Temporal and Spatial Evolution and Obstacle Diagnosis of Resource and Environment Carrying Capacity in the Loess Plateau

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Research Article

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Temporal and Spatial Evolution and Obstacle Diagnosis of Resource and Environment Carrying Capacity in the Loess Plateau

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Abstract: In the Loess Plateau, natural resources are scarce and the ecological environment is fragile. Sustainable development requires special attention paid to resource and environmental carrying capacity (RECC). This paper selects 24 representative cities in five natural areas of the Loess Plateau, uses the entropy-weight-based TOPSIS method to evaluate and analyze the RECC of each city and region from 2013 to 2018, establishes a diagnosis model to identify the obstacle factors restricting the improvement of RECC and constructs the theoretical framework of RECC' system mechanism. Results show that the RECC of Loess Plateau is increasing in general but relatively small. The environmental and social subsystem have the highest and lowest carrying capacity respectively. There is an obvious contradiction between economic development and the environment. Population density, investment in technological innovation, per capita sown area of crops, and per capita water resources are the main obstacles affecting the improvement of RECC in the Loess Plateau. Such evaluation and diagnosis could support ecological civilization and sustainable development.

Keywords: Loess Plateau; resources and environment; carrying capacity; entropy-weight-based TOPSIS method; obstacle indicators

Introduction

The current global sustainable development is facing challenges such as population growth (Warner and Jones 2017), climate change (Lam and Law 2016, Mavi et al. 2019), over-exploitation of resources (Barrett 1996), and resource depletion (Wunderlich and Martinez 2018). Human needs are continually increasing, but the natural resources and environment available for human use are limited. The rapid social and economic development often comes at the expense of natural resources and the environment, resulting in increasingly severe resource and environmental problems, and such costs will restrict the further development of human society. How to deal with resource and environmental issues and realize the harmonious co-generation of humans and nature is a major problem to be solved urgently. The antagonistic relationship between humans and nature has led people to enter a reflective development model. From *"The Limits of Growth"* in the 1970s

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(Meadows et al. 1972) to the United Nations Conference on Environment and Development in the 1990s, people gradually began to pursue sustainable development.

China is currently under tremendous pressure from economic growth, energy consumption, and environmental crisis (Peng and Deng 2020). Greenhouse gas emissions, energy shortages, and reduced environmental capacity restrict China's sustainable development (Yang et al. 2010). With rapid economic development, the contradiction between the social economy and the ecological environment has become increasingly prominent in most resource-based cities in China. The coordinated development between the two is significant for the sustainable development of resource-based cities (Li et al. 2020). Evaluating the resource and environmental carrying capacity (RECC) of a region provides solutions for realizing the harmonious coexistence of humans and nature. Analyzing the relationship between regional resources, environment, and human activities plays a vital role in regional sustainable development (Bao et al. 2020).

The Loess Plateau is located in western China and is one of the four largest plateaus in China. It is the most concentrated and largest loess region in the world, with a total area of 640,000 square kilometers, which scope mainly includes most or a part of the administrative region of Shanxi, Inner Mongolia, Henan, Shaanxi, Gansu, Qinghai, and Ningxia of China. The Loess Plateau is the birthplace of Chinese civilization. Historically, the forest coverage rate has exceeded 50%. At that time, soil erosion had a slight impact on the Yellow River (Shi and Shao 2000). Nowadays, the vegetation status in the Loess Plateau has changed to a great extent. Due to unreasonable human production activities and excessive development, ignoring the destruction and deterioration of the environment, the grassland boundary of the Loess Plateau has moved south, the forest area is gradually shrinking, soil erosion is severe, and it is now a barren land (Chen et al. 2007, Zhou et al. 2013). The reason is that the extraction and transport of resources driven by societal and economic pressures influence biodiversity and redefine the ecological status of the ecosystem (Cornelia et al. 2007). Paying attention to RECC analysis, we can understand the current status and development trend of regional carrying capacity, which is of great significance for promoting ecological balance, achieving harmony between man and land, and promoting the coordinated development of resources and environment (Liao et al. 2020).

The Loess Plateau is a typical ecologically fragile area in China. Exploring whether the socio-economic development is in harmony with the resources and environment, and evaluating and analyzing the RECC is of great significance to the construction of local ecological civilization and sustainable development. The resource environment and the social economy are complex and dynamic systems. Scholars comprehensively use different methods for different research objects and constantly improve and innovate the research methods of RECC.

By combining human activities with resources and the environment in carrying capacity analysis, this paper constructs a RECC evaluation system, which includes social, economic, resource, and environmental factors. It discusses the resource and environment carrying level of the representative region of the Loess Plateau. This paper will supplement the existing research in the following ways:

(1) Comprehensively evaluate regional RECC from the social, economic, resource, and environmental

dimensions. Combining the classification of RECC with each subsystem, and an independent and comprehensive evaluation of each subsystem, it is helpful for researchers to evaluate the carrying level of each index of the Loess Plateau.

(2) From a regional perspective, according to the characteristics of the natural areas, the Loess Plateau is subdivided into five representative regions, and several representative cities are selected in each natural region. These cities represent typical cities in the Loess Plateau. Studying the RECCs of these cities can not only help understand the urbanization process of some cities in Northwest China but also help establish early warning mechanisms in the Loess Plateau and other ecologically vulnerable areas.

(3) Using the obstacle factors diagnosis model to identify the RECC obstacle factors in the urban agglomeration of the Loess Plateau, and explore the greatest resistance to the improvement of RECC.

(4) Taking the Loess Plateau as an example, this article puts forward theoretical suggestions for sustainable development and the construction of ecological civilization in ecologically fragile areas. It establishes the conceptual framework of the RECC influence mechanism to further explain the process of regional ecological development.

Following this section, Section Two illustrates the RECC interactive framework; Section Three presents the research methods and data sources; Section Four presents the RECC evaluation results of representative cities and regions in the Loess Plateau and discusses the obstacle factors to improving RECC; Section Five discusses the deficiencies of this paper and the possibility of future research, and further proposes the impact mechanism of RECC; Section Six summarizes the findings of the research and presents some policy suggestions.

Interactive framework of RECC

The evaluation of RECC is mainly based on the theory of resources scarcity (Malthus et al. 1992), the theory of growth limit (Meadows et al. 1972), the theory of harmony between man and nature (Marsh 2003), and the theory of sustainable development (McManus 2014), etc. There is abundant research on RECC, which covers the water resources carrying capacity (Ait-Aoudia and Berezowska-Azzag 2016), the land resources carrying capacity (Thapa and Paudel 2000, Nakajima and Ortega 2016), and the atmospheric environment carrying capacity (Su and Yu 2020), the urban resources and environment carrying capacity (Zhang et al. 2018) in different countries and regions. The results revealed that most countries consumed too many resources, thereby decreasing the overall global sustainability of the natural resources that sustain human society (Lei and Zhou 2012). After the scholars have continuously enriched the definition of RECC, they have begun to study methods and models. At present, the evaluation methods of RECC mainly include entropy method and analytic hierarchy process (Zhao et al. 2020, Jayanthi et al. 2020, Diao et al. 2019), strategic environmental assessment, and environmental impact assessment (Martinez-Grana et al. 2014), ecological footprint method (Volodya et al. 2018), fuzzy evaluation method (Yin et al. 2020), emergy analysis (Jung et al. 2018, Paoli et al. 2017), cluster analysis (Reghunathan et al. 2016, Souza Filho et al. 2014), system dynamics model (Cui et al. 2019), logistic growth model (Streimikiene and Girdzijauskas 2008), artificial neural network model (Wu et al. 2019, Wang et al. 2018), state-space model (Tang et al. 2016), dynamic modeling (Lane et al. 2014) and other models are used to evaluate the status quo and predict the future of RECC. The entropy-weight-based TOPSIS method has high credibility and accuracy and avoids the subjectivity of weight determination (Li et al. 2019).

After more than a hundred years of development, RECC has developed from single element research on land resources, water resources, and ecological resource carrying capacity to comprehensive multi-element research involving resources, environment, and ecology. Furthermore, RECC is considered to be the extension and development of carrying capacity, ecological carrying capacity, resource carrying capacity, and environmental carrying capacity. RECC is mainly influenced by regional resources, environment, and human activities. Regional resources and environment, as the carried subject, play a supporting role in RECC, while human social and economic activities endow RECC with bearing pressure. Generally speaking, regional resources and environment provide resources and environmental supplies for human activities, while human social and economic activities will, in turn, exploit resources and pollute the environment. The coordination among the three is the key to influence the RECC level. Fig.1 illustrates the interactive framework of the influencing factors of RECC.

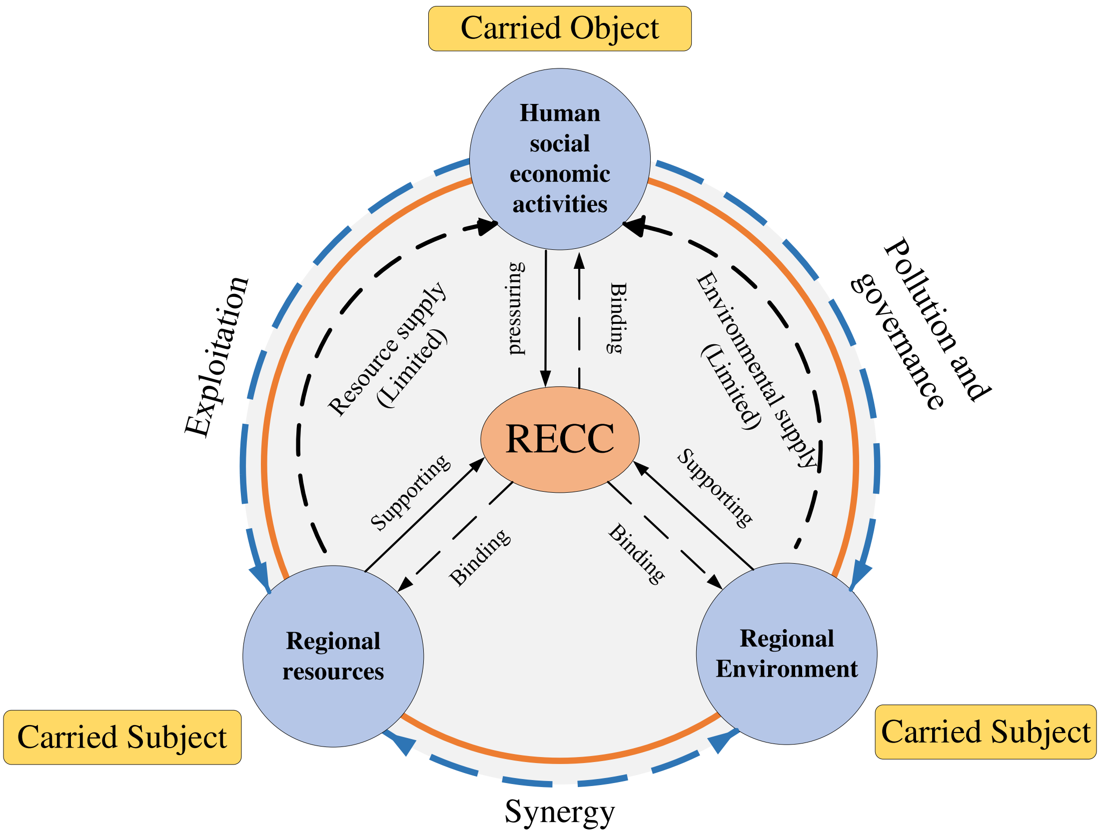


Fig.1 Interaction between the influencing factors of RECC

Research methods and data sources

Overview of the Research area

This paper divides the Loess Plateau into five plateau or plain areas according to the different regional characteristics: Shanxi Plateau, Shan-Gan-Jin Plateau, Longzhong Plateau, Ordos Plateau, Hetao Plain. This paper selects 24 representative cities in each region to evaluate and analyze the RECC of the Loess Plateau. Table 1 and Fig.2 show the locations of specific natural areas and cities.

Fig.2 The spatial location of the Loess Plateau region and its representative cities

Table 1 Classification of natural areas in the Loess Plateau

Natural area	Representative cities
Shanxi Plateau	Taiyuan, Datong, Shuozhou, Luoyang, Xinzhou, Jinzhong
Shan-Gan-Jin Plateau	Yan'an, Tongchuan, Qingyang, Guyuan, Sanmenxia, Lvliang
Longzhong Plateau	Lanzhou, Tianshui, Xining, Dingxi, Baiyin
Ordos Plateau	Yulin, Ordos
Hetao Plain	Bayannaoer, Baotou, Wuzhong, Zhongwei, Yinchuan

Data sources and RECC evaluation index system construction

Most data in this paper derive from *China City Statistical Yearbook (2014-2019)*, *Provincial Statistical Yearbook (2014-2019)*, *Provincial Water Resources Bulletins (2013-2018)*, *Statistical Communiques on National Economic and Social Development of Cities (2013-2018),* the remaining missing data is supplemented according to the statistical yearbooks of each city.

Given the regional characteristics of the Loess Plateau and the complexity of RECC, this paper comprehensively considers multiple dimensions when establishing the RECC index system, taking economy, society, resources, and the environment as the system layer, and combines practical issues in the selection of the criteria layer, such as residents' quality of life, environmental pollution, energy consumption, etc. The specific evaluation index system is shown in Table 2.

Table 2 Indicator systems of RECC

Target layer	System layer	Criteria layer	Basic index layer (units)	Indicator type
RECC	Economic subsystem	Economic development	Per capita GDP (yuan) (X_1)	+
			The tertiary industry share of GDP (%) (X_2)	+
			Expenditure for science and technology share of GDP (%) (X_3)	+
		Social progress	Per capita general budget revenue of local finance (yuan) (X_4)	+
			Per capita fixed asset investment (yuan) (X_5)	+
	Social subsystem	Population pressure	Urbanization rate (%) (X_6)	+
			Natural population growth rate (‰) (X_7)	-
			Population density (person/km^2) (X_8)	-
		Health services	Number of beds of medical and health institutions (bed) (X_9)	+
		Urban Construction	Per capita area of paved roads (m^2) (X_{10})	+
	Resource subsystem	Water resources	Per capita water resources (m^3) (X_{11})	+
			Water consumption in municipal districts of per unit GDP (ton/10,000 yuan) (X_{12})	-
		Land resources	Sown area of crops per capita (hectares/10,000 people) (X_{13})	+
			Urban construction land area per capita (km^2/10,000 people) (X_{14})	+
		Energy resources	Energy consumption of per unit GDP (a ton of standard coal/10,000 yuan) (X_{15})	-
	Environmental subsystem	Environmental governance capability	Ratio of industrial solid wastes comprehensively utilized (%) (X_{16})	+
			Ratio of wastewater centralized treated of sewage work (%) (X_{17})	+
		Environmental pollution intensity	Volume of industrial wastewater discharged per capita (ton) (X_{18})	-
			Volume of SO_2 emission per capita (ton/10,000 people) (X_{19})	-
		Environmental resource supply	Per capita area of green land (hectares/10,000 people) (X_{20})	+
			Green coverage ratio of built-up areas (%) (X_{21})	+

Entropy TOPSIS model

Entropy originated in physics and was later used in the system's multi-objective decision-making. The weight is determined by collecting raw data. The smaller the entropy index, the greater the entropy weight, which means the index is more important, and vice versa. TOPSIS method is a common and effective method in multi-objective decision analysis. This paper adopts the entropy-weight-based TOPSIS method, which can avoid the interference of the results caused by subjective factors, and make its conclusions objective and effective. This paper calculates the specific methods and steps of each city over the years as follows:

1) Construction of standardized evaluation matrix

The original evaluation matrix of the RECC index is expressed by formula (1). In the original matrix, the positive correlation index (the greater the better) (formula (2)) and the negative correlation index (the smaller the better) (formula (3)) are subjected to the range transformation method to obtain a standardized matrix (formula (4)).

$$U = \begin{bmatrix} V_{11} & \cdots & V_{1n} \\ \vdots & \ddots & \vdots \\ V_{m1} & \cdots & V_{mn} \end{bmatrix} \quad (1)$$

$$r_{ij} = \frac{V_{ij} - \min(V_{ij})}{\max(V_{ij}) - \min(V_{ij})} \quad (2)$$

$$r_{ij} = \frac{\max(V_{ij}) - V_{ij}}{\max(V_{ij}) - \min(V_{ij})} \quad (3)$$

$$R = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix} \quad (4)$$

In Eqs. (2), (3), (4), R is the standardized evaluation matrix where r_{ij} is the standardized value of the j index in the i city. $i = 1, 2, \ldots, m$, where m is the number of cities evaluated and $j = 1, 2, \ldots, n$, n is the number of indicators evaluated. r represents the data value of different evaluation indicators in different cities after the range change.

2) Determination of indicator weights

$$W_j = \frac{1 - e_j}{n - \sum_{j=1}^{n} e_j} \quad (5)$$

In Eqs. (5), W_j is the entropy weight of the evaluation index, e_j is the entropy of the evaluation index, in which $e_j = -\frac{1}{\ln m}(\sum_{i=1}^{m} p_{ij} \ln p_{ij})$, $p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}$, when $p_{ij} = 0$, $p_{ij} \ln p_{ij} = 0$.

3) Construction of the evaluation matrix

The calculated weights are assigned to each indicator with corresponding weights through formula (6) to carry out comprehensive evaluation objectively.

$$Y=\begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{mn} \end{bmatrix}=\begin{bmatrix} r_{11}\times W_1 & \cdots & r_{1n}\times W_n \\ \vdots & \ddots & \vdots \\ r_{m1}\times W_1 & \cdots & r_{mn}\times W_n \end{bmatrix} \quad (6)$$

4) Determination of positive and negative ideal solutions

Y^+ is the maximum value of the j_{th} evaluation index in the i_{th} evaluation object (formula (7)); Y^- is the minimum value of the j_{th} evaluation index in the i_{th} evaluation object (formula (8)).

$$Y^+=\left\{\max y_{ij} \mid i=1,2,\ldots,m\right\},1\le i\le m \quad (7)$$

$$Y^-=\left\{\min y_{ij} \mid i=1,2,\ldots,m\right\},1\le i\le m \quad (8)$$

5) Calculation of relative closeness

The Euclidean metric calculation formula (Equations (9) (10)) is used to calculate the relative closeness. (Equation (11)), among which, the closer the closeness is to 1, the stronger the carrying capacity of the city.

$$D_i^+=\sqrt{\sum_{j=1}^{n}(y_j^+-y_{ij})^2} \quad (9)$$

$$D_i^-=\sqrt{\sum_{j=1}^{n}(y_j^--y_{ij})^2} \quad (10)$$

$$CI_i=\frac{D_i^-}{D_i^++D_i^-}(0\le CI_i\le 1, i=1,2,\ldots,m) \quad (11)$$

Obstacle factors diagnosis model

Based on the analysis of the temporal and spatial changes of RECC over the years, to further explore the obstacles restricting the improvement of RECC in the Loess Plateau, the obstacle degree model is introduced to diagnose the obstacle factors (Chen and Liu 2006, Wu and Hu 2020). The obstacle degree model is expressed as in Eqs. (12)

$$P_{jk}=\frac{(1-r_{jk})\times w_j\times 100\%}{\sum_{j=1}^{n}(1-r_{jk})\times w_j} \quad (12)$$

In formula (12), w_j is the weight of the j indicator, p_{jk} is the obstacle degree of the j_{th} index in the k_{th} year.

Results

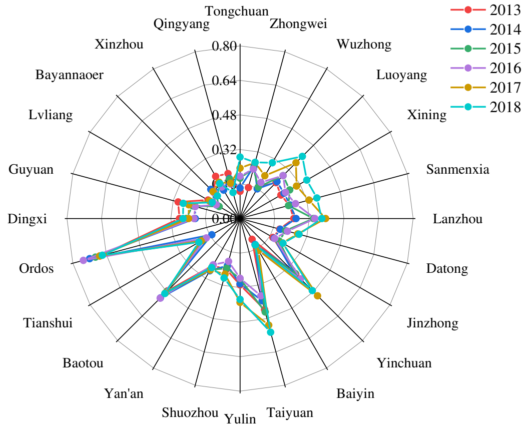
RECC of 24 cities

The carrying capacity index of each subsystem and the RECC index of 24 cities were calculated using the abovementioned model. In general, the RECC of most cities is on the rise (Fig.3 and Table 3). The carrying capacity of various subsystems and the RECC of Ordos have all ranked first in six years, and its performance is relatively excellent. Taiyuan, Baotou, and Yinchuan ranked second to fourth. Among all cities, Luoyang has the highest growth rate of index value in six years. The largest increase in the ranking is Sanmenxia, which rose from 20th in 2013 to 10th in 2018. Besides, there is a significant difference in RECC among the 24 cities. Taking 2018 as an example, Ordos (0.6554) has the best carrying capacity, and Lvliang (0.1944) has the worst carrying capacity. The problem of uneven regional development on the Loess Plateau is obvious.

From the perspective of the economic subsystem, the carrying capacity of the economic subsystem in most cities has increased to varying degrees in six years (Fig. 3-a, Table 3), among which Tongchuan has the highest economic subsystem index growth rate among 24 cities in six years.

From the perspective of the social subsystem, the urban agglomerations showed a rapid and positive development trend from 2013 to 2018 (Fig. 3-b, Table 3). In 2018, the average carrying capacity of all urban social subsystems increased by 33.58% compared with 2013. After 2013, the carrying capacity of the social subsystem of Ordos showed a continuous downward trend, and it rebounded slightly in 2018. The carrying capacity of the social subsystem of the urban agglomeration tended to be average. As the city with the lowest social subsystem carrying capacity in 2013, Guyuan has the highest growth rate of social subsystem carrying capacity.

From the perspective of resource and environmental subsystems (Fig. 3-c, 3-d, Table 3), 70.83% of the cities have a downward trend in the resource subsystem carrying capacity, with the highest growth rate of Xining, the capital of Qinghai Province. According to the data in 2018, except for the Ordos, the carrying capacity of the resource subsystems in Bayannaoer, Yinchuan, Baotou, Xining, and Taiyuan are relatively high. And there is 29.17% of the urban resource subsystem carrying capacity index is still below 0.3, which is a relatively low level. Some cities in the upper reaches of the economic ranking, such as Ordos and Yulin, have experienced a decline in the carrying capacity of the environmental subsystem. Meanwhile, some cities, such as Bayannaoer, experienced a decline in the carrying capacity of the environmental subsystem when the carrying capacity of the resource subsystem increased. Statistics show that the carrying capacity of the environmental subsystem in Sanmenxia has the highest growth rate in six years, while Yulin has the largest decline.



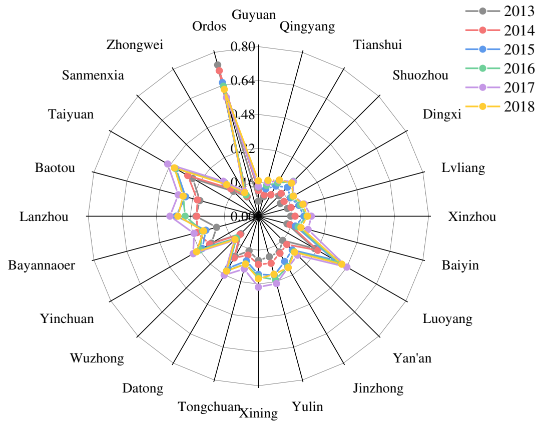
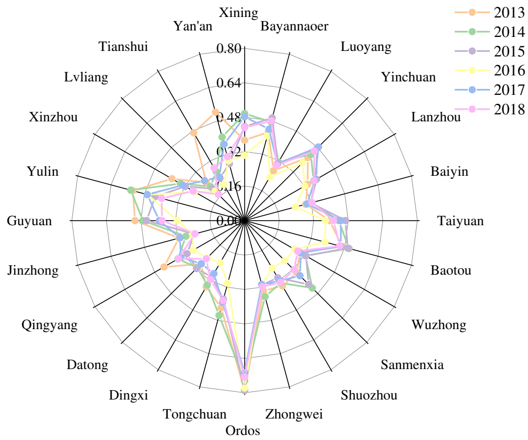


Fig. 3-a The calculation results of economic carrying capacity

Fig. 3-b The calculation results of social carrying capacity



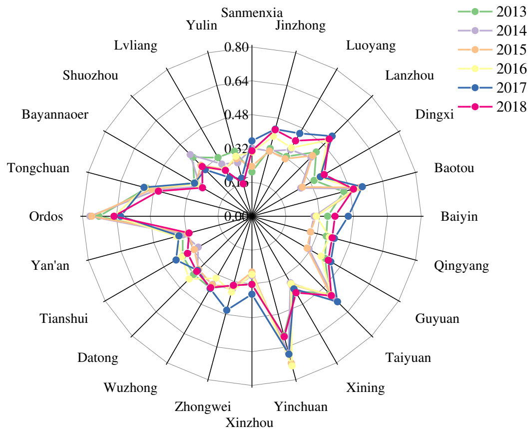
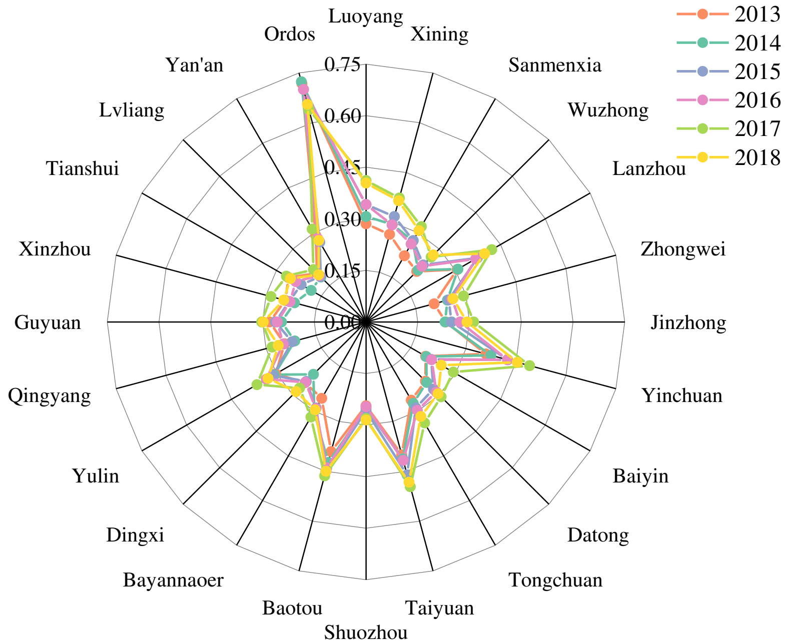


Fig. 3-c The calculation results of resource carrying capacity

Fig. 3-d The calculation results of environmental carrying capacity



Note: The growth rate of the carrying capacity of each city decreases clockwise at 12 o'clock

Fig.3 The calculation results of RECC in 24 cities from 2013 to 2018

Table 3 The growth rate of the carrying capacity of each subsystem in 24 cities from 2013 to 2018 (%)

	Economic subsystem	Social subsystem	Resource subsystem	Environmental subsystem	RECC

Luoyang	73.21	48.52	10.62	26.40	41.53
Xining	63.54	41.18	15.73	2.04	38.53
Sanmenxia	55.37	26.98	-5.21	47.97	38.01
Wuzhong	77.06	33.56	-3.80	-0.52	32.54
Lanzhou	52.19	28.77	10.20	20.19	30.20
Jinzhong	81.38	22.46	-5.79	-0.35	27.80
Yinchuan	30.71	43.83	-24.26	27.71	26.58
Zhongwei	29.58	32.02	10.35	1.02	26.23
Baiyin	26.57	48.83	10.12	9.73	26.18
Datong	48.44	37.12	-11.77	-5.24	21.36
Tongchuan	125.94	37.94	-8.44	-11.07	20.92
Taiyuan	24.95	28.17	4.42	2.44	20.63
Shuozhou	16.95	61.64	-5.23	-15.60	17.06
Baotou	3.69	28.52	-2.33	10.54	15.19
Dingxi	-14.10	31.26	12.61	-14.33	15.00
Bayannaoer	-5.77	58.88	-10.98	16.34	14.64
Qingyang	21.90	43.19	-25.69	-50.11	8.47
Yulin	-42.14	83.41	-17.76	8.02	7.83
Guyuan	-8.29	134.27	-24.72	4.41	6.62
Xinzhou	-16.87	52.02	-29.23	0.58	1.95
Tianshui	2.87	70.70	-40.09	-7.01	-2.30
Lvliang	-12.74	53.64	-31.56	-21.79	-3.20
Yan'an	4.22	48.00	-40.93	-9.05	-5.96
Ordos	-1.70	-16.18	-8.12	-9.84	-8.65

RECC analysis of five natural areas

From 2013 to 2018, the carrying capacity of the economic and social subsystems of the Loess Plateau region fluctuated upwards, the carrying capacity of the resource subsystems fluctuated downwards, and the carrying capacity of the environmental subsystems remained generally stable (Fig. 4-a). RECC has increased by 15.61% in six years. Overall, the carrying capacity of the resource subsystem and the environmental subsystem have exceeded the average level of RECC. From the perspective of growth rate, from 2013 to 2018, the carrying capacity of each subsystem is social, economic, environmental, and resource in descending order.

From 2013 to 2018, the RECC of the Hetao Plain, Shanxi Plateau, Longzhong Plateau, and Shan-Gan-Jin Plateau showed an upward trend, and their overall growth rates decreased sequentially (Fig. 4-b, Fig. 5). The Ordos Plateau remained stable overall, with a decrease of 3.57% in six years. The data shows that from 2013 to 2018, the average RECC index of the Ordos Plateau was the highest (0.5070), and the Shan-Gan-Jin

Plateau was the lowest (0.2618).

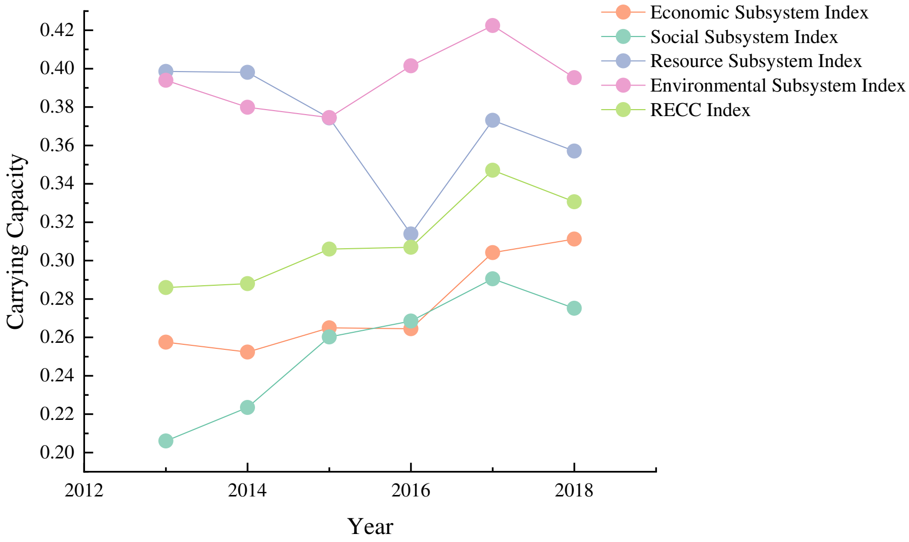


Fig. 4-a Average RECC between 24 cities from 2013 to 2018

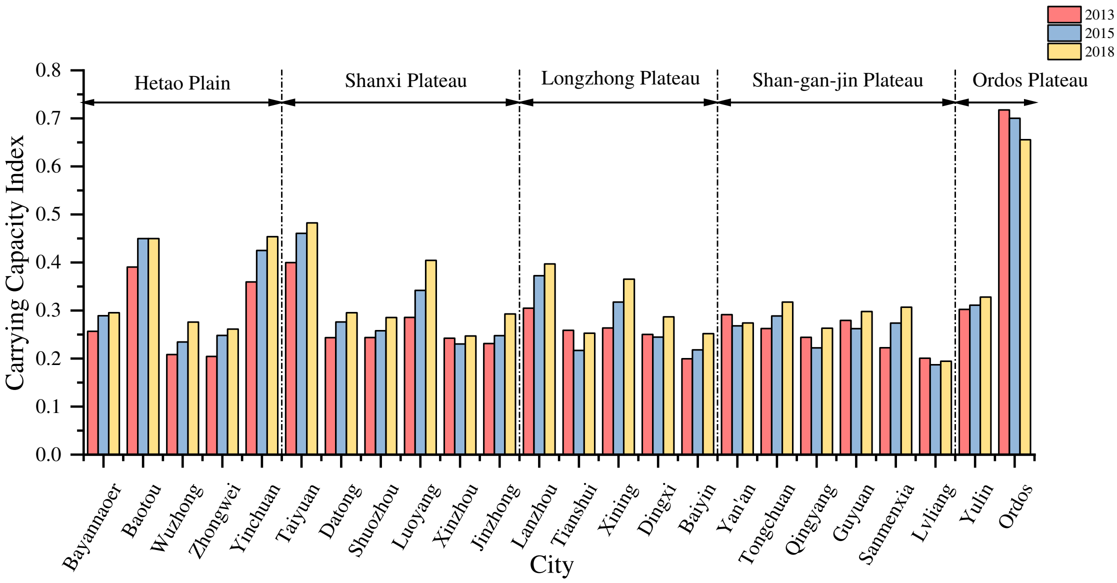


Fig. 4-b RECC performances against the 24 cities in 2013、2015 and 2018

Fig. 4 The RECC performance of 24 cities

Economic subsystem

From the perspective of economic subsystems, the carrying capacity of the economic subsystems of the five natural areas showed an overall upward trend from 2013 to 2018 (Fig. 5-a). Shanxi Plateau has the highest overall growth rate at 28.56%. The data shows that the economic subsystem carrying capacity index of the Ordos Plateau is the highest, reaching 0.5167 in 2018, which is much higher than the other four natural areas.

Social subsystem

From the perspective of social subsystems, the carrying capacity of the social subsystems of the five natural areas showed an overall upward trend from 2013 to 2018 (Fig. 5-a). Shan-Gan-Jin Plateau has the highest overall growth rate at 54.37%. The overall carrying capacity of the social subsystem of the Ordos Plateau has not changed much in six years. It increased slightly from 2014 to 2016 and then showed a downward trend in the next two years. The Ordos Plateau has the highest social subsystem carrying capacity, with an average value of 0.4645 in six years. The growth rate of the social subsystems of Guyuan and Qingyang in the Shan-Gan-Jin Plateau ranks in the top two of the 24 cities, increasing the index value of the Shan-Gan-Jin Plateau substantially.

Resource subsystem

From 2013 to 2018, only the resource subsystem carrying capacity of the Hetao Plain increased slightly, while the index value of the other natural areas decreased to varying degrees. Fig. 5-b shows that the overall decline rate of Shan-Gan-Jin Plateau is the highest at 22.15%. The data shows that the resource subsystem carrying capacity index of the Ordos Plateau is the highest, with an average value of 0.6414 in six years, which is far ahead of the other four natural areas.

Environmental subsystem

From 2013 to 2018, the environmental subsystems carrying capacity of the Longzhong Plateau and Shanxi Plateau showed an upward trend, while the carrying capacity of the Hetao Plain and the Shan-Gan-Jin Plateau remained stable, while the carrying capacity of the Ordos Plateau showed a downward trend (Fig. 5-b). Overall, the difference in the carrying capacity of environmental subsystems among the five natural areas is relatively small, which is the index with the smallest difference among all the subsystems. In the six years, the highest average value of the environmental subsystem index is the Ordos Plateau (0.4723), and the lowest average value is the Shan-Gan-Jin Plateau (0.3517). From the perspective of resource and environmental systems, the best performing area is the Hetao Plain, where the carrying capacity of the resource subsystem and the environmental subsystem have both improved. While in areas where the carrying capacity of the environmental subsystem has increased, the carrying capacity of the resource subsystem of the Longzhong Plateau and Shanxi Plateau has shown a downward trend. The carrying capacity of the resource subsystem and the environmental subsystem of the Shan-Gan-Jin Plateau and the Ordos Plateau both decreased. It shows that the economic-resource-environmental development in most areas of the Loess Plateau is not coordinated.

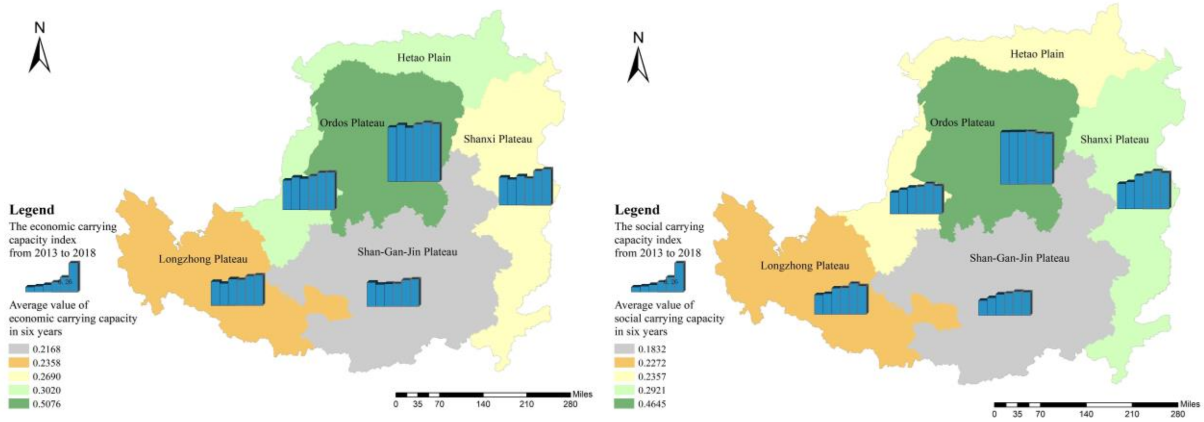


Fig. 5-a Temporal and spatial pattern of carrying capacity (left: economic carrying capacity; right: social carrying capacity)

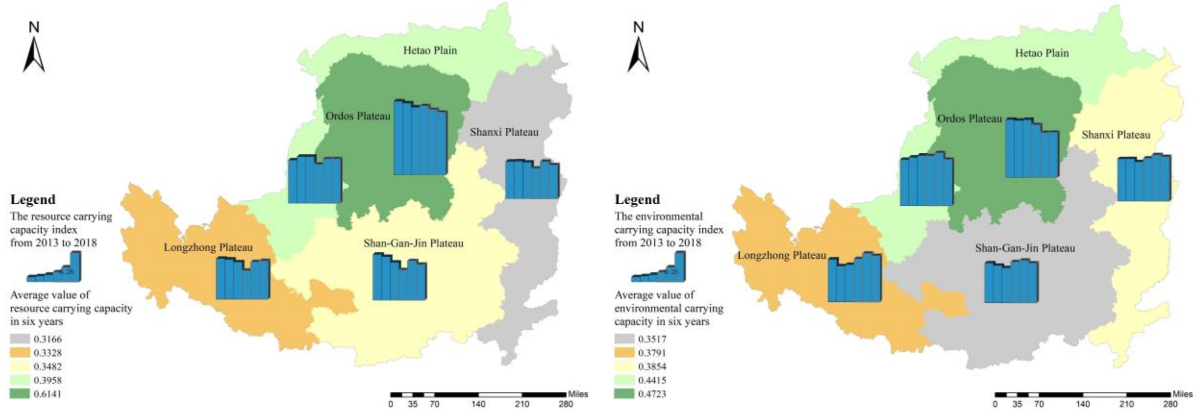


Fig. 5-b Temporal and spatial pattern of carrying capacity (left: resource carrying capacity; right: environmental carrying capacity)

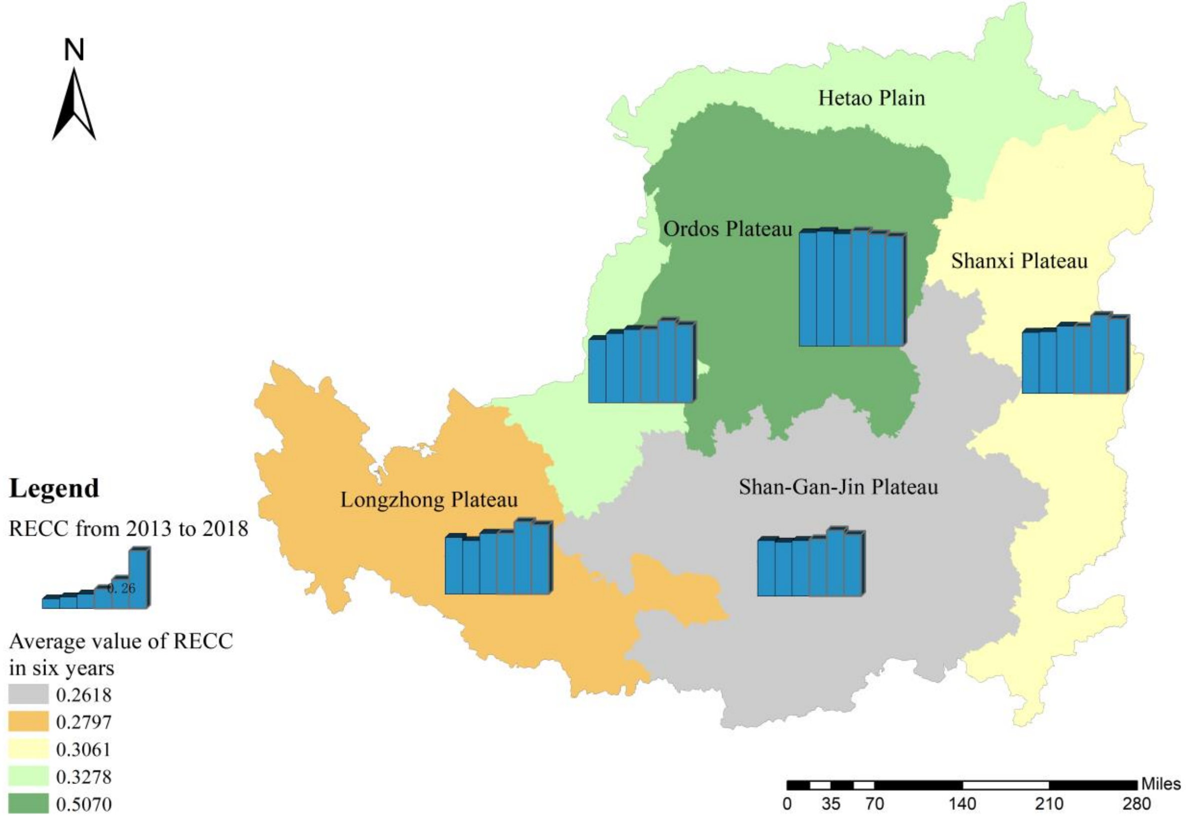


Fig. 5 Temporal and spatial pattern of RECC index

Obstacle factors diagnosis

According to the obstacle factors diagnosis model, we measured the RECC index data of 24 cities from 2013 to 2018 to explore and identify obstacles restricting the improvement of RECC in these cities, which could put forward reasonable countermeasures and suggestions for the optimal development of the Loess Plateau.

Twenty cities have shown improved RECC from 2013 to 2018. Fig. 6 shows the top five obstacles for these cities. The primary obstacles belong to the resource subsystem (in six cities), environmental subsystem (in six cities), and social subsystem (in five cities). Resources, environmental, and social factors put pressure on the improvement of RECC in most cities.

The left side of Fig. 6 shows the primary obstacle indicators of each city. The top obstacle factor is population density (X_8), which is the primary obstacle to the improvement of RECC in Jinzhong, Datong, Taiyuan, and Dingxi. Followed by the four indicators of per capita sown area of crops (X_{13}), per capita urban construction land area (X_{14}), the ratio of industrial solid wastes comprehensively utilized (X_{16}), and green coverage ratio of built-up areas (X_{21}), all of which appear three times. The largest value among all obstacle indicators is the per capita area of paved roads in Baiyin (X_{10}), which reached 59.88%.

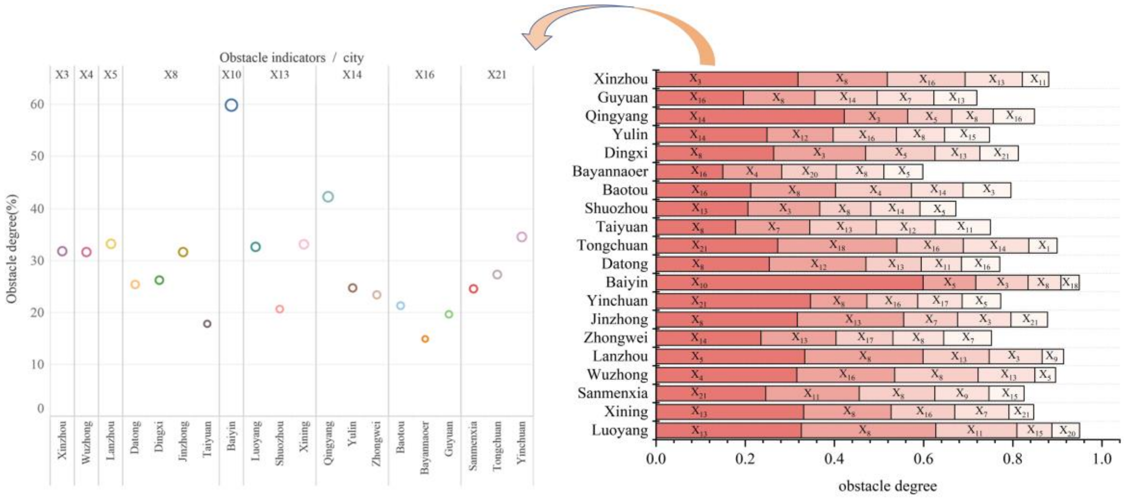


Fig. 6 Obstacle indicators for RECC in 20 cities in 2018 (top five)

Tianshui, Lvliang, Yan'an, and Ordos showed a downward trend in RECC from 2013 to 2018. As shown in Table 4, the main obstacles affecting these four cities in recent years are resource, environmental and social factors. Tianshui and Ordos have the most indicators belonging to the resource subsystem, each accounting for 36.67%, while Lvliang and Yan'an have the most indicators belonging to the environmental subsystem, accounting for 33.33% and 36.67% respectively. The obstacle factors belonging to the social subsystem rank second in Tianshui, Yan'an, and Ordos, accounting for 30%, 23.33%, and 30% respectively.

In 2018, the five major obstacles to the improvement of RECC in the four cities are expenditure for science and technology share of GDP (X_3), population density (X_8), per capita sown area of crops (X_{13}), ratio of industrial solid wastes comprehensively utilized (X_{16}) and per capita water resources (X_{11}), among which the indicator of population density (X_8) appears in all four cities. It indicates that the Loess Plateau is facing a severe population concentration problem, which has become the main factor restricting the improvement of RECC in the Loess Plateau.

Table 4 Obstacle indicators for cities with negative RECC growth from 2013 to 2018 (top five)

Year			2013	2014	2015	2016	2017	2018
items			obstacle indicators / obstacle degree					
Obstacle ranking	Tianshui	1	X_7/12.20	X_7/11.50	X_7/14.94	X_{11}/17.63	X_{11}/17.16	X_3/25.07
		2	X_{18}/9.34	X_{18}/8.47	X_{11}/11.27	X_7/16.24	X_7/15.53	X_8/16.01
		3	X_{14}/7.91	X_{11}/8.07	X_{18}/11.18	X_3/12.95	X_3/12.20	X_{13}/14.35
		4	X_2/7.26	X_{14}/7.95	X_1/9.46	X_9/9.20	X_{14}/9.35	X_{16}/13.86
		5	X_{17}/6.58	X_9/7.16	X_{14}/8.16	X_{14}/7.30	X_8/8.88	X_{11}/12.78
	Lvliang	1	X_{20}/14.83	X_{20}/12.98	X_{20}/11.21	X_{20}/13.40	X_8/17.44	X_{13}/24.02

	2	X_{14}/10.52	X_{14}/8.83	X_{21}/8.16	X_{21}/9.61	X_{7}/15.18	X_{8}/23.00
	3	X_{19}/9.18	X_{11}/8.75	X_{11}/8.02	X_{4}/8.63	X_{13}/14.66	X_{3}/20.04
	4	X_{9}/9.02	X_{19}/7.98	X_{4}/7.19	X_{14}/8.63	X_{16}/10.59	X_{11}/8.67
	5	X_{10}/7.75	X_{9}/7.53	X_{1}/6.79	X_{1}/7.39	X_{4}/8.49	X_{16}/7.44
Yan'an	1	X_{12}/13.41	X_{12}/17.21	X_{12}/14.88	X_{12}/15.90	X_{5}/15.61	X_{17}/19.78
	2	X_{5}/9.98	X_{20}/10.76	X_{17}/13.22	X_{17}/12.17	X_{10}/12.52	X_{8}/15.63
	3	X_{20}/8.23	X_{21}/9.73	X_{10}/8.89	X_{5}/10.22	X_{8}/11.99	X_{3}/14.09
	4	X_{21}/7.67	X_{13}/7.05	X_{19}/7.52	X_{10}/8.24	X_{17}/11.61	X_{5}/13.93
	5	X_{14}/6.55	X_{10}/6.09	X_{20}/6.96	X_{8}/7.31	X_{3}/6.74	X_{16}/10.26
Ordos	1	X_{11}/13.11	X_{14}/19.19	X_{11}/18.04	X_{14}/25.13	X_{14}/16.87	X_{14}/29.32
	2	X_{19}/11.77	X_{11}/14.75	X_{19}/12.73	X_{18}/12.45	X_{11}/11.84	X_{8}/14.17
	3	X_{7}/10.26	X_{19}/10.58	X_{13}/8.67	X_{3}/10.38	X_{7}/10.30	X_{18}/9.78
	4	X_{13}/9.74	X_{7}/8.82	X_{5}/7.85	X_{7}/9.82	X_{20}/8.24	X_{10}/9.35
	5	X_{20}/9.16	X_{13}/8.57	X_{9}/6.26	X_{8}/8.01	X_{8}/7.15	X_{1}/8.97

Discussion

Specific issues in the social context

The results show that the carrying capacity of the economic subsystem of the Ordos Plateau is significantly ahead of other natural areas. According to the latest data from the comprehensive statistical information of cities in western China, in 2019, Yulin and Ordos, located in the Ordos Plateau, ranked sixth and eighth among the cities in Western China with GDP of 413.628 billion yuan and 360.503 billion yuan, respectively. In the Loess Plateau, it is second only to Xi'an, and its economic level is developing well. The resources and energy advantages of the Ordos Plateau have made significant contributions to the economic development of the region. The outstanding performance of the economic subsystem carrying capacity of the Hetao Plain is due to its developed Hetao economy, where the soil is fertile, with developed animal husbandry and aquaculture, and is also the most important agricultural area in Northwest China. The carrying capacity of the economic subsystem of Tongchuan City, which is located on the Shan-Gan-Jin Plateau, has increased the most. This is mainly due to the implementation of the Western Development Strategy, the economic construction goals set out in the 13th Five-Year Plan for National Economic and Social Development of Tongchuan city, and Tongchuan city’s support for high-tech industries in recent years.

From the perspective of social subsystems, Guyuan has performed best in recent years. The reason is that between 2013 and 2018, the per capita area of paved roads and the number of beds in medical and health institutions in Guyuan City increased significantly, the allocation of health resources was more reasonable, and the level of urban construction continued to increase. The urbanization rate of Guyuan has increased by 44.72% in six years, meeting the social development and the increasing service demand of the people.

From the perspective of the resource subsystem, the Shan-Gan-Jin Plateau has declined the most. The reason is that the Shan-Gan-Jin Plateau has serious soil erosion, low vegetation coverage, and the destruction of forestry resources, which restrict the carrying capacity of its resource subsystem. The total water resources per capita of Yan'an and Sanmenxia, located in the Shan-Gan-Jin Plateau, have different degrees of decline, while Lvliang, Guyuan, and Qingyang are limited by the impact of the reduction in the sown area of crops per capita.

From the perspective of environmental subsystems, the Ordos Plateau has declined the most. The reason is that the carrying capacity of the environmental subsystems of Ordos and Yulin in the Ordos Plateau has different degrees of decline. Besides, the ecological environment of the loess area is very fragile. At the same time, the ecological environment protection measures are not enough in the process of resource extraction, which causes the ecological environment to continue to deteriorate, and further leads to a decline in the carrying capacity of the environmental subsystem. Yulin is the city with the most decline among the 24 cities. The comprehensive utilization rate of general industrial solid waste in Yulin City continued to decline in 2017 and 2018, and its utilization rate in 2018 was only 30.29% of 2013. According to the *Bulletin of the State of the Ecological Environment in Shaanxi Province in 2018*, the comprehensive index of environmental air quality in Yulin City in 2018 was 5.38 lower than the average value of 5.72 in Shaanxi Province. The number of days with good ambient air quality in Yulin City in 2018 decreased by 13 days compared with 2017, the city with the largest decrease in Shaanxi Province. Yulin's ecological environment index also ranks low in the province. In general, the carrying capacity of the environmental subsystem of the Ordos Plateau needs to be further strengthened.

Conceptual framework of the RECC influence mechanism

This paper divides the RECC system into two parts: the carried subject and the carried object. The carried subject includes the resource and environmental system, reflecting their ability to support the RECC system, while the carried object includes economic and social systems, reflecting their bearing pressure on the RECC system. This paper uses the entropy-weight-based TOPSIS model to measure and analyze the urban RECC in the Loess Plateau and finds that Ordos is the best city with RECC. Although its RECC has declined in the past two years, its index has remained almost stable from 2013 to 2016, showing an inverted "U" shape, which is similar to existing research (Zheng et al. 2020). The carrying capacity of the resource subsystem has shown a decreasing trend in recent years. According to indicator data, Datong, Shuozhou, Yan'an, and Tianshui are facing problems such as the reduction of total water resources. Taiyuan, Lvliang, Jinzhong, Xinzhou, Baotou, and Dingxi are facing problems such as the reduction of sown area of crops, and this is also a common problem faced by most first-tier cities in China, which is similar to existing research (Zhao et al. 2018, Zhang et al. 2019). Besides, this paper introduces the obstacle factors diagnosis model and finds that the population density (X_8) is the main obstacle to the improvement of RECC for most cities. For cities with a low or negative RECC growth rate, the investment in technological innovation (X_3) also plays a major inhibitory role. The difference between this paper and the existing research (Yang and Yang 2017) is that the RECC fluctuations in Qingyang, Dingxi, and Tianshui are more frequent, caused by the different research areas and research time. Besides, this paper finds that cities with better RECC on the Loess Plateau are mainly located in the north, such as Ordos, Baotou, Taiyuan, and Yinchuan, while cities with higher RECC growth rates in recent years are mainly located in the south, such as Luoyang, Xining, Sanmenxia, Lanzhou, and Zhongwei.

The coordinated development of human-land relationships has a positive effect on sustainable economic development and the cultivation of social values. It is also a prerequisite for improving regional RECC, and further is a guarantee for regional sustainable development and ecological civilization construction. The construction of ecological civilization must take into account economic and social development and the protection of resources and the environment, and respect the rigid constraints of resources and the environment, and correctly understand the regional RECC (Fig. 7). Based on the empirical analysis of the Loess Plateau, this paper finds that the pressure from the social subsystem and the constraints of the resource and environmental subsystems mainly restrict the improvement of RECC. Among them, population pressure, water resources, land resources, environmental governance capabilities, environmental pollution intensity, and environmental resource supply are particularly prominent. The results show that the current economic-resource-environmental development of the Loess Plateau is not coordinated, among which the problem between resource exploitation and environmental protection is a prominent contradiction. The coordinated development and synergy among regional economic and social factors, resource factors, and ecological environment factors are the key to achieving sustainable development.

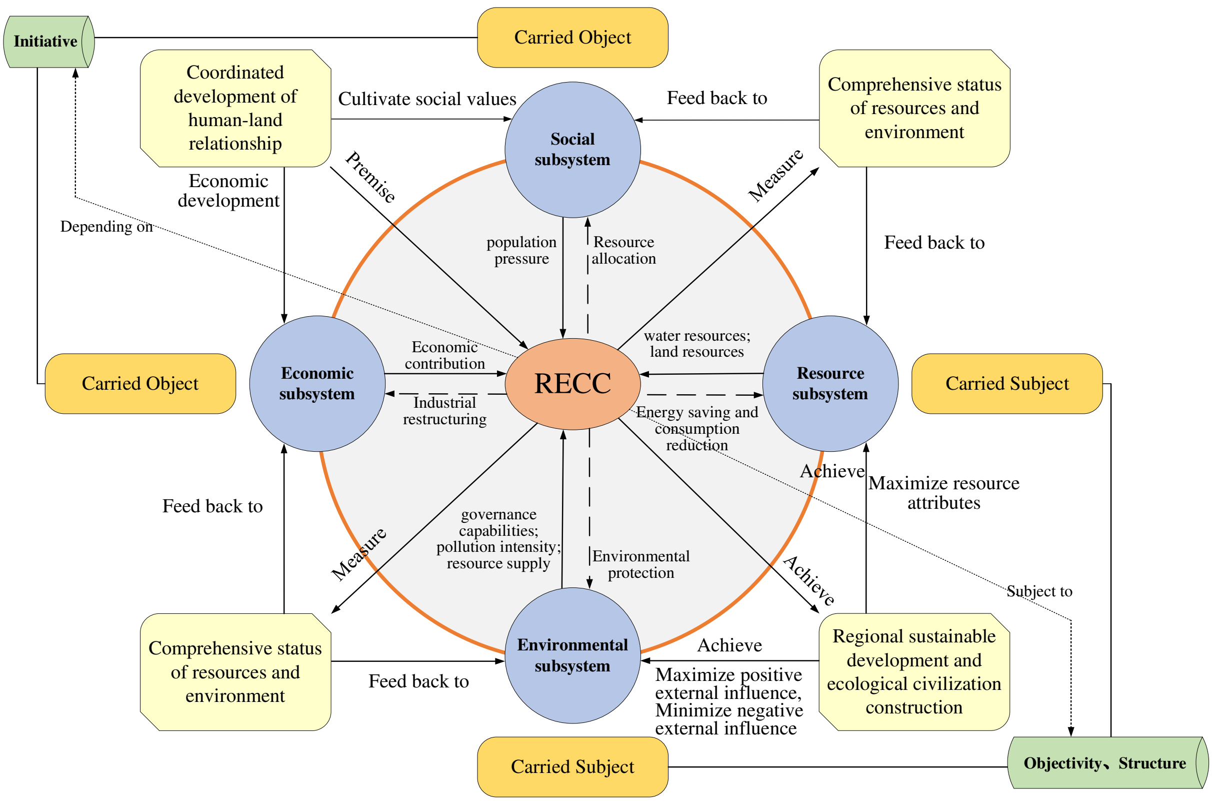


Fig. 7 Conceptual framework of RECC impact mechanism

Limitations

This paper establishes a specific index system to evaluate the regions and cities of the Loess Plateau to hope to analyze and compare the actual RECC levels in various regions more comprehensively. However, it should be noted that this paper selects cities as representative objects, and does not take into account the vast rural areas. The RECC evaluation of the entire Loess Plateau still needs to be further strengthened, and the consideration of rural area indicators can be added in the future. Besides, this paper did not choose cities such as Xi'an, Xianyang, Baoji, and Weinan located in the Loess Plateau to participate in the evaluation because they are geographically closer to the Guanzhong Plain and are representative cities in the Guanzhong Plain urban agglomeration. It can be included in the comprehensive analysis when discussing the carrying capacity of the Loess Plateau in the future.

Conclusions and policy implications

This paper selects 24 representative cities in the five natural areas of the Loess Plateau, establishes an index system that includes economic, social, resource, and environmental carrying capacity, and uses the entropy-weight-based TOPSIS model and obstacle factors diagnosis model to evaluate the RECC and diagnosis its inhibited factors which could support regional sustainable development. The main conclusions of this paper are as follows:

(1) Ordos is the city with the best RECC on the Loess Plateau. However, the carrying capacity of each subsystem and the RECC have been decreasing.

(2) In the Loess Plateau, except for the Ordos Plateau, the RECCs of all other natural areas have increased. The highest growth rate is 22.32% in Hetao Plain, and the least growth rate is 10.22% in Shan Gan Jin Plateau.

(3) The contradiction between economic development and the environment in the Loess Plateau is obvious. The overall RECC of the Loess Plateau is relatively low. The average RECC index in 2018 was 0.3306, with an increase of 15.61% in six years. The rate of increase is low, and there is still a lot of room for improvement.

(4) Population density, investment in technological innovation, per capita sown area of crops, and per capita water resources are the main obstacles to the improvement of RECC.

The research results show that the regional economic and social development level, resource optimization capabilities, and environmental pollution control efforts will affect the regional RECC to varying degrees. To improve the RECC continuously, this paper puts forward the following suggestions: First, focus on solving the contradiction between resources and the environment in the Loess Plateau; second, increase the proportion of tertiary industry and fiscal expenditures, and vigorously develop emerging industries; third, focus on the coordinated development of the Loess Plateau; fourth, appropriate implementation of the city-building plan to solve the problem of excessive population concentration.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors’ contributions

Huan Huang: Conceptualization, Funding acquisition, Supervision. Rui Wang: Writing - original draft, Software, Methodology, Formal analysis. Jue Wang: Writing - review & editing, Methodology, Formal analysis. Jixing Chai: Formal analysis, Validation.

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Figures

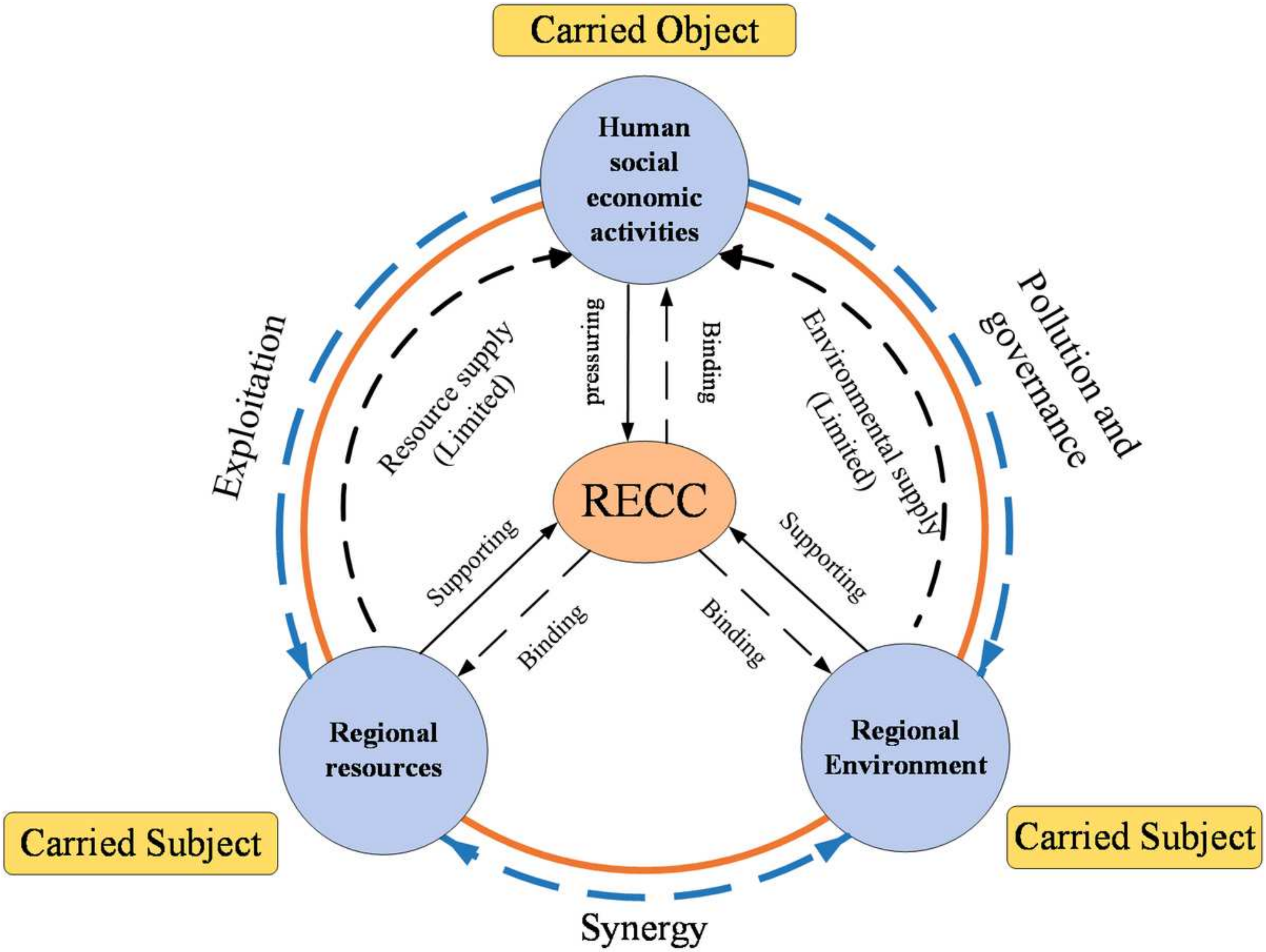


Figure 1

Interaction between the influencing factors of RECC

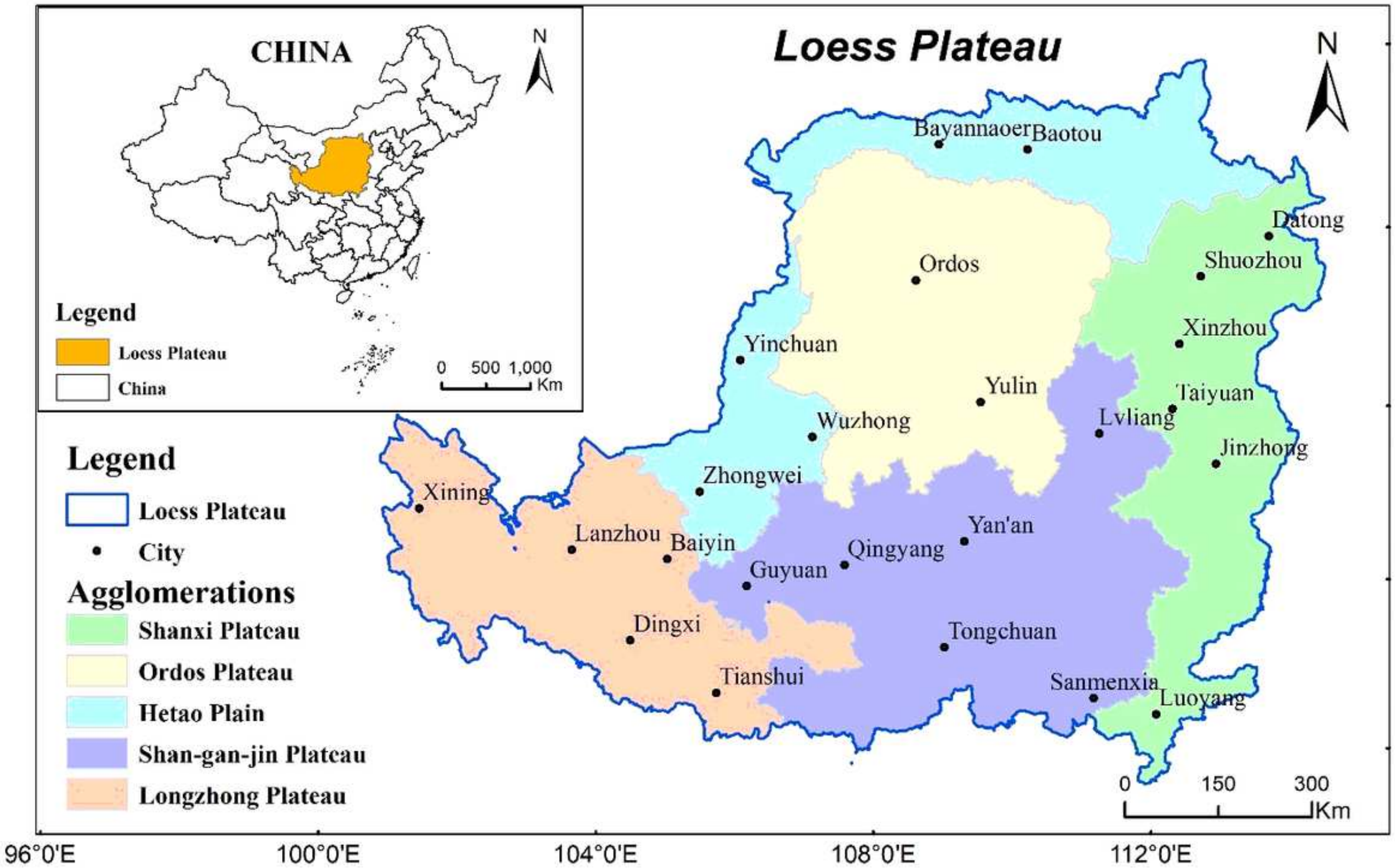


Figure 2

The spatial location of the Loess Plateau region and its representative cities Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

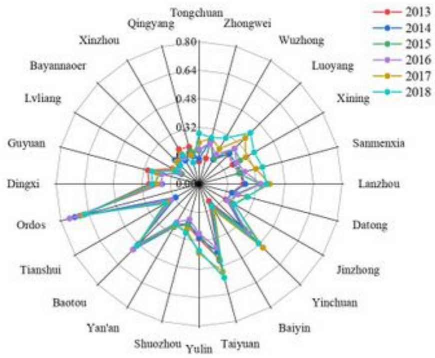


Fig. 3-a The calculation results of economic carrying capacity

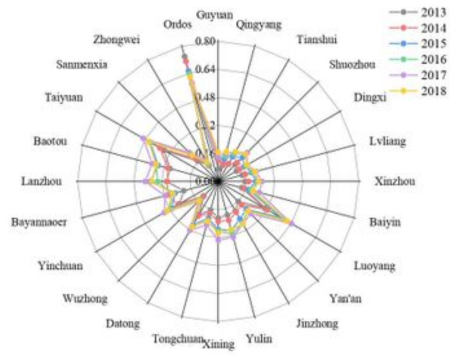


Fig. 3-b The calculation results of social carrying capacity

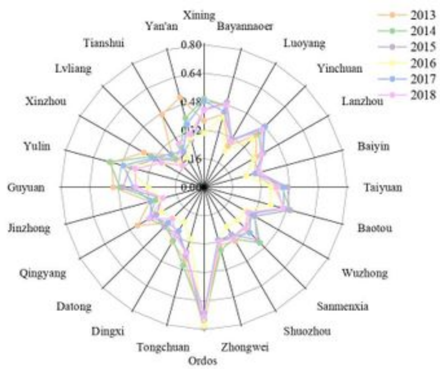


Fig. 3-c The calculation results of resource carrying capacity

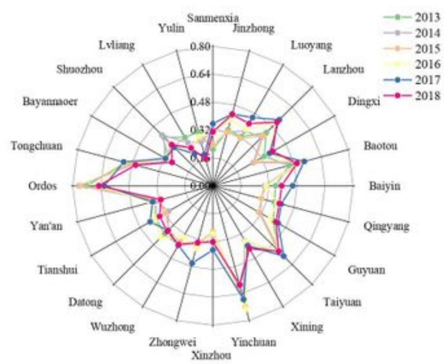
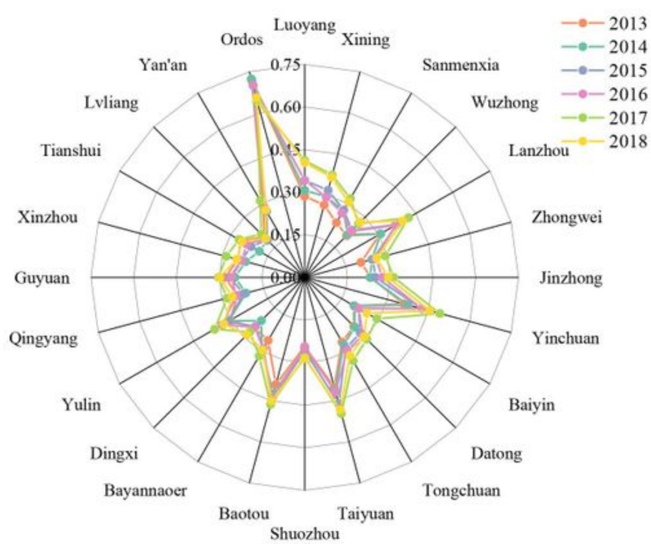


Fig. 3-d The calculation results of environmental carrying capacity



Note: The growth rate of the carrying capacity of each city decreases clockwise at 12 o'clock

Figure 3

The calculation results of RECC in 24 cities from 2013 to 2018

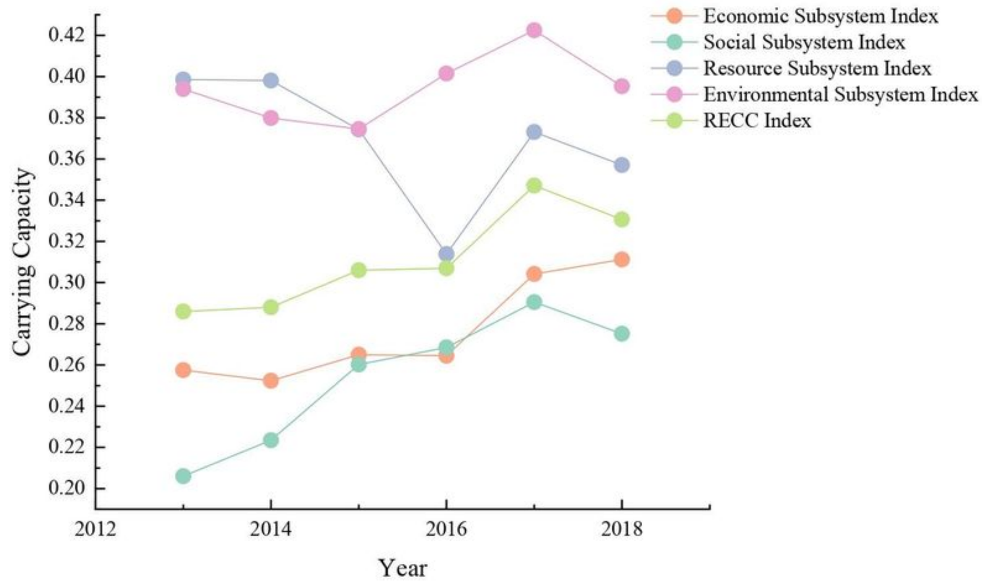


Fig. 4-a Average RECC between 24 cities from 2013 to 2018

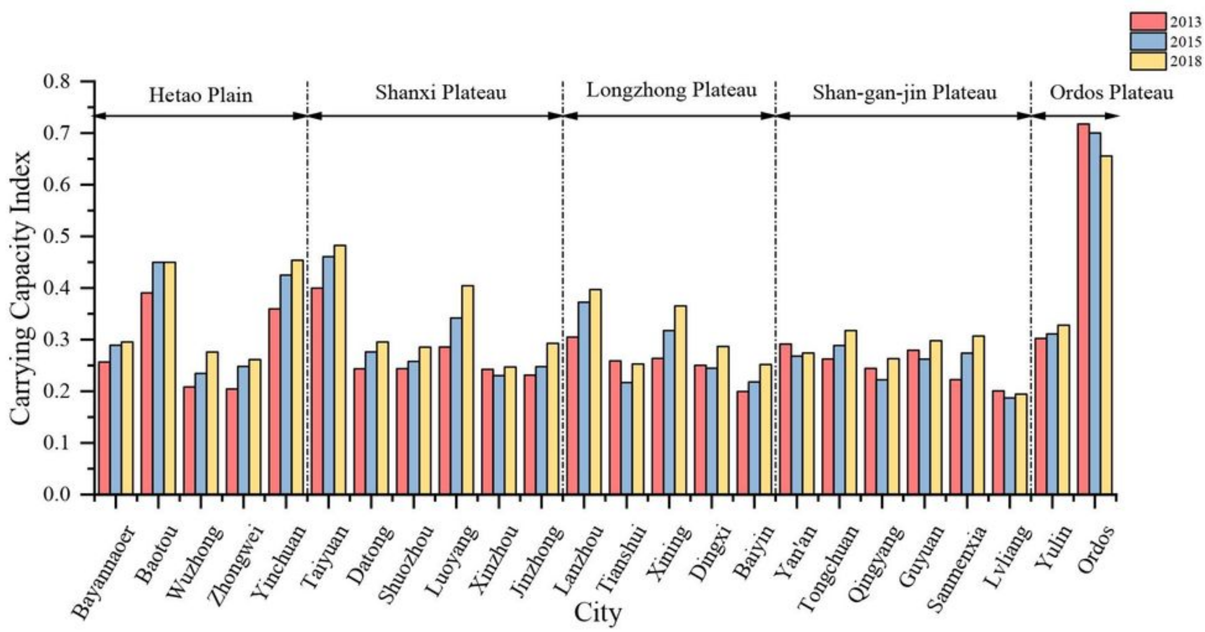


Figure 4

The RECC performance of 24 cities 4-a Average RECC between 24 cities from 2013 to 2018 4-b RECC performances against the 24 cities in 2013、2015 and 2018

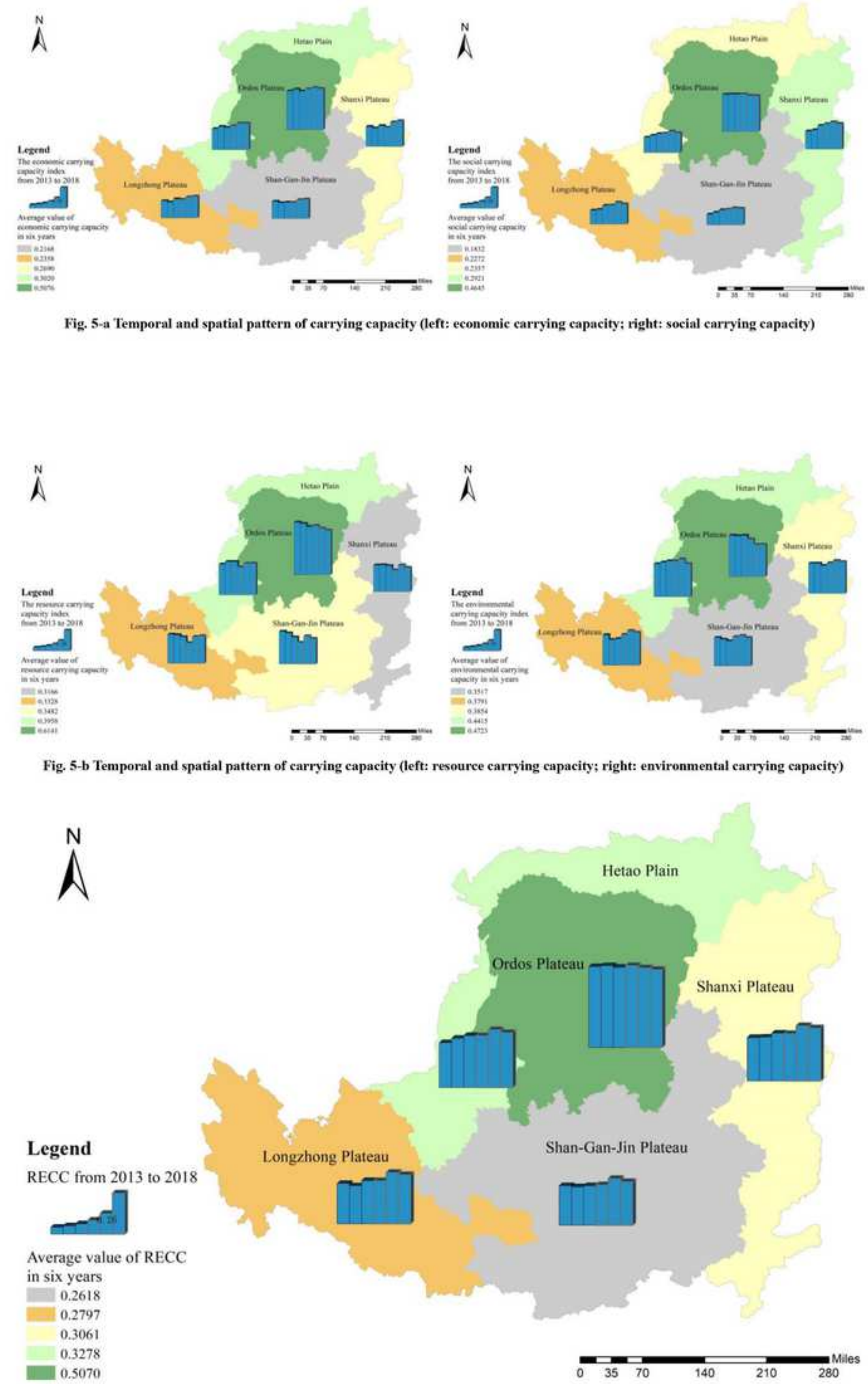


Figure 5

Temporal and spatial pattern of RECC index Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

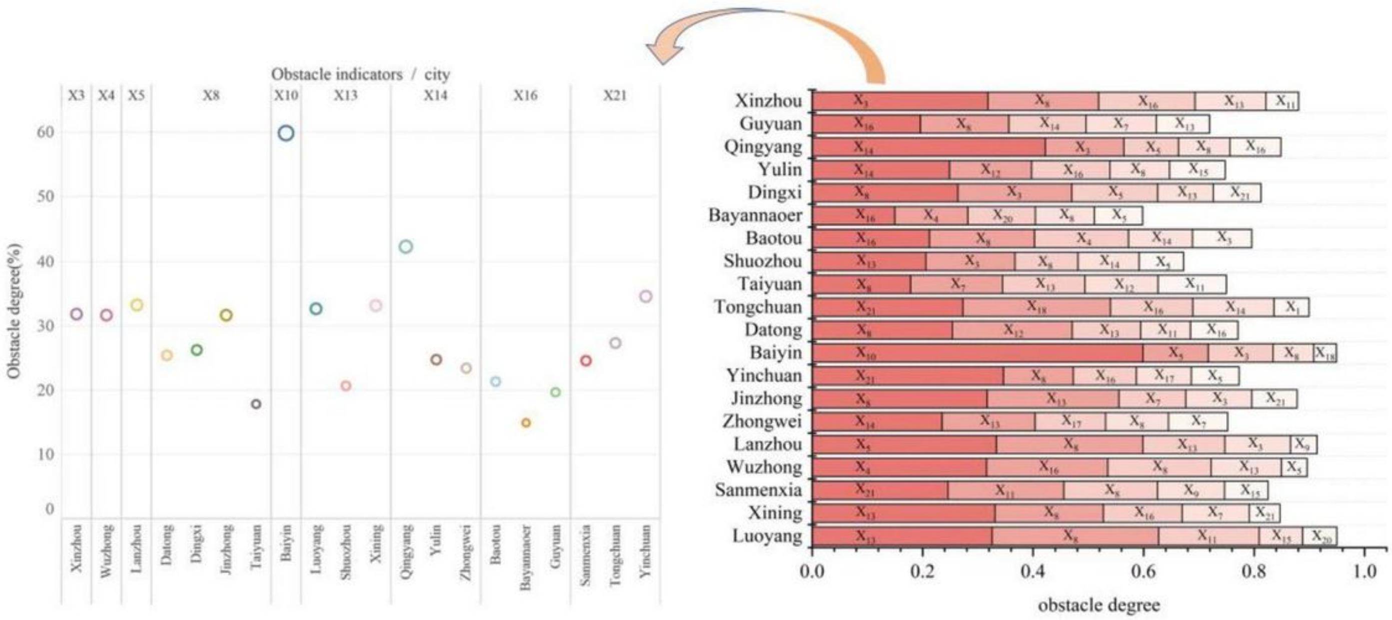


Figure 6

Obstacle indicators for RECC in 20 cities in 2018 (top five)

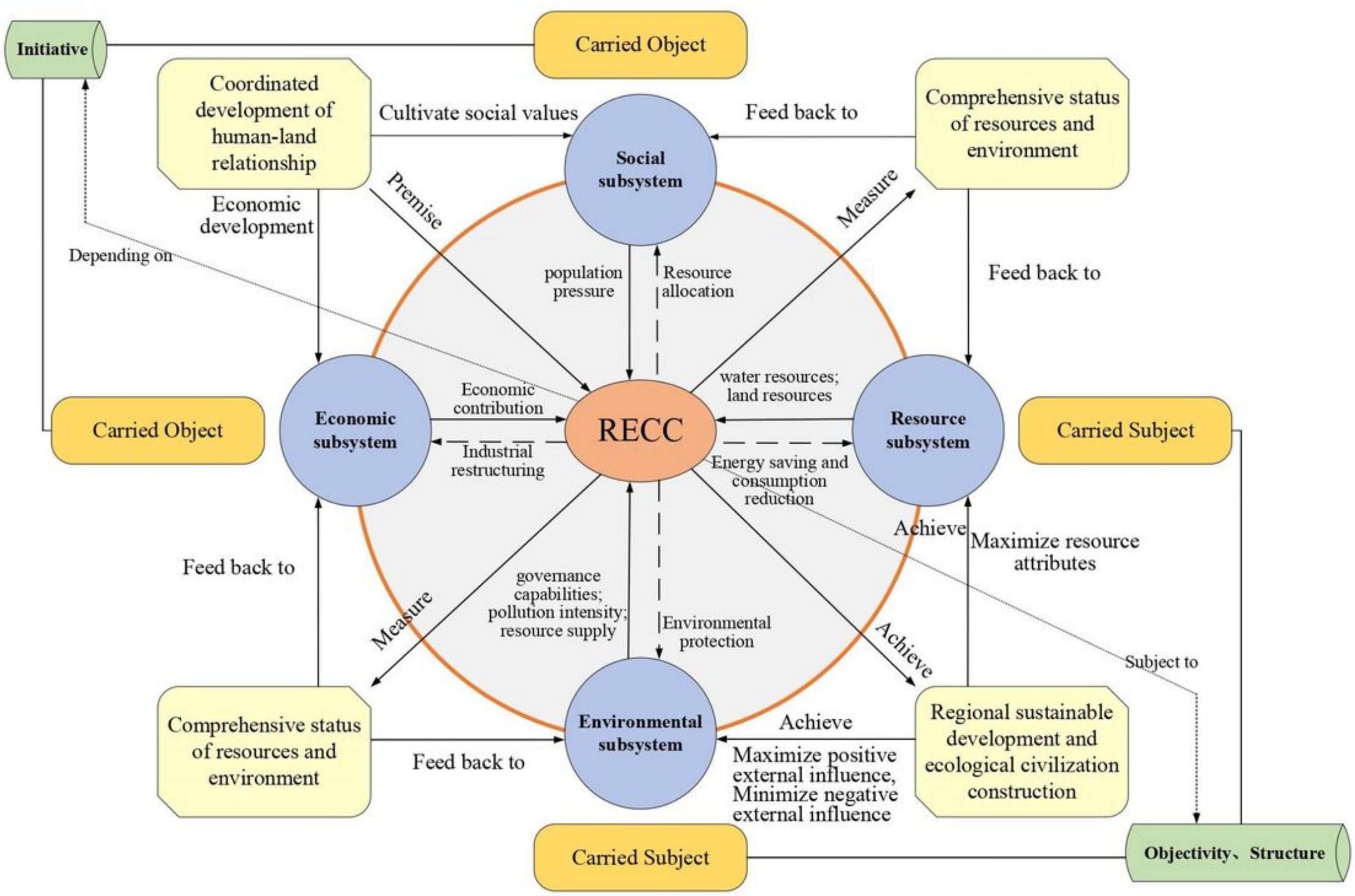


Figure 7

Conceptual framework of RECC impact mechanism

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- SupplementaryFile.docx