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Evaluation of Land Carrying Capacity of 31 Provinces in China Based on a Natural–Societal-Supply–Demand Framework

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Abstract: Land carrying capacity (LCC) refers to the ability of land resources to support human activities, and has become an important tool for research into the man–land relationship. Due to the 31 provinces of China possessing huge differences in resource and social development, it is necessary to understand the key factors and differences in LCC in each province. This paper provided a framework for the Natural–Societal-Supply–Demand of LCC, and analyzed the LCC of the 31 provinces of China via the cross relationship between the four subsystems. In total, 22 indicators were selected, and the weight of the indicators was calculated via the gray correlation coefficient. Through this framework, the LCC is endowed by natural resources and is improved by social development; the comprehensive LCC of the 31 provinces was evaluated using geographic information data and statistical data, and the main causes of overload were analyzed by using the obstacle model. The results show that (1) The natural resources of most provinces in China cannot support the current population; (2) Social development has significantly improved the LCC; and (3) The shortage of natural resources is the key factor in LCC overloading in most provinces. Insufficient food supply, insufficient carbon sequestration, the shortage of construction land, and insufficient water supply are the main causes of overload in China.

Keywords: land carrying capacity; evaluation framework; China; obstacle indicators

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1. Introduction

In the past two decades, the population in China has increased from 1.267 billion to 1.405 billion, and the urbanization rate has increased from 36.2% to 64.7% [1,2]. Rapid population growth and urbanization has led to more tension between human and land resources. Therefore, in order to ensure the sustainable development of land resources, it is necessary to evaluate the land carrying capacity (LCC) in China. China has a broad variety of land and there are great differences among the 31 provinces in terms of resource endowment, economic foundation, social development, etc. In order to formulate a more targeted sustainable land development strategy, it is necessary to understand the difference in LCC among provinces, and reveal the key factors of LCC in each province.

LCC is determined as the ability of land resources to carry human life and human activities under the given economic, social, technological, and environmental conditions [3,4]. As LCC comprehensively and systematically describes the relationship between the human and the land resources, it has become the foundation for man–land research and sustainable development research [5,6]. The study of LCC originated in the research on the man–land relationship by Malthus in 1798 [7]. With the depletion of resources and the deterioration of the environment, people gradually realized the importance of sustainable development, and increasing attention has been paid to the research of LCC [8]. According to the logic of the research framework, the current research into LCC can be divided into three categories. One is the framework based on the relationship between the land supply and the human need, such as agricultural carrying capacity [9,10], ecological footprint [11,12], and carbon carrying capacity [11,13]. These studies can calculate the maximum population that land resources can carry via mathematical models, and provide an objective and accurate reference for government management and decision-making [14]. The second is the framework based on impact factors, which incorporate a set of impact factors for LCC into a framework and return a logical value as a quantitative indicator of LCC [15]; this includes the state space model [16] and the system dynamics model [17]. It can reflect the nonlinearity and complexity of the man–land relationship and evaluate LCC comprehensively [18]. The third one is the Pressure–State–Response (PSR) framework and its extensions, such as the Driving Force–State–Response (DSR) framework, the Driving Force–Pressure–State–Impact–Response (DPSIR) framework and the Driving Force–Pressure–State–Impact–Response–Management (DPSIRM) framework, which can evaluate LCC from the perspective of a causal relationship [19,20].

In order to provide targeted suggestions for the sustainable development of land resources in China, it is necessary to understand the respective and integrated LCCs of natural resources and social systems, and find out what the main causes are for the overload of the LCC. However, all of these frameworks have their deficiencies: the first framework only evaluates one aspect of LCC and neglects the comprehensiveness of LCC; the second framework can only evaluate the size of LCC, but it is difficult to judge whether the LCC is overloaded; the third framework studies the relationship between human and land resources, but it cannot analyze the impact of natural factors and societal factors on LCC separately. Therefore, this paper proposes a new evaluation framework for LCC, based on Natural–Societal-Supply–Demand (NSSD), and establishes an evaluation system based on the cross integrated NSESD. The specific objectives of this study are the following: (1) to analyze the natural endowment of land resources in the 31 provinces of China; (2) understand the impact of human society on LCC; (3) evaluate the comprehensive LCC of the 31 provinces; (4) analyze the key factors causing the overload of LCC in each province and put forward corresponding suggestions.

2. Materials and Methods

2.1. Establish Evaluation Framework

Land provides various resources, which are consumed by human survival and socio-economic activities. Therefore, the evaluation framework of LCC can be divided into two parts: the natural parts represent the consumption of human survival, and the societal parts represent the consumption of socio-economic activities. The key to the evaluation of land resource carrying status is the evaluation of the supply and demand relationship between the supply of land resources and the demand of human society. Therefore, the framework of LCC can also be divided into demand parts and supply parts.

According to Maslow's needs-hierarchy theory [21,22], human needs are divided into five levels: physiological needs, safety needs, love and belonging needs, esteem needs, and self-actualization needs. The physiological needs of humans include food, shelter, water, air, transportation, public facilities, and education, which constitutes the demand subsystems of LCC [21]. Among these physiological needs, the food, air, water, and shelter are endowed by the animality of humans, and transportation, public facilities, and education are the societal needs endowed by the sociality of humans. Therefore, the demand subsystem can be divided into natural parts and societal parts. The demand subsystem should be met by the provision of various natural and societal carriers [22], which constitute the supply subsystems of LCC. Corresponding to the demand subsystem, it is also divided into the supply of food, shelters, water, air, transportation, public facilities, and education. Among them, food, shelter, air, and water are provided by nature, and all of them can be improved though technology. Transportation, public facilities, and education are provided by human society. Consequently, the supply subsystems of LCC also consist of nature parts and societal parts.

Therefore, the evaluation framework of LCC is proposed via four subsystems: Natural Supply (NS), Societal Supply (SS), Natural Demand (ND), and Societal Demand (SD). The four subsystems interact with each other and work together to form the comprehensive LCC.

According to the cross relationship between the four subsystems, this paper constructed a comprehensive evaluation framework of LCC; this is called the Natural–Societal-Supply–Demand (NSSD) model. The structure of the Natural–Societal-Supply–Demand (NSSD) framework is shown in Figure 1.

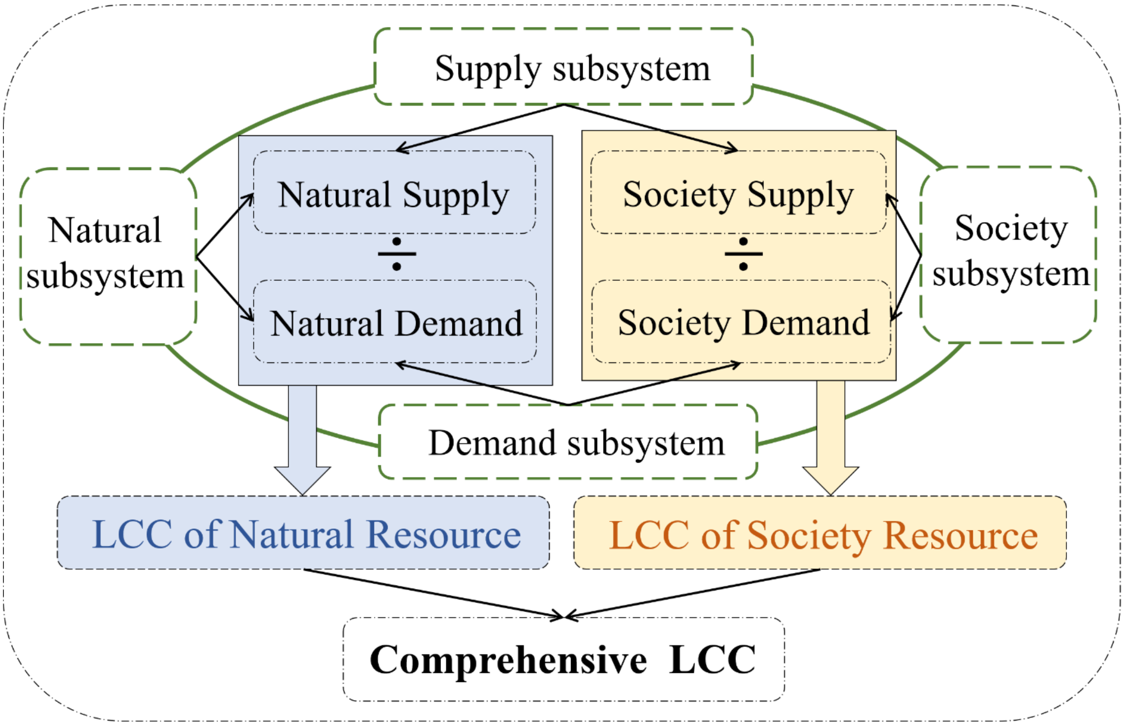

Figure 1. The structure of NSSD framework.

2.2. Evaluation Indicators

2.2.1. Food

Under natural conditions, the food supply depends on the productivity of cultivated land. The productivity of cultivated land is determined by natural factors such as light, temperature, water, soil, and nutrients, and societal factors such as agricultural input and agricultural facilities. The Global Argo-ecological Zone (GAEZ) model, built by the Food and Agriculture Organization of the United Nations (FAO), used the method of gradual revision to estimate the production potential [23]: (1) first, it estimates the light and temperature production potential of planting a certain crop in each grid, according to temperature and solar radiation; (2) it estimates the production potential in combination with the available water, soil properties and terrain effects; (3) it simulates the agroclimatic potential productivity of crops suitable for planting under ideal soil conditions and management conditions; (4) calculates the comprehensive grain production potential by comprehensively considering agricultural technology, soil, terrain and cultivated land distribution [24]. The agroclimatic potential productivity can express the influence of natural factors on productivity well. Therefore, it is used as the evaluation indicator of food supply in the natural subsystem. The difference between the actual grain output and the agroclimatic potential productivity can be used to measure the productivity improvement caused by agricultural technology. Therefore, it is used to describe the food supply of the societal subsystem. The demand of food has a positive correlation with social development. Therefore, the theoretical per capita grain demand is used to express the natural demand of humans, and grain consumption per capita is used to measure the demand of the societal subsystem.

2.2.2. Air

The carbon sequestration function of the ecosystem, including the release of oxygen and the sequestration of carbon dioxide, is the way for the natural subsystem to ensure human air demand. According to the chemical equation of photosynthesis of green vegetation ($6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$), there is a linear correlation between carbon and oxygen, so only the value of carbon was used to evaluate LCC [25]. The carbon sequestration of the ecosystem refers to the sum of carbon dioxide fixed by cultivated land, forest, grassland, and water, which can be estimated by the net primary productivity (NPP). Under current scientific and technological conditions, the main way to improve the carbon sequestration capacity of the societal system is to increase the area of the ecosystem. Therefore, NPP was used to describe the supply parts of the natural subsystem, and the area of afforestation was used to describe the supply parts of the societal subsystem. The carbon emission mainly comes from human respiration and fossil energy combustion [13,26]. The total carbon sequestration from human respiration and household energy consumption was used to describe the demand of the natural subsystem, and the total carbon sequestration from fossil fuel combustion [27] and cement production [13] was used to describe the demand of the societal subsystem.

2.2.3. Shelters

Construction land provides space for human living and production. According to the Maslow's needs-hierarchy theory, the natural demand of humans can be represented by residential land, and social demand is represented by other construction land. Construction land can be divided into residential land and other construction land (the construction land carrying social and economic activities, such as land for public facilities, industrial land, and land for transportation facilities). Therefore, the supply of the natural subsystem is expressed by the area of the residential land, and the supply of the societal subsystem is expressed by the area of other construction land. The demand for construction land can be calculated by the per capita construction land standard, stipulated by the government and the total population.

2.2.4. Water

The water supply of the natural subsystem is evaluated by natural water resources. The water supply of the societal subsystem consists of water exploitation and water allocated from other regions. The residents' water consumption is used to describe the demand of the natural subsystem, while the water consumption of the industry is used to describe the demand of the societal subsystem.

2.2.5. Transportation, Public Facilities, Education

These three physiological needs can only be provided for by the societal subsystem. The demand for transportation can be described by the sum of total passenger traffic and total freight traffic, and the supply for transportation can be described by the length of the transport routes in supply parts. The public facilities can be described by the gross domestic product (GDP) in demand parts, and the investment in urban infrastructure in supply parts. The education can be described by the number of enrolments in demand parts, and can be described by expenditure for education in supply parts.

Based on the above analysis and the characteristics of the NSSD framework, the evaluation indicators are listed in Table 1; the calculation method and data source of each indicator are shown in Table 2.

Table 1. The evaluation system of the LCC.

Indicators	Natural Subsystem	Societal Subsystem
Supply subsystem	NS1: Agroclimatic potential productivity	SS1: The improvement of productivity
	NS2: NPP	SS2: Area of afforestation
	NS3: Area of the residential land	SS3: Area of other construction land
	NS4: Natural water resources	SS4: Total water supply
	<Null>	SS5: Length of transport routes
	<Null>	SS6: Investment in urban infrastructure
	<Null>	SS7: Expenditure for education
Demand subsystem	ND1: Theoretical per capita grain demand	SD1: Grain consumption per capita
	ND2: The total carbon sequestration from human respiration and household energy consumption	SD2: The total carbon sequestration from the fossil fuels combustion and cement production
	ND3: Total residential land demand	SD3: Total public land demand.
	ND4: Residents' water consumption	SD4: Water consumption of industry
	<Null>	SD5: Sum of passenger traffic and freight traffic
	<Null>	SD6: GDP
	<Null>	SD7: Average school enrolment per 100,000 population

Table 2. The calculation method and data source of each evaluation indicator.

Indicators	Calculation Method	Data Source
NS1	GAEZ model	GAEZ v3.0 [28]
NS2		MOD17A
NS3		Land use and cover data
NS4		The water resources bulletins of China in 2021
SS1	Actual productivity–Potential productivity	2021 China Statistics Yearbook
SS2		China Statistics Yearbook in 2021
SS3	Total construction land-Residential land	Land use and cover data
SS4		The water resources bulletins of China in 2021
SS5		China Statistics Yearbook in 2021
SS6		China Statistics Yearbook in 2021
SS7		China Statistics Yearbook in 2021
ND1	Per capita food demand [29,30]	China Statistics Yearbook in 2021
ND2	IPCC emission factor method [13,31]	National standard of China: GB 50137—2011
ND3	Per capita residential land demand × Population	National standard of China: GB 50137—2011
ND4		The water resources bulletins of China in 2021
SD1		China Statistics Yearbook in 2021
SD2	IPCC emission factor method [13,31]	China Statistics Yearbook in 2021
SD3	Per public land demand × Population	National standard of China: GB 50137—2011
SD4		The water resources bulletins of China in 2021
SD5		China Statistics Yearbook in 2021
SD6		China Statistics Yearbook in 2021
SD7		China Statistics Yearbook in 2021

2.3. Evaluation Method of Each Subsystem

In order to increase the objectivity of the evaluation, the gray correlation entropy method was used to determine the weight of each LCC indicator [32]. Gray Relational Analysis is a kind of gray system analysis method. It is a method to measure the degree of correlation between factors, according to the degree of similarity or difference in the development trend of factors [33]. The calculation steps are as follows [32,33]:

2.3.1. Standardization of Indicators

To eliminate the influence of dimensions, the indicators should first be standardized. For positive indicators, the formulas are shown in Formula (1):

$$y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{1}$$

and for negative indicators, the formulas are shown in Formula (2):

$$y_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \tag{2}$$

In Formulas (1) and (2), i and j represent indicator and regions respectively; x_{ij} is the initial value of indicators j in region i, and y_{ij} is the normalized value.

2.3.2. Find the Optimal Vector

The optimal vector consists of the optimal values for each indicator:

$$G = (g_1, g_2 \ldots g_n) \tag{3}$$

where g_i was taken at the optimal value, G is the optimal vector. For positive indicators, the maximum value was taken as the optimal value, and for negative indicators, the minimum value was taken as the optimal value.

2.3.3. Calculate the Gray Correlation Coefficient

The optimal vector was taken as the reference, and the correlation analysis method was used to calculate the correlation coefficient of index j. The correlation coefficient was used to indicate that the actual value of the indicator is close to the corresponding indicator value in the reference series. The formulas are shown in Formula (4).

$$\delta_{ij}(y_i, G) = \frac{\min_i \min_j |y_{ij} - g_i| + \rho \max_i \max_j |y_{ij} - g_i|}{|y_{ij} - g_i| + \rho \max_i \max_j |y_{ij} - g_i|} \tag{4}$$

where ρ is the resolution coefficient ($0 < \rho < 1$), which is always taken as 0.5; $\min_i \min_j |y_{ij} - g_i|$ and $\max_i \max_j |y_{ij} - g_i|$ represents the minimum difference and maximum difference between the two levels, respectively. $\delta_i(y_i, G)$ is the gray correlation coefficient of index j and optimal vector G.

2.3.4. Determine the Weight

The weight coefficient is expressed by Formula (5):

$$\omega_j = \delta_j / \sum_{j=1}^{n} \delta_j \tag{5}$$

where δ_j is the gray correlation coefficient, and ω_j is the weight of indicator j.

2.4. Calculation of LCC and Its Classification

According to the definition of the NSSD framework in Section 2.1, LCC is proposed via four subsystems. The value of each subsystem can be calculated by the weighted sum of all indicators in the subsystem. In addition, the LCC can be calculated by the ratio of supply and demand.

Therefore, the first step of calculating LCC is to calculate the value of each subsystem, which is expressed as Formula (6):

$$Y_k = \sum_{k=1}^{n} y_{kj}\omega_{\mathrm{j}} \tag{6}$$

where Y_k is the index of each subsystem, and k = 1, 2, 3, 4 is used to represent the value of NS, SS, ND, and SD, respectively.

Then, the LCC of the natural subsystem (NLCC) and LCC of the societal subsystem (SLCC) can be calculated by Formulas (7) and (8):

$$\mathrm{NLCC} = \mathrm{NS}/\mathrm{ND} \tag{7}$$

$$\mathrm{SLCC} = \mathrm{SS}/\mathrm{SD} \tag{8}$$

The comprehensive LCC refers to the ratio of the comprehensive supply and comprehensive demand, which is expressed as Formula (9):

$$\mathrm{LCC} = \frac{\mathrm{NS} + \mathrm{SS}}{\mathrm{ND} + \mathrm{SD}} \tag{9}$$

LCC, NLCC, SLCC can both be classified into three categories, according to the ratio of the supply and demand relationship. When the ratio is equal to 1, the supply can just meet the demands of humans; when the ratio is above 1, the supply still has some surplusage, and the LCC is surplus; when the ratio is below 1, the land system cannot afford the needs of humans, and the LCC is overloaded. Therefore, LCC can be classified into 3 categories, as shown in Table 3.

Table 3. Classification law of LCC.

Categories	LCC (NLCC, SLCC)
Surplus	LCC > 1
Balanced	LCC = 1
Overloaded	LCC < 1

2.5. Obstacles Indicators Analysis

The obstacle model can calculate the obstacle degree of evaluation indicators, and find out the key constraints of LCC and calculate their impact [32,34]. It can help provide a scientific basis for formulating scientific and reasonable policies. The calculate methods are shown in Formulas (10)–(12) [32,34]:

$$F_{ij} = W_i \times \omega_j \tag{10}$$

$$O_{ij} = \frac{F_{ij} \times (1 - y_{ij})}{\sum_{j=1}^{m} (F_{ij} \times (1 - y_{ij}))} \tag{11}$$

$$U = \sum O_{ij} \tag{12}$$

where ω_j is the weight of the indicator, W_i is the weight of the subsystem, F_{ij} is the final comprehensive weight of the indicator, O_{ij} is the obstacle degree of indicators, and U is the obstacle degree of the subsystem.

2.6. Data Sources

The social and economic data were collected from the national bureau of statistics of China in 2021 (http://data.stats.gov.cn, accessed on 5 July 2022). The water data were collected from the water resources bulletins of China in 2021 (http://data.stats.gov.cn, accessed on 5 July 2022). The production potential data was obtained from the GAEZ v3.0 (http://webatchive.iiasa.ac.at./Research/LUC/GAEZ, accessed on 5 July 2022) [28]. The NPP data is from NASA (http://data.stats.gov.cn, accessed on 5 July 2022). The dataset for land use and cover at a 1 km resolution was provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn, accessed on 5 July 2022). SPSS18.0 and ArcGIS10.2 were used for data processing, calculation, and mapping.

3. Results

3.1. The Evaluation Results of Each Subsystem

The NS, SS, ND and SD of the 31 provinces of China in 2020 were calculated using Formula (6). To facilitate comparison, the NS, SS, ND and SD of each province were made into a line chart, respectively, as shown in Figure 2, and the statistical analysis of the four subsystems is shown in Table 4. In addition, the spatial distribution of the results is shown in Figure 3. It can be found that:

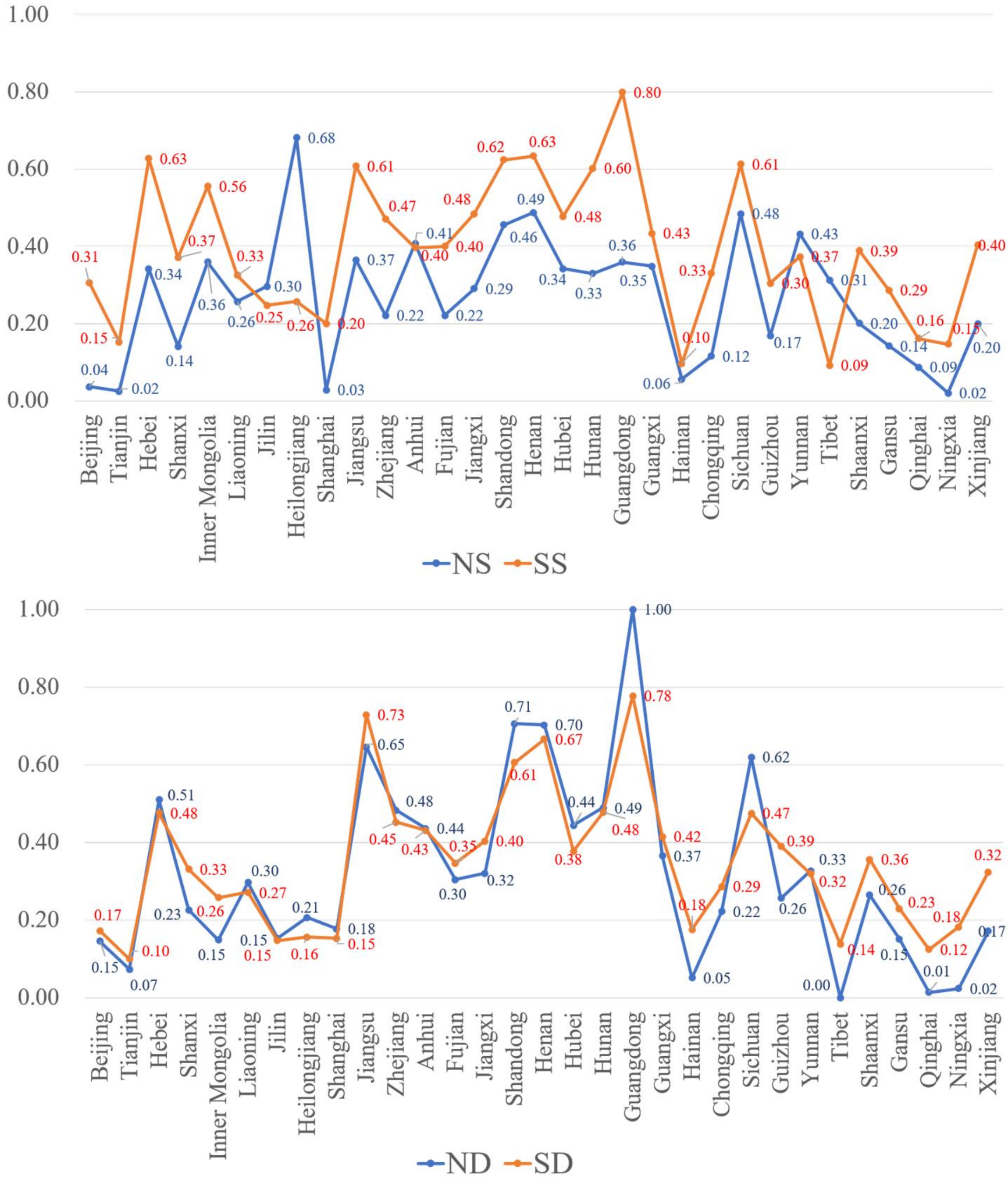

Figure 2. The evaluation results of the four subsystems of China in 2020.

Table 4. The statistical analysis of the four subsystems.

	NS	SS	ND	SD
Average	0.2650	0.3926	0.3209	0.3470
Standard deviation	0.1593	0.1781	0.2333	0.1764
Coefficient of variation (CV)	0.6009	0.4537	0.7270	0.5082

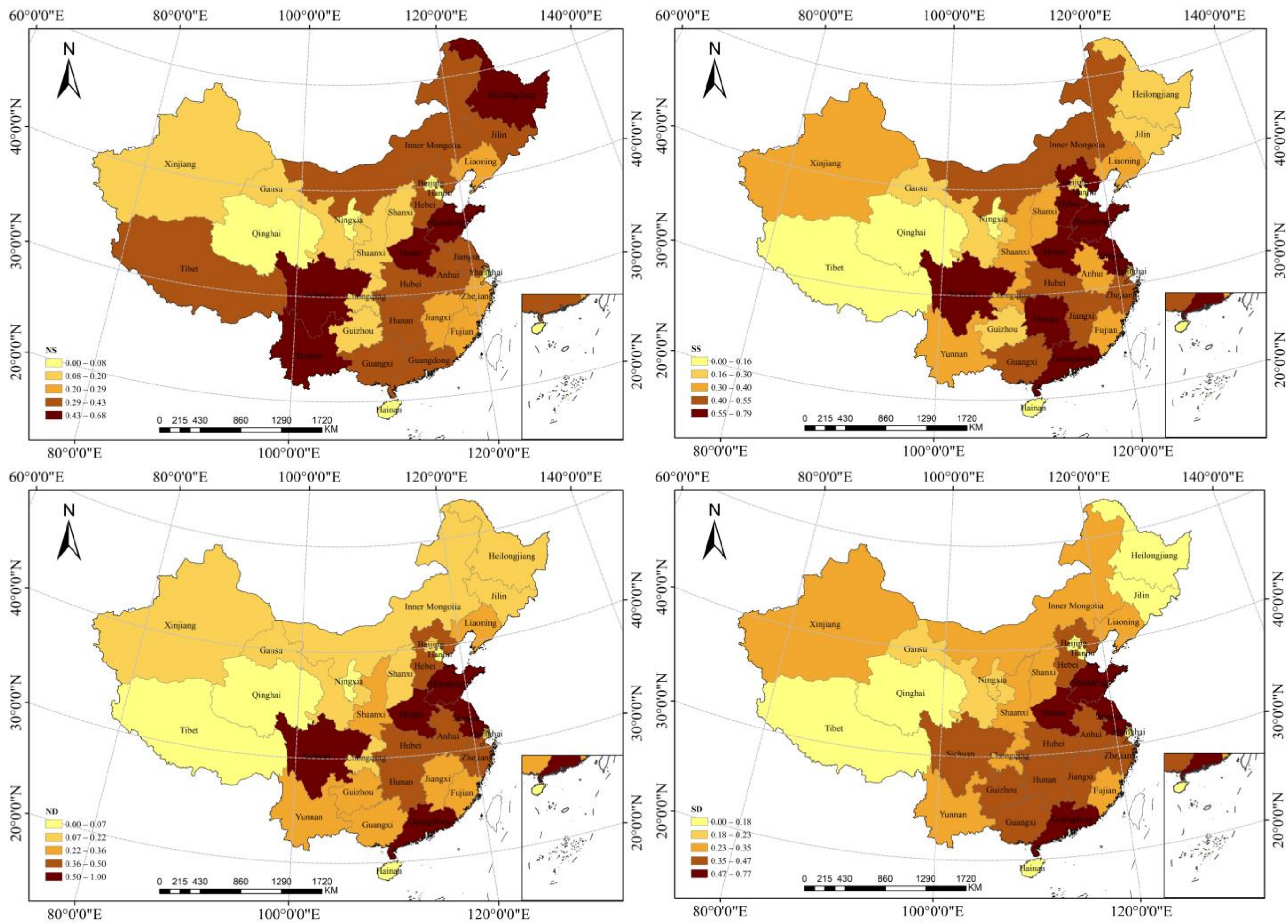

Figure 3. The evaluation results of the NS, SS, ND, and SD subsystems of 31 provinces.

(1) The spatial distribution of the NS is generally low in the northwest and high in the southeast; the highest value is distributed along the four major rivers of China. Among them, the NS of Heilongjiang province is highest in all provinces, which is approximately 2.5 times higher than the average value and almost 34 times higher than the lowest one (Qinghai province). The NS of Heilongjiang, Anhui, Henan, Shandong, Sichuan, and Yunnan are all significantly higher than other provinces. Beijing, Tianjin, Shanghai, Hainan, and Ningxia are significantly lower than the average.

(2) The spatial distribution of the SS is very different from that of the NS. The SS is low in the southwest and northeast, and high in the south-central area of China. The highest value was mainly distributed in several major urban agglomerations: Beijing-Tianjin-Hebei Urban Agglomeration, Yangtze River Delta, Chengdu-Chongqing Urban Agglomeration and Guangdong-Hong Kong-Macao Urban Agglomeration. The SS of Guangdong province is highest and is approximately 2.0 times than the average value. The SS of Hebei, Jiangsu, Henan, Shandong, Hunan, and Sichuan are all significantly higher than other provinces. The SS of Tianjin, Shanghai, Hainan, Tibet, Qinghai, and Ningxia are significantly lower than the average.

(3) The ND of the 31 provinces ranges from 0.05 to 1.00. Guangdong has the highest ND, which is 3.12 times than the average. The value of Guangdong, Jiangsu, Shandong, Henan, and Sichuan are significantly higher than the others, and Tianjin, Shanghai, Hainan, Tibet, Qinghai, and Ningxia are obviously lower than the average. The spatial distribution of the highest value is more obviously concentrated in several urban agglomerations.

(4) The SD of the 31 provinces ranges from 0.10 to 0.78. Guangdong has the highest value and is 2.32 times higher than the average. Other high SD provinces include Jiangsu, Shandong, and Henan. Additionally, the SD of Tianjin, Beijing, Shanghai, Jilin, Heilongjiang, Hainan, Tibet, and Qinghai are obviously lower than the average. Compared with the ND, the spatial distribution of the high value areas of the SD is more concentrated.

(5) According to the curve in Figure 2 and the value of CV, it shows that the four subsystems vary greatly between provinces, and their spatial distribution is very uneven. The CV of ND is the highest among the four subsystems. However, the curve of the NS and SS are relatively similar. The value of the SS is higher than that of the NS, except in Jilin, Heilongjiang, Anhui, Yunnan, and Tibet. The curve of the ND and SD are not only very similar in trend, but also in value. The values of the ND and SD are very close in most provinces, but they have great differences in some provinces, especially in Guangdong, Sichuan, Tibet, and Hainan.

3.2. Analysis of LCC

According to the evaluation model and grading standard given in Section 2.4, the NLCC, SLCC, and LCC indexes of the 31 provinces of China were calculated. The classification results are shown in Figures 4–6. The details of the spatial distribution pattern were as follows:

(1) The natural subsystems of most provinces in China cannot meet the natural needs of human beings. Only 7 provinces belong to surplus regions of NLCC, and 23 provinces are overloaded with NLCC. Surplus provinces are concentrated in the sparsely populated provinces in northeast and southwest China. Most of the overloaded provinces are concentrated in the southeast of China. Among them, Guangdong, Beijing, Tianjin, Shanghai, and Zhejiang are seriously overloaded. The other 6 provinces in central and southeast China are slightly overloaded, and 12 provinces are obviously overloaded.

(2) The overload of the societal subsystem seems not as serious as that of the natural subsystem, and the societal supply of most provinces can meet the societal needs of humans. There are 24 provinces belonging to surplus regions in SLCC. The surplus area is mainly located in Northeast China. SLCC is overloaded in 7 provinces, including Ningxia, Guizhou, Henna, Anhui, Jiangsu, Tibet and Hainan.

(3) The number of overloaded provinces in LCC is 17, which is obviously less than that of NLCC and much more than that in SLCC. The overloaded provinces are mainly concentrated in the eastern coastal area and the middle-east of China. The distribution of surplus area coincides with that of NLCC and CLCC.

In general, only depending on the natural endowment, most provinces of China cannot support the current population, but the influence of the societal subsystem has improved the comprehensive LCC of most provinces. This improvement of Beijing and Tianjin is the most obvious. There are also some special cases, for example, Hainan belongs to an overloaded region in LCC, due to insufficient SLCC; Ningxia belongs to an overloaded region, both in NLCC and SLCC. This indicates that each province has its own weaknesses in LCC, which needs to be further discussed.

Figure 4. The evaluation results NLCC of China in 2020.

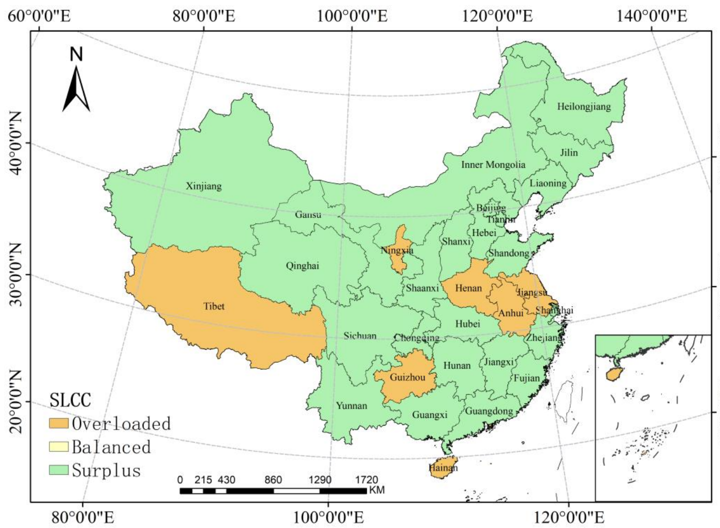

Figure 5. The evaluation results SLCC of China in 2020.

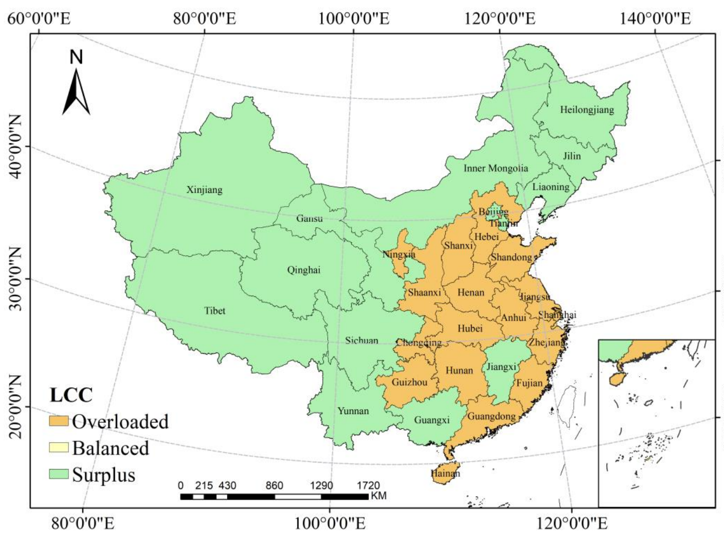

Figure 6. The evaluation results LCC of China in 2020.

3.3. Obstacles Indicators Analysis

Based on the obstacle degree calculation method, the obstacle degree of supply indicators in 31 provinces was obtained and is listed in Table 5. The indicators according to the degree of obstacle were ranked, and the indicators were selected in order until the total obstacle degree was greater than 50%. The selected indicators represent the weakness in the LCC system, which is called the obstacle indicator. The obstacle indicator with the largest obstacle degree was called the primary obstacle indicator. Identifying the obstacle indicators and primary obstacle indicators can help analyze the key factors leading to LCC overload, and help propose targeted policies and recommendations for the future development of the cities analyzed. The obstacle indicators are arranged from left to right in Figure 7.

(1) The NLCC overloaded province can be divided into three types, according to the primary obstacle indicators. Among them, Beijing, Tianjin, Shanxi, Shanghai, Jiangsu, Anhui, Shandong, Gansu, Qinghai, Ningxia, and Xinjiang are mainly limited by NPP; Fujian, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Guizhou, Yunnan, and Shaanxi are mainly limited by area of the residential land; Hebei, Liaoning, and Henan are mainly limited by water resources.

(2) The SLCC overloaded province can be divided into three types, according to the primary obstacle indicators of SLCC: Jiangsu is mainly limited by area of afforestation, Henan and Anhui are mainly limited by area of other construction land, and Hainan, Ningxia, Tibet, and Guizhou are mainly limited by investment in urban infrastructure.

(3) The LCC overloaded province can be divided into two types according to the obstacle indicators: Hebei, Shanxi, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Hubei, Hunan, Guangdong, Hainan, Chongqing, Shaanxi, and Ningxia are mainly limited by natural obstacles, and Shandong, Henan, and Guizhou are limited by both natural and societal obstacles.

(4) The shortage of natural resources is the key factor affecting LCC overloading in most provinces. Agroclimatic potential productivity (NS1), NPP (NS2), area of the residential land (NS3), and total water resources (NS4) were the most common obstacle indicators of LCC in China. Among the 31 provinces, there were 11 provinces primarily limited by NPP, 11 provinces primarily limited by area of the residential land, 6 provinces primarily limited by total water resources, and 3 provinces primarily limited by agroclimatic potential productivity.

(5) According to the corresponding physiological supply of these primary obstacle indicators, the overloaded types can be classified into four types: areas with an insufficient food supply, areas with an insufficient carbon sequestration, areas with a shortage of construction land, and areas with an insufficient water supply. Figure 8 shows the spatial distribution of these areas. Areas with an insufficient food supply were mainly in the southeast, areas with an insufficient carbon sequestration and areas with an insufficient water supply were concentrated in north China, and areas with a shortage of construction land were concentrated in central China. These obstacle indicators are the main problems that need to be solved in the future for these regions.

Table 5. The obstacle degree of all supply indicators in 31 provinces.

	NS1	NS2	NS3	NS4	SS1	SS2	SS3	SS4	SS5	SS6	SS7
Beijing	0.136	0.167	0.137	0.141	0.070	0.077	0.086	0.074	0.022	0.037	0.053
Tianjin	0.122	0.154	0.130	0.129	0.061	0.075	0.065	0.069	0.063	0.070	0.062
Hebei	0.141	0.206	0.071	0.221	0.058	0.042	0.000	0.087	0.078	0.028	0.068
Shanxi	0.135	0.160	0.128	0.154	0.057	0.054	0.046	0.078	0.053	0.067	0.068
Inner Mongolia	0.148	0.126	0.123	0.193	0.034	0.000	0.009	0.081	0.083	0.105	0.097
Liaoning	0.122	0.147	0.103	0.152	0.062	0.073	0.060	0.072	0.052	0.085	0.072

Table 5. *Cont.*

	NS1	NS2	NS3	NS4	SS1	SS2	SS3	SS4	SS5	SS6	SS7
Jilin	0.101	0.117	0.124	0.141	0.038	0.076	0.095	0.072	0.070	0.090	0.075
Heilongjiang	0.000	0.002	0.145	0.153	0.127	0.105	0.115	0.056	0.081	0.115	0.102
Shanghai	0.127	0.160	0.131	0.131	0.065	0.077	0.080	0.062	0.047	0.068	0.052
Jiangsu	0.145	0.224	0.047	0.202	0.056	0.123	0.100	0.000	0.058	0.005	0.039
Zhejiang	0.166	0.142	0.149	0.140	0.077	0.085	0.033	0.072	0.058	0.032	0.046
Anhui	0.108	0.149	0.097	0.142	0.066	0.088	0.096	0.059	0.078	0.049	0.069
Fujian	0.162	0.095	0.166	0.143	0.068	0.068	0.038	0.065	0.074	0.055	0.066
Jiangxi	0.165	0.111	0.182	0.122	0.034	0.065	0.058	0.062	0.078	0.054	0.069
Shandong	0.114	0.242	0.000	0.235	0.049	0.116	0.058	0.088	0.049	0.000	0.049
Henan	0.091	0.196	0.051	0.244	0.018	0.105	0.094	0.088	0.043	0.000	0.068
Hubei	0.142	0.120	0.173	0.123	0.066	0.070	0.041	0.057	0.060	0.076	0.072
Hunan	0.182	0.118	0.209	0.119	0.008	0.015	0.052	0.058	0.074	0.090	0.075
Guangdong	0.257	0.137	0.187	0.181	0.076	0.096	0.002	0.046	0.000	0.018	0.000
Guangxi	0.173	0.086	0.172	0.104	0.058	0.076	0.071	0.059	0.083	0.044	0.074
Hainan	0.120	0.135	0.136	0.120	0.064	0.072	0.074	0.066	0.072	0.077	0.064
Chongqing	0.136	0.148	0.159	0.126	0.054	0.047	0.070	0.075	0.062	0.058	0.065
Sichuan	0.203	0.054	0.237	0.077	0.000	0.072	0.081	0.086	0.070	0.046	0.074
Guizhou	0.140	0.132	0.163	0.110	0.053	0.051	0.064	0.073	0.074	0.082	0.059
Yunnan	0.167	0.000	0.189	0.120	0.052	0.056	0.077	0.081	0.089	0.098	0.072
Tibet	0.141	0.129	0.161	0.000	0.070	0.073	0.094	0.078	0.087	0.092	0.074
Shaanxi	0.148	0.113	0.155	0.152	0.057	0.049	0.070	0.079	0.051	0.062	0.065
Gansu	0.126	0.146	0.137	0.137	0.066	0.041	0.065	0.068	0.069	0.078	0.067
Qinghai	0.128	0.146	0.143	0.105	0.066	0.043	0.073	0.072	0.073	0.083	0.069
Ningxia	0.119	0.154	0.133	0.128	0.060	0.065	0.065	0.063	0.072	0.074	0.066
Xinjiang	0.107	0.186	0.141	0.139	0.129	0.067	0.016	0.000	0.069	0.077	0.068

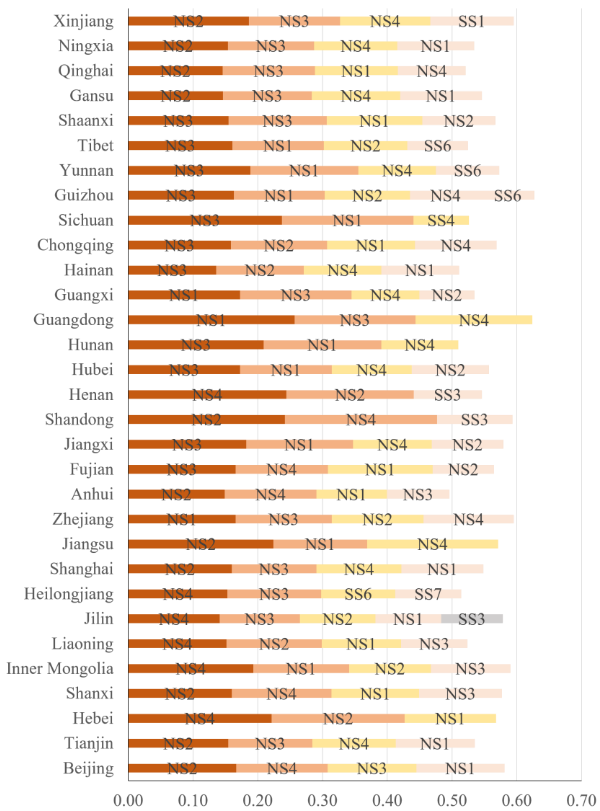

Figure 7. The obstacle indicators for supply subsystem of 31 provinces.

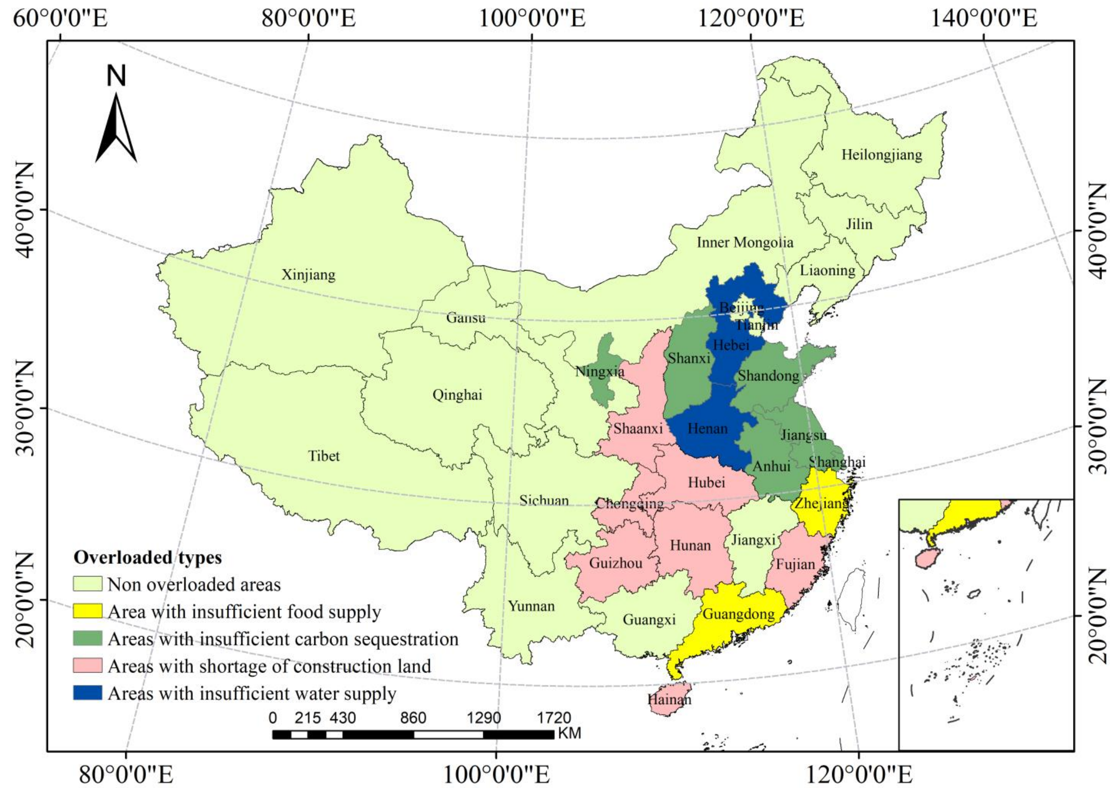

Figure 8. The overloaded types of the LCC overloaded provinces.

4. Discussion

The sustainable use of land resources by human beings will cause the consumption and destruction of land resources, and the development of human society and the use of science and technology will also enhance the carrying capacity of land resources. How do the natural system and social system affect the comprehensive LCC, respectively? To solve this problem, the paper provided a Natural–Societal-Supply–Demand evaluation framework of LCC, and evaluated the LCC of the natural subsystem, the LCC of the societal subsystem, and a comprehensive LCC though the cross relationship of the four subsystems. Instead of evaluating LCC only from the perspective of the supply–demand relationship, like other existing research, this paper divided it into four parts to evaluate the LCC endowed by natural resources and societal resources, respectively.

The research found that China's natural resources cannot carry the current population. The spatial distribution of the NS indicated that the influence of the natural system on LCC is in line with the natural geographical law. However, the development of human society has greatly improved LCC, enabling some provinces to carry the current population and even have some surplus. The spatial distribution of SS indicated that the improvement of the societal system on LCC is mainly related to the degree of social development. It shows that there is still room to improve LCC with the higher level of social development in the future. The difference in spatial distribution between the NS and SS also shows that the imbalance of natural resources and social development among provinces is serious. The spatial distribution of the ND and SD is similar, and basically consistent, with the population distribution. It shows that the distribution of population, and the distribution of social and economic development, is relatively coordinated.

Through the obstacle analysis, this paper found that the key to China's land resource carrying capacity is the shortage of natural resources. Among them, insufficient carbon sequestration and the shortage of construction land are the main problems faced by most provinces. To solve the problem of overloading in these provinces, it is necessary to strictly control the bottom line of food security, improve the productivity of grain, plant trees, reduce carbon emissions, save water, and improve the use efficiency of construction land.

However, as this paper only considers the function of land itself, the energy and environmental factors were not considered. In addition, the study only considered the region's own resources, and did not consider interregional exchanges and other mobility factors. These contexts need to be further evaluated in future studies.

5. Conclusions

This paper provided a Natural–Societal-Supply–Demand evaluation framework of LCC, which divided the evaluation system of LCC into four subsystems: the natural subsystem, the societal subsystem, the supply subsystem, and the demand subsystem. First, though the evaluation of the four subsystems, the natural endowment of land resources and the improvement of the societal subsystem of the 31 provinces of China were analyzed. Second, according to the cross-relationship of the four subsystems, the ability of natural land resources to support human living and the ability of society to support human socio-economic activities can be evaluated; the comprehensive LCC of the 31 provinces was also evaluated. Then, the obstacle degree model was used to analyze the key causes of overload. According to the evaluation results, the main conclusions can be drawn as following:

(1) The NS of China shows great regional differences. The distribution of the NS is generally low in the northwest and high in the southeast of China, and the highest area is distributed along the four major rivers of China. Heilongjiang has the highest NS, while Qinghai has the lowest. The NS of 23 provinces cannot meet the natural needs of human beings, among which Guangdong, Beijing, Tianjin, Shanghai, and Zhejiang are seriously overloaded.
(2) The SS is low in the southwest and northeast, and high in the south central area of China. The highest value of SS mainly coincides with the several major urban agglomerations. The societal subsystem of 7 provinces cannot meet the societal needs, among which Ningxia, Guizhou, Henna, Anhui, and Jiangsu are slightly overloaded, and Tibet and Hainan are obviously overloaded.
(3) The number of overloaded provinces in LCC is 17, and most of them are concentrated in the middle-east and eastern coastal area of China. The societal subsystem of Beijing, Tianjin, Hebei, Jiangsu, Yunnan, and Shanghai has significantly made up for the shortcomings of the NS, and has improved the comprehensive LCC.
(4) The shortage of natural resources is the key factor affecting LCC overloading in most provinces. Agroclimatic potential productivity, NPP, area of the residential land, and total water resources were the most common obstacle indicators of LCC. Hebei, Shanxi, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Hubei, Hunan, Guangdong, Hainan, Chongqing, Shaanxi, and Ningxia are mainly limited by natural obstacles; meanwhile, Shandong, Henan, and Guizhou are limited by both natural and societal obstacles.
(5) The areas with an insufficient food supply were mainly in the southeast, the areas with an insufficient carbon sequestration and the areas with insufficient water supply were concentrated in north China, and areas with a shortage of construction land were concentrated in central China. For China, ensuring food security, achieving carbon neutrality, improving the use efficiency of construction land, and rationally allocating water resources, are the key points to improve LCC and realize the sustainable utilization of land resources.

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References

1. National Bureau of Statistics of China. Nanjing. 2020. Available online: http://data.stats.gov.cn (accessed on 5 July 2022).
2. Wei, X.; Shen, L.; Liu, Z.; Luo, L.; Chen, Y. Comparative analysis on the evolution of ecological carrying capacity between provinces during urbanization process in China. *Ecol. Indic.* **2020**, *112*, 106179. [CrossRef]
3. Shi, Y.; Shi, S.; Wang, H. Reconsideration of the methodology for estimation of land population carrying capacity in Shanghai metropolis. *Sci. Total Environ.* **2018**, *652*, 367–381. [CrossRef] [PubMed]
4. Tong, S.; Feng, Z.; Yang, Y.; Lin, Y.; Wu, Y. Research on Land Resource Carrying Capacity: Progress and Prospects. *J. Resour. Ecol.* **2018**, *9*, 331–340. [CrossRef]
5. Lin, L.; Liu, Y.; Chen, J.; Zhang, T.; Zeng, S. Comparative analysis of environmental carrying capacity of the Bohai Sea Rim area in China. *J. Environ. Monit.* **2011**, *13*, 3178. [CrossRef]
6. Liu, R.Z.; Borthwick, A.G.L. Measurement and assessment of carrying capacity of the environment in Ningbo, China. *J. Environ. Manag.* **2011**, *92*, 2047–2053. [CrossRef]
7. Malthus, T.R. Essai sur le principe de population—En tant qu'il influe sur le progrès futur de la société, avec des remarques sur les théories de M. Godwin, de M. Condorcet et d'autres auteurs suivi de Une vue sommaire du principe de population. *Sib. Math. J.* **1980**.
8. Savari, M.; Yazdanpanah, M.; Rouzaneh, D. Factors affecting the implementation of soil conservation practices among Iranian farmers. *Sci. Rep.* **2022**, *12*, 8396. [CrossRef]
9. Kumar, P.; Rai, S.C.; Verma, R. Evaluating the status of gross and net food availability in special reference to carrying capacity of land of Sikkim. *Curr. Res. Environ. Sustain.* **2021**, *3*, 100099. [CrossRef]
10. Yanti, R. The Sustainable of Environmental Carrying Capacity to Support on Food Security (Nagari Sulit Air, X Koto Diatas District, Solok, West Sumatra). *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *197*, 012030. [CrossRef]
11. Čuček, L.; Klemeš, J.J.; Kravanja, Z. A Review of Footprint analysis tools for monitoring impacts on sustainability. *J. Clean. Prod.* **2012**, *34*, 9–20. [CrossRef]
12. Yang, Y.; Cai, Z. Ecological security assessment of the Guanzhong Plain urban agglomeration based on an adapted ecological footprint model. *J. Clean. Prod.* **2020**, *260*, 120973. [CrossRef]
13. Liao, S.; Wang, D.; Xia, C.; Tang, J. China's provincial process CO2 emissions from cement production during 1993–2019. *Sci. Data* **2022**, *9*, 165. [CrossRef] [PubMed]
14. Cheng, J.; Zhou, K.; Chen, D.; Fan, J. Evaluation and analysis of provincial differences in resources and environment carrying capacity in China. *Chin. Geogr. Sci.* **2016**, *26*, 539–549. [CrossRef]
15. Luan, C.; Liu, R.; Peng, S.; Li, W. Improving integrated environmental zoning from the perspective of logic scoring of preference and comparative advantage: A case study of Liangjiang New Area, China. *J. Clean. Prod.* **2021**, *325*, 129350. [CrossRef]
16. Wu, K.; Chen, K.; Gao, Y.; Jiang, S.; Huang, H. Applying a Set of Potential Methods for the Integrated Assessment of the Marine Eco-Environmental Carrying Capacity in Coastal Areas. *Sustainability* **2022**, *14*, 4416. [CrossRef]
17. Guo, S.; Li, C.; Liu, S.; Zhou, K. Land carrying capacity in rural settlements of three gorges reservoir based on the system dynamic model. *Nat. Resour. Model.* **2018**, *31*, e12152. [CrossRef]
18. Liu, H. Comprehensive carrying capacity of the urban agglomeration in the Yangtze River Delta, China. *Habitat Int.* **2012**, *36*, 462–470. [CrossRef]
19. Wei, C.; Guo, Z.Y.; Wu, J.P.; Ye, S.F. Constructing an assessment indices system to analyze integrated regional carrying capacity in the coastal zones—A case in Nantong. *Ocean Coast. Manag.* **2014**, *93*, 51–59. [CrossRef]
20. Xu, K.; Wang, J.; Wang, J.; Wang, X.; Chi, Y.; Zhang, X. Environmental function zoning for spatially differentiated environmental policies in China. *J. Environ. Manag.* **2020**, *255*, 109485.1–109485.10. [CrossRef]
21. Maslow, A.H. Dynamics of personality organization. II. *Psychol. Rev.* **1943**, *50*, 541–558. [CrossRef]
22. Ren, Y.; Shen, L.; Wei, X.; Wang, J.; Cheng, G. A guiding index framework for examining urban carrying capacity. *Ecol. Indic.* **2021**, *133*, 108347. [CrossRef]

23. Zhou, W.; Elshkaki, A.; Zhong, S.; Shen, L. Study on relative carrying capacity of land resources and its zoning in 31 provinces of China. *Sustainability* **2021**, *13*, 1459. [CrossRef]
24. Pu, L.; Zhang, S.; Yang, J.; Chang, L.; Xiao, X. Assessing the impact of climate changes on the potential yields of maize and paddy rice in Northeast China by 2050. *Theor. Appl. Climatol.* **2020**, *140*, 167–182. [CrossRef]
25. Du, Q.; Wang, N.; Che, L. Forecasting China's Per Capita Carbon Emissions Under a New Three-Step Economic Development Strategy. *J. Resour. Ecol.* **2015**, *6*, 318–323.
26. Fang, J.Y.; Yang, Y.H.; Wenhong, M.A.; Mohammat, A.; Shen, H.H. Ecosystem carbon stocks and their changes in China's grasslands. *Sci. China* **2010**, *53*, 757–765. [CrossRef]
27. Liu, Z.; Guan, D.; Wei, W.; Davis, S.J.; Ciais, P.; Bai, J.; Peng, S.; Zhang, Q.; Hubacek, K.; Marland, G. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature* **2015**, *524*, 335–338. [CrossRef]
28. Fischer, G.; Nachtergaele, F.O.; Prieler, S.; Teixeira, E.; Tóth, G.; Velthuizen, H.V.; Verelst, L.; Wiberg, D. *Global Agro-Ecological Zones (GAEZ v3.0)*; IIASA: Laxenburg, Austria; FAO: Rome, Italy, 2012.
29. Traill, W.B.; Bedouin, R.; Gourlie, K.; Husch, J.; Lustre, A. Report of the Evaluation of Codex Alimentarius and other FAO and WHO Food Standards Work. *Acta Gastro-Enterol. Belg.* **2003**, *28*, 10–32.
30. Food and Agriculture Organization of the United Nations. *Population supporting capacity of land in the Asia and Pacific Region: Note by FAO*; Unpublished; FAO: Rome, Italy, 1982.
31. IPCC Climate Change 2007, Synthesis Report. 2008. Available online: http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html (accessed on 5 July 2022).
32. Zhang, F.; Wang, Y.; Ma, X.; Wang, Y.; Yang, G.; Zhu, L. Evaluation of resources and environmental carrying capacity of 36 large cities in China based on a support-pressure coupling mechanism. *Sci. Total Environ.* **2019**, *688*, 838–854. [CrossRef]
33. Kuo, Y.; Yang, T.; Huang, G.W. The use of grey relational analysis in solving multiple attribute decision-making problems. *Comput. Ind. Eng.* **2008**, *55*, 80–93. [CrossRef]
34. Huang, H.; Wang, R.; Wang, J.; Chai, J.; Xiao, Y. Temporal and spatial evolution and obstacle diagnosis of resource and environment carrying capacity in the Loess Plateau. *PLoS ONE* **2021**, *16*, e0256334. [CrossRef]