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Measurements and Spatial–Temporal Evolution of Urban Comprehensive Carrying Capacity in the Yellow River Basin

Yinghua Lin [1,2,3], Fengjun Jin [1,3,*], Li Ma [1,3] and Jianwei Meng [2]

[1] Key Laboratory of Regional Sustainable Development Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; linyh.19b@igsnrr.ac.cn (Y.L.); mali@igsnrr.ac.cn (L.M.)
[2] School of Geography and Environment, Liaocheng University, Liaocheng 252059, China; 2110140212@stu.lcu.edu.cn
[3] University of Chinese Academy of Sciences, Beijing 100049, China
* Correspondence: jinfj@igsnrr.ac.cn

Abstract: An evaluation index system was conducted to determine the urban comprehensive carrying capacity of the Yellow River Basin using four subsystems (resources, society, ecology, and economy). The urban comprehensive carrying capacity level of nine provinces in the Yellow River Basin from 2008 to 2019 was determined using the entropy weight TOPSIS model, and the spatial and temporal dynamics of the urban comprehensive carrying capacity of each province were investigated. There were four key results. (1) The urban comprehensive carrying capacity of the upstream and downstream provinces decreased from 2008 to 2011 and increased from 2011 to 2019; in the midstream provinces, it increased from 2008 to 2011 but decreased after 2011. (2) The urban comprehensive carrying capacity of the Yellow River Basin was "high in the east and west, low in the middle" from 2008 to 2017, while in 2019, the distribution was "high in the west and low in the east." The gap between the urban comprehensive carrying capacities of the nine provinces and regions gradually narrowed over the study period. (3) The urban comprehensive carrying capacity of the Yellow River Basin increased annually during the study period. (4) The urban comprehensive carrying capacity was mainly influenced by the social and ecological subsystems.

Keywords: Yellow River Basin; provincial; urban comprehensive carrying capacity; entropy weight TOPSIS

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Citation: Lin, Y.; Jin, F.; Ma, L.; Meng, J. Measurements and Spatial–Temporal Evolution of Urban Comprehensive Carrying Capacity in the Yellow River Basin. *Land* **2023**, *12*, 1846. https://doi.org/10.3390/land12101846

Academic Editors: Alexandru-Ionuţ Petrişor and Fabrizio Battisti

Received: 14 July 2023
Revised: 9 September 2023
Accepted: 12 September 2023
Published: 27 September 2023

1. Introduction

As an important economic zone in China, the Yellow River Basin is both a major agricultural production area and an important energy, chemical, raw material, and industrial base. It has a pivotal, strategic position in the pattern of national economic and social development and ecological civilization construction.

Ecological protection and high-quality development of the Yellow River Basin have become major national strategies. However, due to climate change and human activity, the Yellow River Basin faces resource and environmental problems and has a low level of development and inadequate development. Therefore, it is especially important to conduct a comprehensive analysis of the Yellow River Basin and its urban comprehensive carrying capacity. As an organic combination of resources, environment, ecosystems, infrastructure, security, and public services, comprehensive carrying capacity reflects the state of each of these elements [1,2]. Therefore, it is of great practical significance to solve the problems faced by the Yellow River Basin and promote its high-quality development by studying the urban comprehensive carrying capacity of the provinces in the basin as the results will help to understand its current situation and ongoing changes.

The term carrying capacity first appeared in the field of ecology, where it refers to the size and number of biological populations exceeding the limits of ecological tolerance, resulting in ecological damage. Previous studies of carrying capacity focused mainly on single elements, such as land carrying capacity, water carrying capacity, mineral carrying capacity, and cultural carrying capacity in the absence of resources [3–8]. The study of single-factor carrying capacity focused on exploring the two-way relationship between the carrier (water resources, mineral resources, environmental capacity, etc.) and the carried object (human beings and their socio-economic activities). It is of great practical significance to study the carrying capacity of land because it is the most important material basis for human survival. Because water, mineral, and environmental resources are external conditions and prerequisites for human economic development and social progress, the regional human–land system is a complex and open system consisting of human beings and their activities and resources in relation to the environment. The relationship between any two sub-elements in this system cannot simply be a two-way relationship. It is an intricate, multi-feedback, multi-loop, and circular network of relationships.

Researchers have recently begun to conduct comprehensive evaluations of multi-factor carrying capacities. They have constructed comprehensive evaluation index systems for carrying capacities from the perspective of multiple elements, carried out empirical analyses and quantitative evaluations, and proposed countermeasures and paths for carrying capacity enhancement [9,10]. At the start of the 21st century, carrying capacity research began to shift from single-factor carrying capacity research to multi-factor integrated carrying capacity research. Shi et al., Sun et al., Li and Zhao, Kong et al., and Ren et al. [11–15] showed that urban comprehensive carrying capacity is an organic system, mainly involving population carrying capacity, resource and environmental carrying capacity, economic carrying capacity, infrastructure carrying capacity, and social carrying capacity. The spatial–temporal development of various carrying capacities and their interactions are restricted by natural factors and social and economic influences. Shao et al., Diao et al., and Long et al. [16–18] constructed an analytical framework to determine the comprehensive carrying capacity of urban agglomerations in terms of their economy, society, environment, ecology, and transportation. They used the mean square deviation, the panel vector regression model, the entropy method, the urban comprehensive carrying capacity measurement model, the urban sustainable development model, and the TOPSIS method to analyze the carrying capacity of the urban agglomerations of Harbin, Chengdu, Guangdong, Hong Kong, and Macao Greater Bay Area and then made a comprehensive measurement of the spatial–temporal development of the comprehensive carrying capacities of these cities. In recent years, Cao and Zhao, Liu, Lu, Huang, Ge and Zheng, Liu et al., Li et al., and Zhao and Li [19–26], and other researchers have analyzed the level of the comprehensive carrying capacity of Chinese provinces, cities, and urban agglomerations. They studied typical cities on the national, urban agglomeration, and urban scales, using the state–space method, the TOPSIS method, the temporal global factor analysis method, the clustering method, the Gini coefficient, kernel density, and temporal and spatial differences. The general intention of the analyses was to construct a system of indicators, including the economy, society, resources, environment, infrastructure, and public services, and select appropriate methods for qualitative and quantitative analyses.

It has been shown that the combined carrying capacity has a “barrel effect,” whereby the size of a city depends on the carrying capacity of one of its shortcomings. However, empirical studies in Shanghai, China, and Tokyo, Japan, have shown that under factor mobility, the minimum factor cannot be the limiting factor in urban development. Therefore, when resources and factors flow and interact during the development of a city, the synergistic effect of multiple factors jointly affects its overall development dynamics [11,26]. However, current quantitative research on comprehensive carrying capacity has not produced a unified index system or standard, and there are only a few studies on the comprehensive carrying capacity of the Yellow River Basin. Therefore, there is a need for further research on the comprehensive carrying capacity of the region.

In summary, studies on the total carrying capacity of cities have largely concentrated on the eastern provinces, cities, and urban agglomerations, while research on the total carrying capacity of the Yellow River Basin provinces is still incomplete. Therefore, to construct an evaluation index system for the comprehensive carrying capacity of the Yellow River Basin provinces, this paper uses the entropy weight TOPSIS model to measure the comprehensive urban carrying capacity level of the nine provinces in the Yellow River Basin using relevant data from 2008 to 2019. The dynamic spatial and temporal changes in the comprehensive urban carrying capacity of the Yellow River Basin provinces are also quantitatively analyzed. The model provides references for an improvement in the comprehensive urban carrying capacity of the Yellow River Basin provinces and the high-quality development of the region.

2. Study Area and Research Methods

2.1. Research Area and Data Sources

The Yellow River Basin (Figure 1) connects the nine provinces of Qinghai, Sichuan, Gansu, Ningxia, Shaanxi, Shanxi, Inner Mongolia, Henan, and Shandong in three areas in the east and west of China. (1) Upstream of the Yellow River, Qinghai, Gansu, Ningxia, and other provinces have a low level of economic development, a fragile natural environment, inadequate social security, and a need for improvements in the levels of science and technology. (2) In the middle reaches of the Yellow River Basin, Shaanxi, Shanxi, Inner Mongolia, and other provinces are rich in resources and energy, but the economic structure is unstable and the over-reliance on resources has resulted in ecological fragility and serious environmental pollution, and the level of economic development quality is poor. (3) The downstream provinces of Henan and Shandong have a high level of development, but they are not capable of scientific and technological innovation, and there is a need for industrial transformation. As a result, there are great differences in the comprehensive urban carrying capacity among the Yellow River Basin provinces, mainly in terms of social, economic, ecological, resource, and scientific and technological conditions. Therefore, it is crucial to thoroughly examine the Basin's urban carrying capacity. The Yellow River Basin's nine provinces and regions were selected as the research area in this study. The study period from 2008 to 2019 was selected to make it easier to organize and gather data. The Statistical Bulletin of National Economic and Social Development and the Provincial Statistical Yearbooks provided data for this study, and the average annual growth rate was utilized to fill in the gaps.

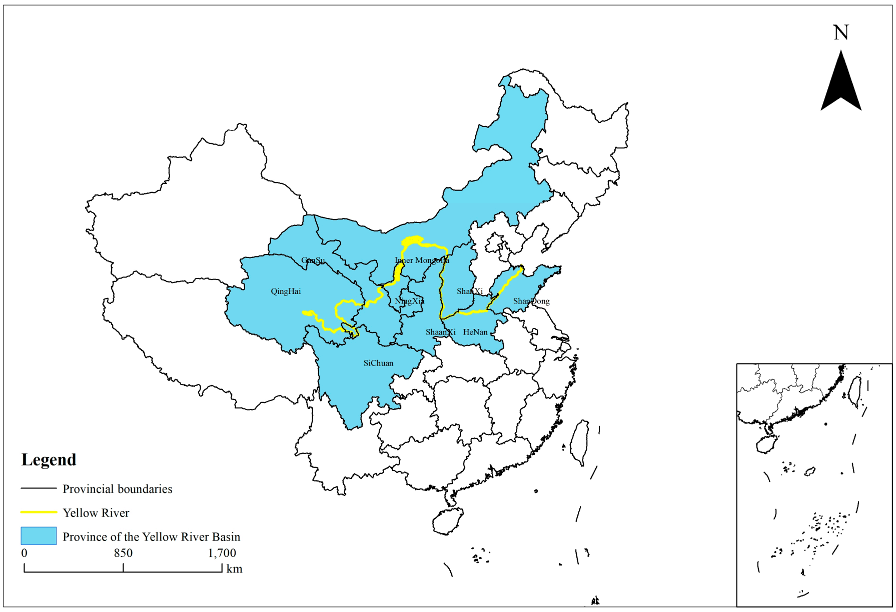

Figure 1. The study area.

2.2. Construction of an Urban Comprehensive Carrying Capacity Evaluation Index System

The comprehensive carrying capacity, a complicated, multi-factor, limited comprehensive system, is affected by a variety of factors. The concept of a "threshold" in this study integrates the findings of previous research and refers to the upper limit that a city can support to achieve sustainable development while being constrained by certain energy resources and economic, social, ecological, and environmental development conditions. This study built on previous research and combined the characteristics of the Yellow River Basin to consider the comprehensive urban carrying capacity as a system that included the following four subsystems: resources, society, ecology, and economy. Using the analytic hierarchy process (AHP) method, the evaluation index system was divided into target layers, criterion layers, and indicator layers, which combined the concept of comprehensive carrying capacity. The comprehensive carrying capacity was used as the target layer, and the criterion layer was formed on this basis. The evaluation index system was constructed based on the basic principles of comprehensiveness, scientificity, accessibility, hierarchy, and dynamism. Finally, the four subsystems including resources, society, ecology, and economy were selected as the criterion layers in the comprehensive carrying capacity of the city, and 24 indicators were selected to form the index layer. Resources and economy are the material basis of the system; good resource and economic conditions can effectively guarantee that the comprehensive carrying capacity of the region is in a high-value state. The ecological conditions are the constraints of the system; they play a limiting and restricting role in the comprehensive carrying capacity of the region. The ultimate purpose of enhancing the comprehensive carrying capacity of urban areas is to improve the social security of the population and to enhance the capacity of social services. The evaluation indexes are divided into "benefit" indexes and "cost" indexes. "Benefit" indexes refer to the indicators that have a positive effect on the comprehensive carrying capacity. The larger the index value of positive indicators, the better. "Cost" indexes refer to the indicators that have a negative effect on the comprehensive carrying capacity. The smaller the index value of the negative indicators, the better (see Table 1).

Table 1. Evaluation index system for the comprehensive carrying capacity of cities in the Yellow River Basin.

Target Layer	Criterion Layer	Indicator Layer	Indicator Attributes	Indicator Weights
Comprehensive carrying capacity (A)	Resource subsystem (B1)	Water resources per capita (C1)	Benefit type	0.1446
		Natural gas supply per capita (C2)	Benefit type	0.0471
		Land development intensity (C3)	Benefit type	0.0813
		Coal production per capita (C4)	Benefit type	0.0670
		Electricity generation per capita (C5)	Benefit type	0.0329
		Food production per capita (C6)	Benefit type	0.0236
	Social subsystem (B2)	Unemployment rate (C7)	Cost type	0.0440
		Population density (C8)	Cost type	0.0411
		Number of beds in health facilities per 1000 people (C9)	Benefit type	0.0504
		Average number of students shared by teachers (C10)	Cost type	0.0038
		Urbanization rate (C11)	Benefit type	0.0084
		Urban roads per capita (C12)	Benefit type	0.0044
	Ecological subsystem (B3)	Forest cover (C13)	Benefit type	0.0353
		Area of crop damage (C14)	Cost type	0.0358
		Harmless domestic waste treatment rate (C15)	Benefit type	0.0409
		Industrial SO_2 emissions per 10,000 people (C16)	Cost type	0.0252
		Investment in industrial pollution control as a proportion of GDP (C17)	Benefit type	0.0345
		Wastewater emissions per capita (C18)	Cost type	0.0057
	Economic subsystem (B4)	Gross national product per capita (C19)	Benefit type	0.0097
		Number of industrial enterprise units (C20)	Benefit type	0.0980
		Value added by tertiary industry (C21)	Benefit type	0.0052
		Per capita disposable income of residents (C22)	Benefit type	0.0500
		Investment in fixed assets (C23)	Benefit type	0.0592
		Local fiscal tax revenue (C24)	Benefit type	0.0517

2.3. Methods

2.3.1. The Entropy Weighting Method to Determine the Index Weights

The entropy weight method is an objective assignment method. It relies only on the degree of variation in the data itself according to the degree of variation in each indicator. The smaller the degree of variation in the indicator, the less information it reflects, and the smaller its corresponding weight. The entropy weight of each indicator was calculated using the information entropy, and the weight of each indicator was corrected with the entropy weight, providing an objective indicator weight. The comprehensive carrying capacity index system for urban areas consisted of 24 indicators. The more information these indicators carry, the smaller the entropy and the larger the weight. The steps to determine the weights using the entropy weight method were calculated as follows:

(1) Construct the original matrix C.

Let the year in the evaluation of the comprehensive carrying capacity of the Yellow River Basin be $Y = \{Y_1, Y_2, Y_3, \ldots, Y_m\}$, containing a total of $S = \{S_1, S_2, S_3, \ldots, S_\mu\}$ provinces and a total of $I = \{I_1, I_2, I_3, \ldots, I_n\}$ indicators, and construct the original matrix for each year as in Equation (1), where $x_{\mu ij}$ is the value of the jth indicator in the ith year of a province, $i \in m, j \in n$

$$C = \{x_{\mu ij}\}_{m\times n} = \begin{Bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{Bmatrix} \quad (1)$$

(2) Standardization using the polarization method.

For the positive index, the treatment is completed as in Equation (2):

$$x\prime_{\mu ij} = (x_{\mu ij} - x_{min})/(x_{max} - x_{min}). \quad (2)$$

For negative vectorization, the indicators are treated as in Equation (3).

$$x\prime_{\mu ij} = (x_{max} - x_{\mu ij})/(x_{max} - x_{min}). \quad (3)$$

(3) Calculate the share of the jth sample under the ith indicator of a province, $P_{\mu ij}$. The standardization matrix H is obtained using standardization:

$$H = \begin{Bmatrix} h_{11} & h_{12} & \cdots & h_{1n} \\ h_{21} & h_{22} & \cdots & h_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ h_{m1} & h_{m2} & \cdots & h_{mn} \end{Bmatrix}. \quad (4)$$

Calculate the probability matrix P:

$$P_{\mu ij} = Z_{ij}/\sum_{i=1}^{m} Z_{ij}. \quad (5)$$

(4) Calculate the information entropy of each index and obtain the entropy weight of each index, where e_j is the information entropy of the jth indicator in the city comprehensive carrying capacity index, and the calculation formula is:

$$e_j = -\alpha \sum_{i=1}^{m} P_{\mu ij} \ln P_{\mu ij},\ \alpha = \frac{1}{\ln m}. \quad (6)$$

Using information entropy, calculate the information utility value; the larger the information utility value, the more information corresponds to:

$$d_j = 1 - e_j. \tag{7}$$

Normalize the information utility values to obtain the entropy weight of each indicator:

$$w_j = d_j / \sum_{j=1}^{n} d_j. \tag{8}$$

2.3.2. Construction of the Entropy-Weighted TOPSIS Model

The TOPSIS method, i.e., the distance method for superior and inferior solutions, is a common comprehensive evaluation method that makes full use of the information in the original data and accurately reflects the closeness of the ideal target's positive and negative distance. The calculation steps of the TOPSIS model are as follows:

(1) Calculate the weighting matrix Z, where $i \in m$, $j \in n$:

$$Z = \{w_j \times x'_{\mu ij}\}_{m \times n} = \begin{Bmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & z_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ z_{m1} & z_{m2} & \cdots & z_{mn} \end{Bmatrix}, \tag{9}$$

(2) Determine the positive ideal solution matrix $Z^+ = \{z_1^+, z_2^+, \cdots, z_n^+\}$ and the negative ideal solution matrix $Z^- = \{z_1^-, z_2^- \cdots, z_n^-\}$:

$$Z^+ = (max\{z_{11,}z_{21}, \cdots, z_{m1}\}, max\{z_{12,}z_{22}, \cdots, z_{m2}\}, \cdots, max\{z_{1n,}z_{2n}, \cdots, z_{mn}\}), \tag{10}$$

$$Z^- = (min\{z_{11,}z_{21}, \cdots, z_{m1}\}, min\{z_{12,}z_{22}, \cdots, z_{m2}\}, \cdots, min\{z_{1n,}z_{2n}, \cdots, z_{mn}\}), \tag{11}$$

(3) Measure the optimal and inferior distances. The Euclidean distance is used to calculate the distance D_i^++ and D_i^- of the ith evaluation object from Z^+ and Z^-:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(z_j^+ - z_{ij}\right)^2},\ D_i^- = \sqrt{\sum_{j=1}^{n} \left(z_j^- - z_{ij}\right)^2} \tag{12}$$

(4) Measure the closeness of the evaluation object to the ideal solution F_i:

$$F_i = D_i^- / \left(D_i^+ + D_i^-\right). \tag{13}$$

Normalize F_i, where the closeness takes the value range of 0–1. The larger the F_i, the better the comprehensive carrying capacity of the city. The calculation formula is as follows:

$$F_i' = F_i / \sum_{i=1}^{m} F_i \tag{14}$$

3. Spatial–Temporal Evolution Results for the Urban Comprehensive Carrying Capacity in the Yellow River Basin

3.1. Analysis of Overall and Subsystem Changes in the Yellow River Basin

We calculated the comprehensive score for the comprehensive carrying capacity of the cities in the Yellow River Basin and the score for each subsystem using the annual change score in the comprehensive carrying capacity of each province in the Yellow River Basin (see Figure 1). Since the development of the Yellow River Basin's comprehensive carrying capacity, its carrying capacity has increased annually from 2012 to 2019. The carrying capacity of all four subsystems improved to some extent. The carrying capacity of the resource and economic subsystems increased annually. The carrying capacity of the ecological subsystem decreased annually from 2008 to 2011, and the overall carrying capacity of the Yellow River Basin decreased slightly from 2008 to 2011. From 2008 to 2011, the ecological subsystem's carrying capacity decreased annually, but after 2012, it began to increase annually. The social subsystem increased annually from 2008 to 2013, with a decreasing trend after 2013. The reason for this was strongly correlated with the increase in population density per unit area and the increase in the unemployment rate. The trend in the ecological subsystem was directly related to the amount of investment in industrial pollution control and the emission of wastewater and waste gas in each province. The economic subsystem increased annually and had a large growth rate related to the national economic development, which improved annually. The carrying capacity of the resource subsystem increased annually due to the increase in the total amount of resources in each province, which drove the annual increase in the per capita resources.

3.2. Analysis of Spatial and Temporal Changes

As Figure 2 shows, the comprehensive carrying capacity of cities in the Yellow River Basin from 2008 to 2019 had a spatial distribution pattern indicating "high in the east and west, low in the middle", and the spatial difference between the cities' comprehensive carrying capacities gradually decreased. In 2008, the ranking of comprehensive carrying capacity from high to low was as follows: Ningxia, Inner Mongolia, Shanxi, Sichuan, Henan, Shandong, Qinghai, Gansu, and Shaanxi. Ningxia had the highest urban comprehensive carrying capacity, while Shaanxi had the lowest. In 2019, the spatial distribution of the comprehensive carrying capacity of the Yellow River Basin provinces changed, although it still displayed a state of "high in the west and low in the east." The comprehensive carrying capacity scores of the nine provinces and regions improved compared with 2008. The carrying capacity gap in the Yellow River Basin narrowed between the provinces from 2008 to 2019, and the cities with the highest and lowest carrying capacities in 2019 were located in Qinghai, Ningxia, Gansu, Henan, Sichuan, Shaanxi, Shandong, Shanxi, and Inner Mongolia. During the study period, the comprehensive carrying capacity of Sichuan, Inner Mongolia, and Shaanxi maintained an essentially upward trend, with small twists and turns in the middle. Gansu was relatively stable from 2008 to 2012, basically remaining at about 0.07, and, from then to 2019, the comprehensive carrying capacity continued to rise. Qinghai displayed an upward trend from 2012 to 2019, reaching the top spot in 2019. Shanxi experienced a trend in development that involved first falling, then becoming relatively stable, then falling and rising again, with turning points in 2014 and 2015. Henan experienced a process of development that involved first falling and then rising, with a turning point in 2011. Shandong remained relatively stable after a slow rise. Ningxia's comprehensive carrying capacity underwent a change process that involved first falling and then rising.

Using the entropy power TOPSIS model, the comprehensive urban carrying capacity level of the nine provinces and regions in the Yellow River Basin was measured spatially. Figure 3 shows the 2008–2019 measurements.

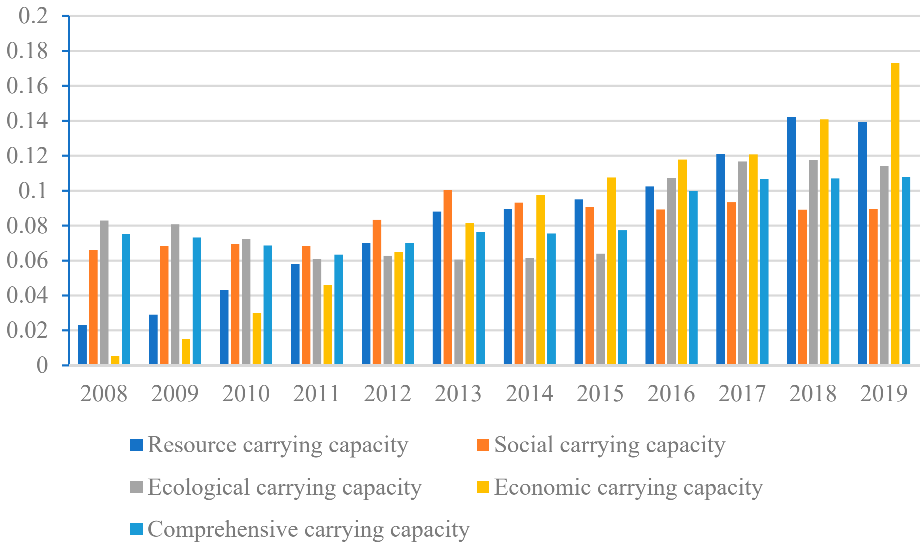

Figure 2. Changes in the comprehensive carrying capacity and carrying capacity of each subsystem in the Yellow River Basin.

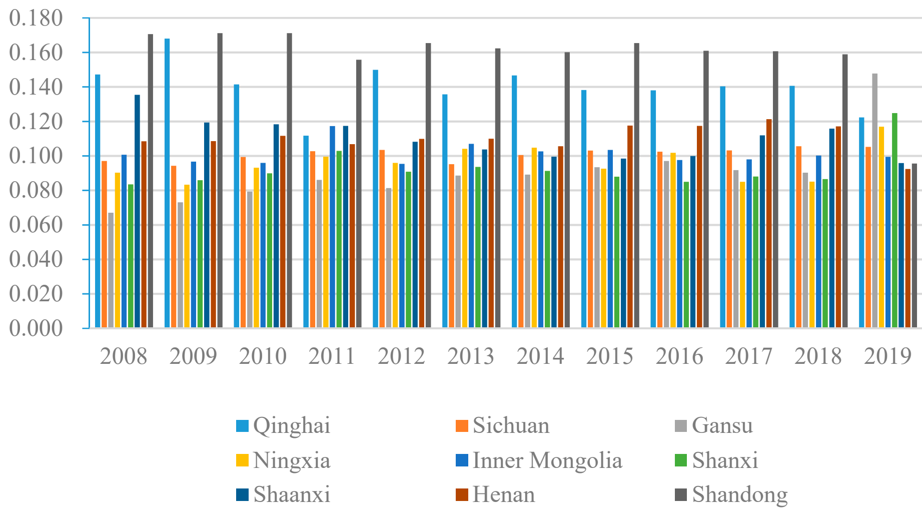

Figure 3. Development of the comprehensive carrying capacity of the Yellow River Basin provinces from 2008 to 2019.

(1) Analysis of the carrying capacity of the ecological subsystem

The carrying capacity of the urban ecosystems in the nine Yellow River Basin provinces gradually increased between 2008 and 2019 (Figure 4). When viewed from a north–south perspective, the north and south were relatively weak, and the center was stronger. When viewed from an east–west perspective, the east and west were relatively weak, and the center was stronger. At the province level, the ecology of the Inner Mongolia Autonomous Region was relatively fragile, and the natural environment of Shanxi, Shaanxi, Henan, Shandong, and Qinghai gradually deteriorated, especially Shanxi, Shandong, and Qinghai. Shandong and Shanxi provinces are mainly dependent on local energy and have a heavy industrial structure. Qinghai Province experiences frequent natural disasters and has low forest cover. The natural environment of Gansu and the Ningxia Hui Autonomous Region were preserved. The natural environment of Sichuan Province gradually improved, which is closely related to the effective treatment of pollutants and to technological innovations used to reduce pollution emissions. The natural environment of Gansu and Ningxia Hui Autonomous Region was maintained in a relatively good state.

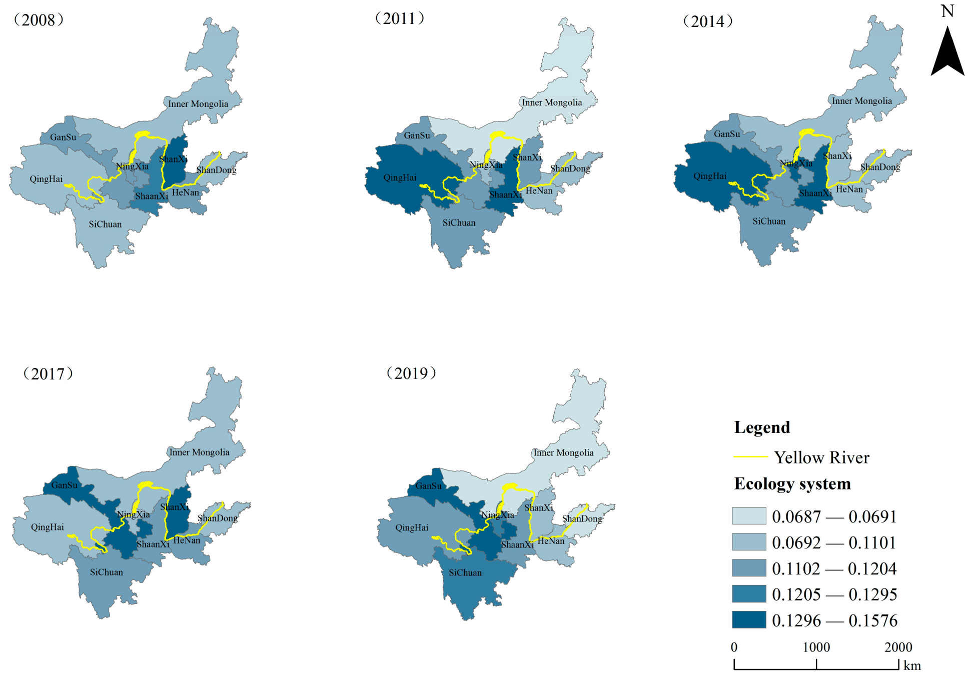

Figure 4. The urban ecosystem carrying capacity scores in the Yellow River Basin in 2008, 2011, 2014, 2017, and 2019.

(2) Analysis of the carrying capacity of the social subsystem

For the social system carrying capacity, the east was higher than the west and the north was higher than the south before 2017 (Figure 5). At the province level, Qinghai, Gansu, and Ningxia experienced a development course from low to high, while Shanxi, Henan, and Sichuan continued to have a low social subsystem carrying capacity, which was influenced by their larger population and the less well-balanced development of education and medical care.

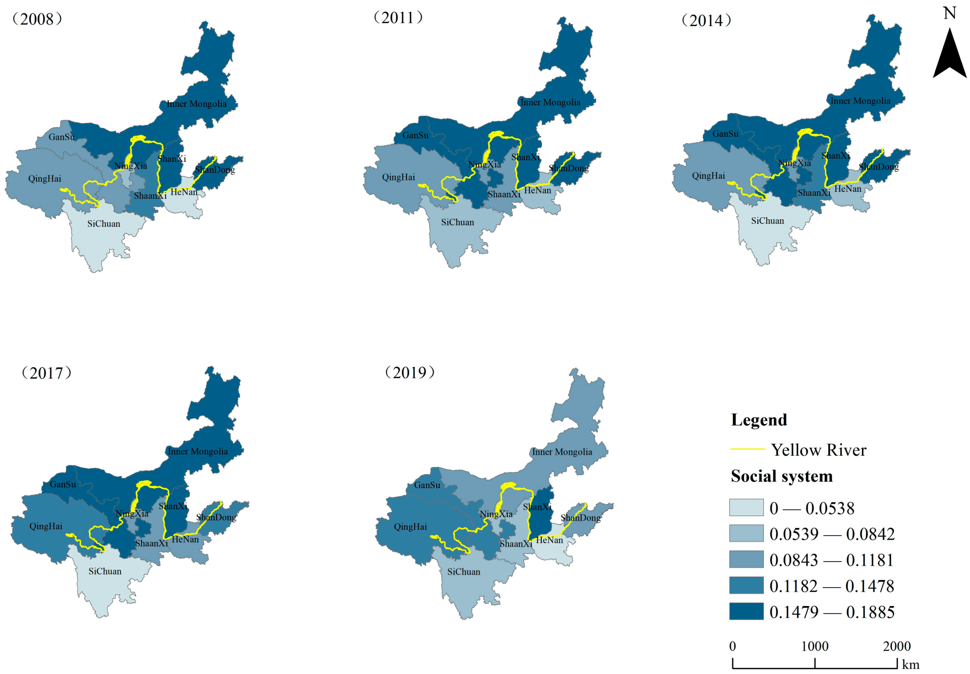

Figure 5. The provincial urban social subsystem carrying capacity scores in the Yellow River Basin in 2008, 2011, 2014, 2017, and 2019.

(3) Analysis of the carrying capacity of the economic subsystem

Regional differences in the economic subsystems existed throughout the study period and were relatively stable, mainly showing that the eastern and southern parts of the region were more economically developed, while the rest of the region had a relatively weak economy (Figure 6). At the province level, Shandong Province was ranked first, and Henan and Sichuan provinces were ranked second. Shaanxi, Shanxi, and the Inner Mongolia Autonomous Region were ranked third. Qinghai, Gansu, and the Ningxia Hui Autonomous Region were ranked fourth, mainly because Shandong Province, Henan Province, and Sichuan Province had more developed non-agricultural industries, higher income levels of residents, more active investment, and higher fiscal revenue. The provinces (autonomous regions) in the third and fourth ranks were mainly in those positions because their industrial structure was not optimized, investment was low, and the scale of tax revenue was relatively small.

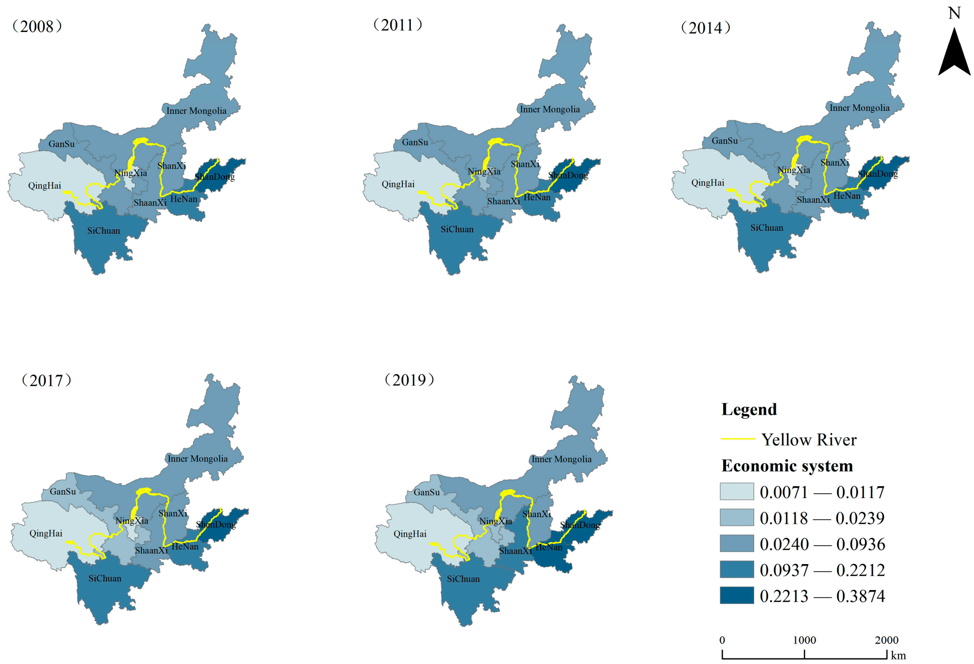

Figure 6. The provincial urban economic subsystem carrying capacity scores in the Yellow River Basin in 2008, 2011, 2014, 2017, and 2019.

(4) Analysis of the carrying capacity of the resource subsystem

In general, the carrying capacity of the resource subsystem in the western part of the Yellow River Basin was the largest, the eastern part was the second largest, and the central part was the smallest (Figure 7). At the province level, the resource-carrying capacity of Qinghai Province was maintained at a high level, where Qinghai was the first-ranked province from 2008 to 2019. Gansu, Ningxia, Shaanxi, and Henan had relatively low resource-carrying capacities, which were closely related to the per capita water, land, and mineral resources in these provinces and regions. The resource-carrying capacity of Shanxi Province changed from a higher to a lower value over the study period and was influenced by its natural resource status and industrial structure. Shandong and Sichuan Provinces had middle-ranked resource-carrying capacities, mainly due to their small per capita water, land, and mineral resources.

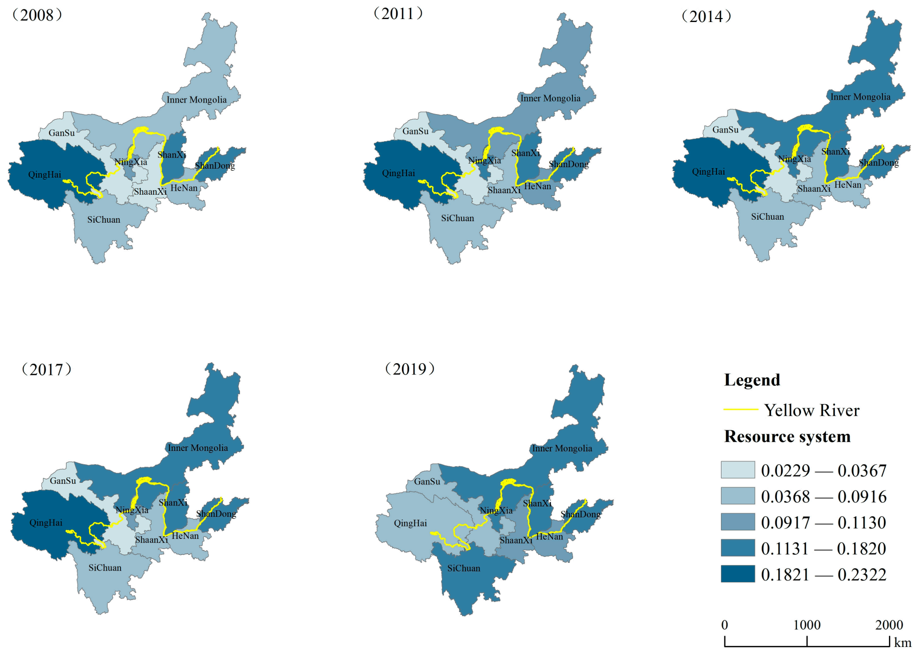

Figure 7. The provincial urban resources subsystem carrying capacity scores in the Yellow River Basin in 2008, 2011, 2014, 2017, and 2019.

(5) Analysis of the comprehensive carrying capacity

From 2008 to 2019, the comprehensive urban carrying capacity of the Yellow River Basin provinces experienced a development process that generally moved from low to high (Figure 8). Overall, the comprehensive carrying capacities of the western provinces were the highest, the central provinces were the lowest, and the eastern provinces were at the middle level from 2008 to 2017. From 2017 to 2019, the central provinces changed from low to high, while the eastern provinces displayed the opposite pattern. At the province level, the comprehensive carrying capacity of Qinghai Province maintained the highest carrying capacity, which was closely related to its small population and high resource and social carrying capacity. The comprehensive carrying capacities of Gansu, Ningxia, and Shanxi were consistently low, which was related to the low level of economic development and the greater pressure on resources. The comprehensive carrying capacities of Inner Mongolia, Henan, and Shandong declined, mainly due to the declining scores of the ecological and social subsystems. Sichuan's comprehensive carrying capacity gradually declined from 2008 to 2011 and remained at a relatively low level since then. The comprehensive carrying capacity of Shanxi Province displayed a pattern that rose and then fell and then stabilized at a medium level.

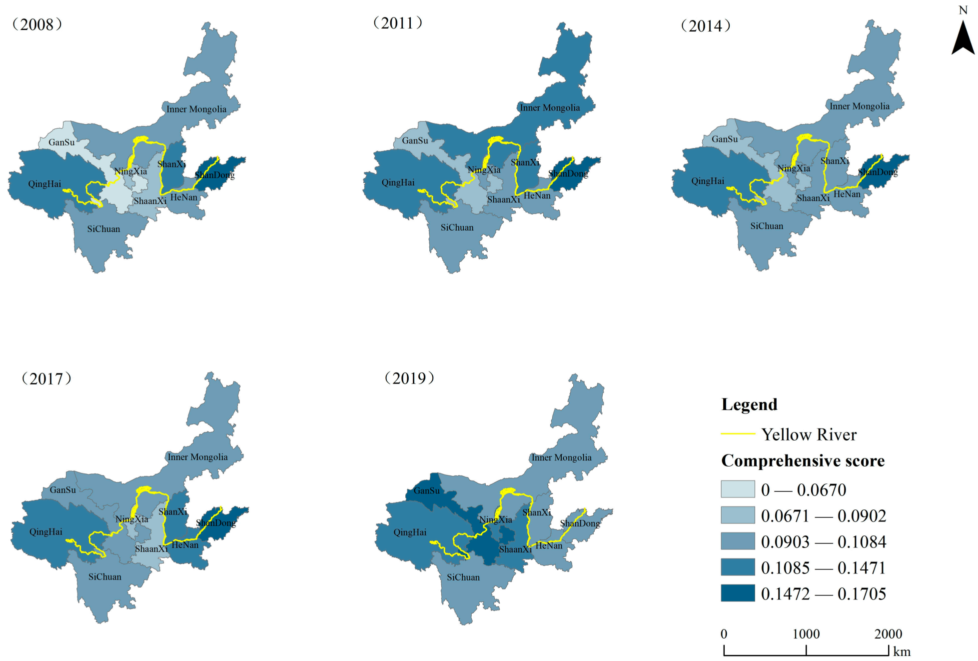

Figure 8. Comprehensive carrying capacity scores for provincial cities in the Yellow River Basin in 2008, 2011, 2014, 2017, and 2019.

3.3. Analysis of Coupling and Influencing Factors of Each Subsystem and the Total System

Even though the trend in the comprehensive carrying capacities of the cities in the Yellow River Basin changed over the study period, when the results of the comprehensive carrying capacities of each province and the comprehensive carrying capacities of the four subsystems were combined, the resource and economic subsystems improved, and the social and ecological subsystem carrying capacities had a negative impact on the comprehensive carrying capacities of the cities (Figure 9). However, the results also showed that the comprehensive carrying capacities of each province and the four subsystems improved. The Yellow River Basin provinces were divided into the following three groups based on how the development of each subsystem affected the total carrying capacity of the region: (1) jointly hindered social and ecological subsystems, which were primarily influenced by both social and ecological subsystems; (2) hindered ecological subsystems, which were primarily influenced by ecological subsystem factors, particularly in Henan; and (3) hindered social subsystems, which included Sichuan, Gansu, Inner Mongolia, and Shandong. The analysis of the newly constructed index system showed that population density, the average number of students per teacher, unemployment, and investment in industrial governance and the closely related wastewater, gas emissions, and area of crop damage were the main factors impeding an improvement in the comprehensive carrying capacity of cities in the Yellow River Basin.

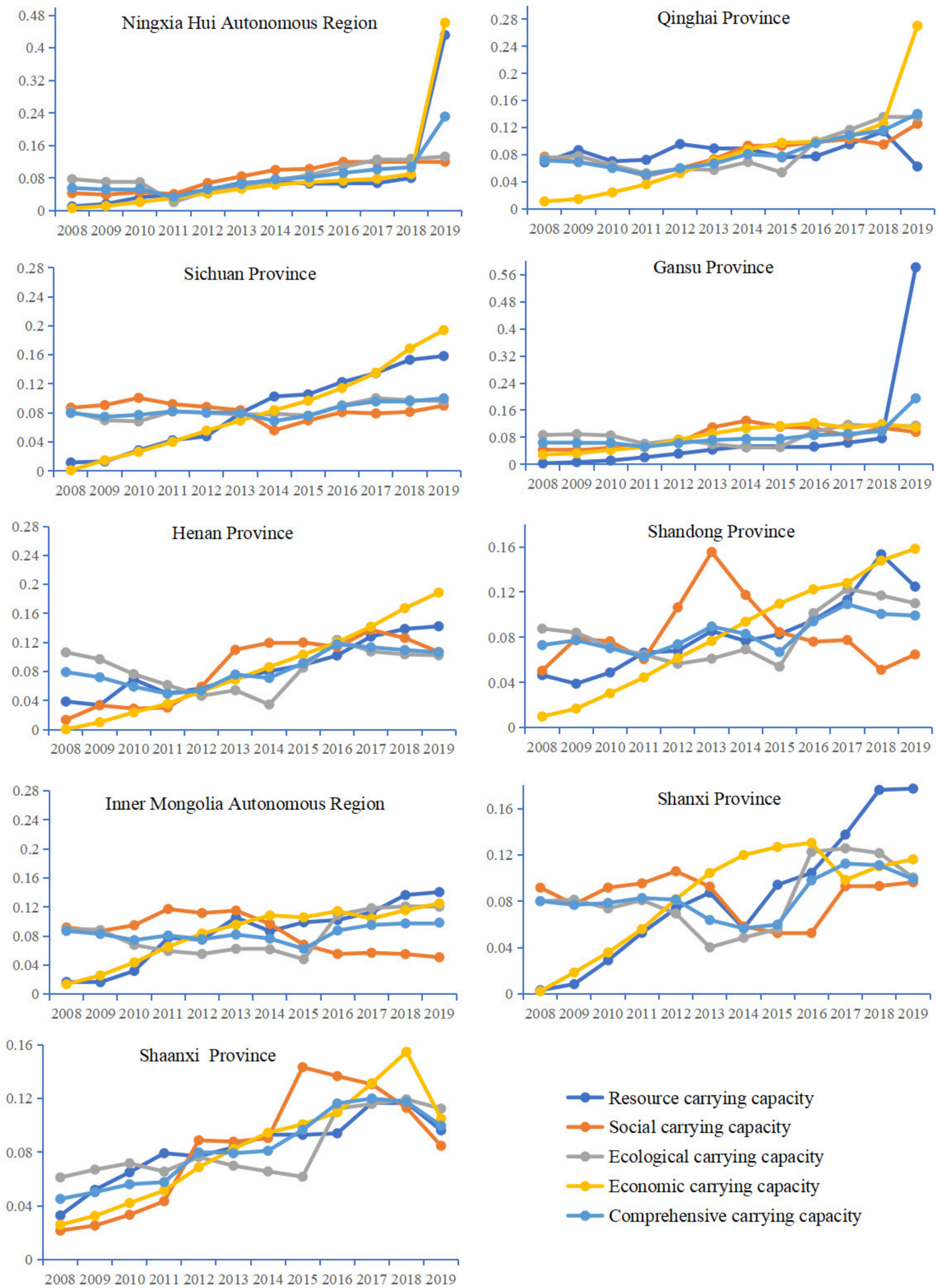

Figure 9. Subsystem and integrated carrying capacity system scores for each province (autonomous region) in the Yellow River Basin from 2008 to 2019.

Population density was mainly limited by natural and socio-economic conditions, resulting in a highly uneven population distribution. The higher population density in the downstream provinces reduced the comprehensive carrying capacity. The average number of students per teacher was closely related to the mobility of skilled workers and the unreasonable distribution of educational resources. The unemployment rate was related to the regional industrial structure and the efficiency of economic development. The investment in industrial governance and the associated wastewater and gas emissions were closely related to the type and structure of industrial development. The industrial structure of the Yellow River Basin depends heavily on energy, leading to high wastewater and gas emissions and reducing the comprehensive carrying capacity.

4. Conclusions and Recommendations

4.1. Discussion

The provinces and cities in the Yellow River Basin have significant differences due to their natural and social environments, resulting in large differences in urban development and large differences in the carrying capacity of cities. Therefore, studies on the comprehensive carrying capacity of cities are of great significance. However, the large provincial scope of the present study may reduce the differences in the carrying capacity between some cities. In the future, we hope to analyze smaller regions as units. However, cities are complex systems and their comprehensive carrying capacity will keep changing over time. Therefore, the evaluation index and evaluation method should also be constantly updated and improved. When selecting the research methodology applied here, it was recognized that the quantitative method has advantages, but there are also certain limitations. Therefore, qualitative and quantitative methods should be combined. Research on the mechanism of the comprehensive carrying capacity of the urban areas in the Yellow River Basin is still relatively rare. In the future, it is necessary to conduct in-depth investigations of the mechanism at the natural, social, and policy levels and to attempt to identify the key influencing factors or bottlenecks, thereby providing a reference for an enhancement in the comprehensive carrying capacity of the urban areas in the Yellow River Basin. The current comprehensive carrying capacity of the urban areas in the Yellow River Basin has been studied to a certain extent, but the comprehensive carrying capacity of the countryside has been less well explored. A certain amount of research has been conducted on the comprehensive carrying capacity of the urban areas in the Yellow River Basin, but there has been less work on the comprehensive carrying capacity of the rural areas, a situation that is not conducive to the coordinated development of the region and the high-quality development of the Yellow River Basin. Therefore, in the future, it will be necessary to conduct research on the comprehensive carrying capacity of rural areas, while further strengthening research on the comprehensive carrying capacity of the urban areas in the region.

4.2. Conclusions

The nine provinces in the Yellow River Basin have distinct natural and socio-economic conditions. Therefore, a comprehensive carrying capacity evaluation index system was built by comparing four aspects including resources, society, ecology, and economy on the provincial scale comprehensively and objectively, based on a summary of previous research findings and an understanding of the current state of urban development in the Yellow River Basin. Different research methodologies were compared and examined, and finally, the entropy weight TOPSIS model was chosen to assess the urban comprehensive carrying capacity levels of the Yellow River Basin provinces from 2008 to 2019. The findings of the quantitative analysis of the spatial and temporal dynamic changes in the comprehensive carrying capacity of each province in the Yellow River Basin showed that:

(1) Overall, the comprehensive carrying capacity of the Yellow River Basin increased annually from 2008 to 2019. The carrying capacities of the resource and economic subsystems increased annually. The carrying capacity of the ecological subsystem decreased annually from 2008 to 2011 and increased annually after 2012, and the carrying capacity of the social subsystem in the 2008–2013 period increased annually and began to show a decreasing trend after 2013. At the provincial level, in the seven upstream and downstream provinces of Qinghai, Sichuan, Gansu, Ningxia, Inner

Mongolia, Henan, and Shandong, the comprehensive carrying capacity fluctuated largely and decreased in the 2008–2011 period and fluctuated and increased from 2011 to 2019. In contrast, the midstream provinces of Shaanxi and Shanxi fluctuated upward in the 2008–2011 period and showed a decreasing trend after 2011.

(2) The Yellow River Basin's nine provinces essentially exhibited a spatial distribution that was "high in the east and west, low in the middle," with the highest comprehensive carrying capacity values in the west, the lowest values in the middle, and moderate values in the east. This was primarily because the eastern provinces had a higher level of economic development, and the western provinces had a higher carrying capacity for resources. These two factors were weak in the central provinces. This was mostly because the western provinces had a higher resource-carrying capacity and a higher level of economic development than the central provinces.

(3) The comprehensive carrying capacity of cities in the Yellow River Basin was mainly driven positively by the resource and economic subsystems, while the carrying capacity of social and ecological subsystems played a negative role. The relationship between the development of each subsystem and the comprehensive carrying capacity of the Yellow River Basin provinces was divided into three categories including social and jointly impeded ecological subsystems, impeded ecological subsystems, and impeded social subsystems. The main factors for the improvement in carrying capacity were population density, the average number of students per teacher, the unemployment rate, the percentage of completed investment in industrial governance, and the closely related wastewater and waste gas emissions and crop-affected areas.

4.3. Recommendations

(1) The provinces in the middle and upper reaches of the Yellow River Basin should take advantage of the "Silk Road Economic Belt" and "ecological protection and high-quality development of the Yellow River Basin" strategies to strengthen international ties, attract foreign investment, and increase the number of businesses by taking advantage of investment attraction opportunities to increase tax revenue and the standard of living for citizens. Using "open source" resources, they should expand employment channels, increase jobs, and increase the employment rate to reduce unemployment. They should highlight their advantages and use them to attract an inflow of skilled workers and reduce the population outflow. They should continue to improve the fertility policy based on reducing the outflow of population, increasing the birth rate, and increasing the number of young people, thereby extending the period of demographic dividend. It should also be possible to reduce population density by expanding the size of cities using effective urban planning to accommodate more people.

(2) The downstream provinces of the Yellow River Basin, i.e., Shandong and Henan, need to reduce their unemployment rates and lower population density to enhance their comprehensive carrying capacity. The current free flow of population and the control of population inflow are not sustainable. Therefore, a reduction in population density still depends on the expansion of the urban scale and corresponding improvements in infrastructure. The government should actively encourage individuals to start their own businesses, increase employment opportunities, and support small and micro-enterprises in response to the rising unemployment in Henan Province. Shandong Province could play a leading role in regional coordinated development, strengthening the regional division of labor and cooperation, implementing integrated development, and seizing the opportunity to actively promote economic development.

(3) Ecological elements are also important factors limiting the comprehensive carrying capacity of the Yellow River Basin provinces. The provincial authorities should increase the rate of investment in industrial governance, reduce the emissions of wastewater and exhaust gas, and accelerate the elimination of outdated and inefficient production processes in conjunction with the development of green industries. They

should develop clean energy and promote clean production. The government should play a guiding role and establish a corresponding reward and punishment system to encourage enterprises to actively invest funds and equipment to participate in environmental pollution control.

(4) Innovation-driven incentives should be used to continue to maintain the growth momentum of resources and economic subsystems.

The social and ecological factors that limit cities' overall carrying capacities should be addressed. However, steps should also be taken to maintain the growth momentum of the resources and economic subsystems. The most fundamental approach is to rely on innovation. All provinces in the Yellow River Basin should strengthen scientific and technological innovation, continue to increase investment in scientific research, and actively promote scientific and technological projects. With the help of scientific research, science and technology should be used to find new and alternative energy sources, leading to a gradual reduction in the use of fossil energy. This process would reduce the ecological damage caused by the use of fossil fuels as an energy source and increase the amount of resources used per capita. There needs to be continuous improvement in waste treatment technologies, the development of a circular economy to extend the industrial chain, and improvements in the efficiency of resource utilization. There should be active guidance for the integration of industry and academia and for the use of new technologies in industrial development. High-tech enterprises should be developed, and industrial structures should be transformed by innovation.

Author Contributions: Conceptualization, Y.L. and F.J.; data and methodology, J.M. and Y.L.; software, J.M.; validation, Y.L.; formal analysis, L.M.; investigation, J.M.; resources, Y.L.; data curation, J.M.; writing—original draft preparation, Y.L. and F.J.; writing—review and editing, F.J. and Y.L.; visualization, Y.L.; supervision, Y.L.; project administration, L.M.; funding acquisition, L.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of China (NSFC) Special Project "Synergistic Paths and Models of High-Quality Development of Yellow River Basin City Clusters and Industries," grant number 72050001; the Natural Science Foundation of China, "Research on the Mechanism and Spatial Effects of Traffic Organization in Urban Agglomerations," grant number 41771134; and Shandong Province Social Sciences Planning Project, "Construction of Tourism Industry Belt in Liaocheng Section of Beijing-Hangzhou Canal and Analysis of Economic Effects," grant number 2016CLYJ02.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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