbance and weakening of existing advantages	efficient resource use, and green development
Moderately balanced type	Huade County; Shangdu County; Siziwang Banner; Guyang County; Chahar Right Middle Banner; Chahar Right Back Banner; Wuchuan County	Supported by factors such as the proportion of cultivated land, cultivated land area per capita, grassland area per capita, annual mean NPP, and the proportion of ecological land; relatively balanced structure but without prominent advantages	Resource-environmental foundation is acceptable, but the advantage system is weak; synergy is insufficient and development potential has not been fully transformed	Address shortcomings, improve resource-use efficiency, strengthen eco-environmental support and development synergy, and promote transformation from balanced support to synergistic enhancement
Socioeconomic-dominant constrained type	Bayan Obo Mining District	Key factors are mainly socioeconomic, especially GDP per capita and per capita disposable income of urban residents; development-driven pattern with relatively weak resource-environmental support	Strong socioeconomic advantages but prominent resource-environmental constraints; clear mismatch between development intensity and carrying capacity; high structural risk	Alleviate resource-environmental constraints, strengthen ecological restoration and environmental governance, and promote green transformation and coordinated development-capacity improvement

Based on the above diagnostic characteristics, the regulatory directions for different county types should show clear differentiation. For the comprehensively advantaged type, the priority should be to consolidate existing advantages and improve quality and efficiency. While maintaining favorable factors such as grassland, ecological space, water resources, and ecological quality, attention should be paid to preventing high-intensity development from disturbing the original carrying-capacity structure. For the moderately balanced type, the priority should be to address shortcomings, strengthen synergy, and promote transformation by improving resource-use efficiency, enhancing eco-environmental support conditions, and reinforcing the synergy between socioeconomic development capacity and resource-environmental support, thereby shifting the carrying-capacity structure from "balanced support" to "synergistic enhancement." For the socioeconomic-dominant constrained type, the priority should be to alleviate constraints, optimize structure, and prevent risks, with greater emphasis on ecological restoration in mining areas, environmental governance, and control of development intensity, so as to promote the green transformation and intensive utilization of resource-exploitation-oriented areas. Overall, the improvement of county-level RECC in the Yinshan region cannot rely on a uniform pathway, but should instead implement differentiated measures according to the structural characteristics of different county types [23]. Specifically, the comprehensively advantaged type should focus on consolidating strengths and improving quality and efficiency, the moderately balanced type should focus on addressing shortcomings and enhancing synergy, and the socioeconomic-dominant constrained type should focus on alleviating constraints and promoting green transformation. This indicates that the key to RECC regulation lies not in simply increasing the composite index, but in developing more targeted differentiated governance pathways based on the advantageous conditions, limiting constraints, and long-term evolutionary characteristics of different counties [24].

4.3. Method Applicability and Research Limitations

Overall, the analytical framework established in this study—"dynamic entropy weighting-based comprehensive evaluation, dominant factor identification, type classification, and evolutionary synthesis"—is well suited to the study of county-level RECC in the Yinshan region. The dynamic entropy weighting method can effectively capture changes in indicator information across different periods and is therefore suitable for multi-temporal county-level comparison. The combination of random forest and Lasso regression helps identify key influencing factors at the overall level. K-means clustering and evolutionary synthesis further transform the results of comprehensive evaluation from the identification of "level differences" to that of "structural differences," thereby enhancing the relevance of county-level disparity diagnosis and discussions of differentiated regulation. Overall, this combination of methods is well aligned with the research objectives of county-scale analysis, multi-temporal comparison, and type-oriented identification.

At the same time, the results of this study are still constrained by the research scale, indicator system, and data conditions. First, the study covers 12 counties and five benchmark years, resulting in a relatively limited total sample size. Therefore, the dominant factor identification results are more suitable as a basis for explanatory analysis and should not be overgeneralized. Second, RECC is inherently complex. Although the indicator system in this study was constructed from the three dimensions of resources, environment, and socioeconomic development, it remains difficult to fully incorporate potential influencing factors such as policy regulation, industrial structure, and governance capacity. Third, the temporal analysis in this study is based on five benchmark years, which can reflect the overall trend of evolution, but remains relatively limited in depicting the continuous process of change in county-level carrying capacity.

Future research could further examine and supplement the key influencing factors, type differentiation, and evolutionary processes of county-level RECC under finer spatial scales and more continuous temporal conditions, so as to improve the granularity and regional applicability of the research findings.

5. Conclusion

(1) County-level RECC in the Yinshan region is jointly driven by multidimensional resource, environmental, and socioeconomic factors, and its dominant factors exhibit clear composite characteristics. The dominant factor identification results show that grassland area per capita, the proportion of built-up land, cultivated land area per capita, per capita disposable income of urban residents, GDP per capita, fractional vegetation cover, water supply per unit cultivated land, the proportion of ecological land, the aridity index, and water yield per unit area all have strong explanatory power for county-level RECC disparities. This indicates that county-level RECC in the study area is not determined by a single natural condition or a single development factor, but rather by the combined effects of resource support, eco-environmental constraints, and socioeconomic regulation.

(2) In 2024, county-level RECC in the Yinshan region can be classified into three types: the comprehensively advantaged type, the moderately balanced type, and the socioeconomic-

advantaged but resource- and environment-constrained type, each corresponding to a different internal support structure. The comprehensively advantaged type includes Urad Middle Banner, Duolun County, Taibus Banner, and Darhan Muminggan Joint Banner, and is characterized by favorable resource-environmental foundations and strong coordinated support. The moderately balanced type includes Huade County, Shangdu County, Siziwang Banner, Guyang County, Chahar Right Middle Banner, Chahar Right Back Banner, and Wuchuan County, and is characterized by a certain degree of support from multiple factors but without prominent advantages. The socioeconomic-advantaged but resource- and environment-constrained type is represented solely by Bayan Obo Mining District, and is characterized by relatively strong socioeconomic support but pronounced resource-environmental constraints. These findings suggest that county-level RECC disparities in the study area are reflected not only in differences in overall level, but also in differences in structure and support pathways.

(3) From 2005 to 2024, the evolution of county-level RECC in the Yinshan region was dominated by long-term stability, supplemented by local adjustment and stage-specific transformation, and overall exhibited the characteristics of “overall stability, local fluctuation, and differentiated divergence.” Among the 12 counties, 10 belonged to long-term stable types, accounting for 83.33%, indicating strong path dependence in the county-level carrying-capacity pattern of the study area. Specifically, Urad Middle Banner, Duolun County, Taibus Banner, and Darhan Muminggan Joint Banner consistently remained in the comprehensively advantaged type; Huade County, Shangdu County, Guyang County, Chahar Right Middle Banner, and Chahar Right Back Banner consistently remained in the moderately balanced type; and Bayan Obo Mining District consistently remained in the socioeconomic-advantaged but resource- and environment-constrained type. Wuchuan County exhibited the boundary-fluctuation adjustment type, whereas Siziwang Banner exhibited the stage-specific transformational evolution type. This indicates that deeper factors such as resource endowment, ecological background, and development mode have jointly shaped the long-term differentiation pattern of county-level RECC in the study area.

(4) Improvement of county-level RECC in the Yinshan region cannot rely on a uniform pathway, but should instead implement differentiated regulation according to the structural characteristics of different county types. For the comprehensively advantaged type, the priority should be to consolidate strengths and improve quality and efficiency, while avoiding the weakening of existing resource-environmental synergies caused by high-intensity development. For the moderately balanced type, the priority should be to address shortcomings, strengthen synergy, and promote the transformation of development potential, so as to shift resource, environmental, and socioeconomic factors from balanced support to synergistic enhancement. For the socioeconomic-advantaged but resource- and environment-constrained type, the priority should be to alleviate resource-environmental constraints, strengthen ecological restoration, and promote green transformation, thereby improving the coordination between development intensity and carrying capacity. This indicates that the key to county-level RECC regulation lies not in simply increasing the composite index, but in developing more targeted differentiated governance pathways based on the advantageous conditions, limiting constraints, and evolutionary characteristics of different types.

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