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RESEARCH ARTICLE

Comprehensive evaluation for sustainable development based on relative resource carrying capacity—a case study of Guiyang, Southwest China

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Abstract
On the basis of resource carrying capacity, this study used the revised theory of relative resource carrying capacity, took Guiyang as the study object, and calculated relative carrying capacities of natural resources, economic resources, environmental resources, and social resources from 2003 to 2017. Natural resources were composed of three indicators (energy resources, water resources, and land resources). Human capital resources were incorporated into social resources. Therefore, on the basis of the revised model of relative resource carrying capacity, conclusions were drawn: when taking the whole country as the reference area, Guiyang had an overloaded population from 2003 to 2017 whether under traditional or improved resource-carrying capacity model. But there were different results from these two models. When taking the entire province as the reference area, the result was the opposite. Whether taking the whole country or the entire province as the reference area, contributions of economic resources and social resources to comprehensive resource-carrying capacity were obviously higher than that of natural resources and environmental resources. When taking Guizhou as the reference area, other districts and counties were in the state of surplus, except that Qingzhen was overloaded after 2010 and Xiuwen was overloaded in 2010, 2011, and 2012. Therefore, corresponding countermeasures on sustainable development of Guiyang had been put forward in this study. It is necessary to control the population size, increase the cultivated land resources properly, accelerate regional economic development, strengthen ecological environmental protection, and save energy resources.

Keywords Relative resource carrying capacity · Revised model · Sustainable development · Guiyang city

Introduction

Since the 1980s, China had entered a period of rapid economic development, but a series of development disadvantages had also followed, such as population explosion, uneven economic development, resource shortage, environmental degradation, and other environmental problems (Peng and Guo 2018). At the same time, as a developing country with rapid urbanization and the largest energy consumption, the serious imbalance of population, economy, and resource development had brought great challenges to the sustainable development of China (Lv et al. 2018; Johnston et al. 2007). The natural resource stock and ecological environment capacity of a region determined its population-carrying capacity during a period, and there was a limit to the carrying capacity. Within this limit, human development and ecological environment resources are sustainable (Sun and Liu 2014). However, once the total population exceeds population-carrying capacity of this region, it will inevitably lead to the imbalance between human development and ecological and environmental protection of resources, and even cause ecological crisis, which seriously threatens local sustainable development (Yang et al. 2001).

Broadly speaking, fast-growing population, growing business activities, industrialization, and inadequate provision of waste management services had led to a growth in the amount of wastes discharged into the environment (Juma et al. 2014). Resource depletion and environmental pollution posed a threat to the stability and sustainability of the ecological

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system. With mightily approving of sustainable conception by a large number of people, protecting resources and environment had aroused people's attentions from all walks of life, and they were also beginning to be aware of the significance of co-development of resources, environment, economy, and society (Wei and Liu 2013). In recent decades, scholars had carried out a lot of researches on resource-carrying capacity, but these researches had some defects: (1) Understanding about resources was circumscribed. Up to now, studies on resource carrying capacity mainly focused on land, water, and key mineral resources. By nature, resources should be the sum of natural and social resources. Also, with the progress of science and technology, and the gradual integration of the global economy, people's living and production within a certain area would become less and less dependent on existing natural resources in this region. Traditional researches on resource-carrying capacity, which took food consumption that met a certain standard of living as the standard of population-carrying capacity, had great limitations. And the higher level requirements such as culture, education, and entertainment needs should also be taken into account in the quality of life standards pursued by human beings. Even from the perspective of some people, for example, the worldwide carrying capacity for mankind had already been, or would be, exceeded in some regions, such as food consumption or fossil fuel use (Paul et al. 2007). Therefore, the extension of resource carrying capacity should be expanded. (2) Dynamic viewpoints were scanty. Traditional studies on resource-carrying capacity only used current living conditions and living standards to estimate current and future resource-carrying capacity. With the development of economy and society, contemporary scholars generally agreed that resource-carrying capacity should be a dynamic concept. (3) Research areas were regarded as closed and isolated systems (Wang 2009). Traditional researches on resource-carrying capacity isolated research areas and took food resources as the only restraint factor of population carrying capacity, thus coming to the one-sided conclusion that the total regional grain output fundamentally determined the population support level in this area. At present, each region was no longer an independent and closed system, and the relationship with the outside world was getting closer and closer. Compared with surrounding areas, the research area was an open and dynamic areal system. There were more and more resource circulation and exchange inside and outside the region, and the mutual dependence and complementarity in resources were getting stronger and stronger (Liang et al. 2018; Pei and Wang 2017).

Therefore, resource-carrying capacity should be studied from the perspective of globalization (Pan and Han 2007). To avoid the above defects, some scholars put forward the research strategy of relative resource-carrying capacity according to per-capital resource ownership and consumption in the reference area as well as the resource stock in the study area, which meant that one or more reference areas larger than the specific research area were selected as comparison criteria to calculate each kind of relative resource-carrying capacity in the study area. Research ideas and methods of relative resource carrying capacity had been applied in the evaluation model of regional sustainable development and the study of the relationship between population distribution and resources (Bao and Cui 2005).

As China was populous and total resources were limited, the total population calculated by conventional methods almost always carried less people than they actually did (Huang and He 2011). In quest of seeking the important path of industrial transformation and upgrading, and achieving the harmonious development of population, resources, and environment, this study expanded the relative resource-carrying capacity model on the basis of the existing resource-carrying capacity framework. The natural resource subsystem contained three indicators: water resources, land resources, and energy resources, while the analysis category that belonged to the social resource subsystem contained the population quality factor. Based on the improved model, this study analyzed the relative resource-carrying capacity state of Guiyang city and revealed the mutual relationship and evolution rule of population, resources, and environment in Guiyang city. This not only provided a reference for Guiyang city to achieve sustainable development but also had theoretical and realistic meanings for enriching and expanding the research background of relative resource-carrying capacity, and also probing into the sustainable development of other man-earth relationships (Yang and Ding 2018).

Literature review

With the continuous emergence of ecological environment problems and the concept of resource environment carrying capacity becoming more and more mature, researches on its theory and evaluation methods had been deepened. It can be seen from the point of existence and development of human beings that resource-carrying capacity took the relationship between resources, environment, and ecology into consideration (Seidl and Tisdell 1999). During the process of researches on human ecology, the concept of carrying capacity was formally proposed by Park and Burgess (Park and Burgess 1920), which referred to the maxim limit of the quantity of individual existence in a certain environmental condition. In the book "The Limits to the Growth," for the worldwide resources (land, water, food, mining, etc.), the relationship between the ecological environment and people was evaluated by using the system dynamics theory, and the relationship among population growth, economic development, excessive consumption of resources, ecological environment deterioration, and limited food production was revealed, thereby reaching the conclusion that in the middle of the twenty-first century, the global economic growth would reach the limit (Arrow et al. 1995). On the basis of the seniors' researches, scholars in China had carried out a great number of studies on the evaluation of resource and environment carrying capacity. Zeng and Wang took the lead in carrying out a quantitative research on the environmental carrying capacity. They established the functional relationship between development variables (measuring human activities) and limiting variables (measuring environmental constraints) and conducted a case study on the environmental carrying capacity of planned communities in Meizhou bay development zone, Fujian province (Zeng et al. 1991). Mao and Yu used the state space method to evaluate environmental carrying capacity of the Bohai rim region quantitatively (Mao and Yu 2001). Liu and Wang selected dozens of indicators from the following four aspects, including economy, society, resource environment, and ecological system, to construct the evaluation index system of environmental resource-carrying capacity and adopted the residual rate method for research (Liu et al. 2006). Fu and Ma constructed the evaluation index system of urban resource and environmental carrying capacity from the aspects of social resources and natural resources and conducted an empirical study on the resource and environmental carrying capacities of 15 sub-provincial cities from 2003 to 2013 by using the principal component analysis method (Fu and Ma 2016). Dai and Sun used the water ecological footprint model combined with the system dynamic model to assess the water resource carrying capacity and its sustainability in Zhangjiakou City, a typical water shortage city in north China (Dai et al. 2019).

While at the same time, foreign scholars had also carried out researches on evaluations of resource and environment-carrying capacity. Millnigtno and Gifford adopted the multi-objective decision-making method to have the capacity of land resources measured in Australia (Millington and Gifford, 1973). Bishop performed related researches on the environmental carrying capacity (Bishop et al. 1974), and Holling carried out relevant researches on the ecological carrying capacity (Holling 1986). Fiala N discussed how a footprint can specify the current sustainability of a system by arbitrarily determining boundaries (Fiala 2008). Rees presented a calculation of the city of Vancouver, Canada, which he argued required 174 times as much land to sustain it as is currently contained within the city (Rees 2008). Slesser proposed the ECCO model (Enhancement of Carrying Capacity Options) as a calculation method for new resource and environmental carrying capacity (Slesser 1990). Outeiro performed a review of ecosystem ecology indicators to compare relative carrying capacities in Ria de Arousa (NW Spain) (Outeiro et al. 2018). Ait-Aoudia M N assessed water resource carrying capacity of Algeria's capital city (Ait-Aoudia and Berezowska-Azzag 2016). Gober Patricia studied a simulation model for urban water planning in Phoenix, Arizona, USA (Gober et al., 2011). Naimi-Ait-Aoudia M assessed the water-carrying capacity in Algiers internationally admitted levels of household consumption and took into account water inputs that can significantly vary according to dry and wet years (Naimi-Ait-Aoudia and Berezowska-Azzag 2014). Oh, K calculated the carrying capacity by an integrated framework for assessing urban carrying capacity which can determine development density based on current infrastructures and land use for an area in Seoul, South Korea (Oh et al., 2005). Hasan Rüstemoğlu made a comprehensive environmental analysis on the factors affecting Germany's green development from 1990 to 2015 (Rüstemoğlu 2019). From the above discussion, it can be seen clearly that researches on resource carrying capacity had developed from single dimension to multi-dimension.

Traditional carrying capacity analysis, which was mostly in a single, closed, static environmental condition, was obtained by the calculation and evaluation of natural resources, emphasizing the strong dependence of human survival and development on natural resources (Liu et al. 1998). Sustainable development was a compound ecological system composed of three subsystems: nature, economy, and society. In a broad sense, resources included natural resources, economic resources, and social resources. Human beings were the main components of social subsystems and carrying objects in the carrying capacity (Liu and Yu 2002). The"P-E-R regional matching model" proposed by Mr. Zhu in 1993 (Zhu 1993) and the "relative resource carrying capacity" proposed by Mr. Huang in 2000 (Huang and Kuang 2000) were two classic research ideas and methods for evaluating regional population, economy, and resource-carrying capacity. Both of them were to study the relationship among population, economy, and resources from the perspective of regional sustainable development. However, the "P-E-R regional matching model" established by Mr. Zhu placed more emphasis on the matching relationship among population, economy, and resource-carrying capacity particularly from the perspective of regional population distribution. The calculation ideas and methods of relative resource carrying capacity put forward by Mr. Huang mainly focused on comparing the contribution of relative carrying capacity of land resources and relative carrying capacity of economic resources to comprehensive carrying capacity.

In terms of analytical method, relative resource-carrying capacity was based on a comparison of several reference areas larger than the study area in contrast to the traditional study of resource carrying capacity, which focused on the calculation of absolute amount of food (or grain). Then, relative carrying capacities of various resources in the study area relative to the reference area were calculated according to per-capita resource ownership and consumption in the reference area (Zhu 1993). Similar methods had been applied in the evaluation model of regional sustainable development and the study of the relationship between population distribution and resources (Jiang 1998; Wang and Liu 2003). Compared with the traditional single resource-carrying capacity, the relative resource-carrying capacity emphasized the openness of the research area and the complementarity between natural resources and economic resources (Huang and Kuang 2000).

However, there was little extensive research on the model, especially on the sustainable development. How to improve the population carrying capacity and promote and enhance the development of regional economic would be an important scientific issue to achieve the sustainable development of regional population, resources, environment, economy, and society. Under the influence of social factors such as enhancement of interregional communication, it was of great significance to study the reduction of human dependence on natural resources and the realization of the complementarity between natural resources and economic resources to improve population carrying capacity. Therefore, based on the traditional relative resource-carrying capacity, this study analyzed the improved relative resource-carrying capacity model and demonstrated the situation of Guiyang's relative resource-carrying capacity from 2003 to 2017 with the improved model, to reveal the trends and characteristics of Guiyang's resource-carrying capacity.

Data sources and research methods

The basic data in this study were mainly from China statistical yearbook (2003-2017), China urban statistical yearbook (2003-2017), China regional statistical yearbook (2003-2017), Guizhou statistical yearbook (2003-2017), Guiyang statistical yearbook (2003-2017), and the field data from 2003 to 2017.

According to the relative resource-carrying capacity (Wang and Zhang 2017), and natural ecological and geographical conditions of Guiyang city, the model was modified appropriately in this study. This study took water resources, cultivated areas, and energy resources as natural resource indicators. Industrial wastewater discharges were taken as environmental resource indicator. GDP was served as economic resource indicator. Social resource indicators were the total retail sales of social consumer goods, and high school and above education population:

$$C_{rwle} = W_1 C_{rw} + W_2 C_{rl} + W_3 C_{re} \quad (1)$$

where C_{rwle} is the relative natural resource-carrying capacity, which is the sum of three components: C_{rw}, C_{rl}, and C_{re} that represent the carrying capacity of water resources, the carrying capacity of cultivated area, and the carrying capacity of energy resources respectively.

$$C_{rw} = I_{rw} \times Q_{rw}, \quad C_{rl} = I_{rl} \times Q_{rl}, \quad C_{re} = I_{re} \times Q_{re}$$

Q_{rw} is the total amount of water resources, Q_{rl} is the total amount of cultivated area, and Q_{re} is the total amount of energy resources in the study area. For the natural resource-carrying capacity index, the calculation formula is as follows: $I_{rw} = P_0/Q_{rw0}$, $I_{rl} = P_0/Q_{rl0}$, $I_{re} = P_0/Q_{re0}$. Among them, I_{rw} is the water resources-carrying index, I_{rl} is the cultivated area carrying index, I_{re} is the energy resources carrying index. P_0 is the total population of the reference area. Q_{rw0}, Q_{rl0}, and Q_{re0} are the total water resources, the cultivated area, and the total energy production in the reference area respectively. W_1 is the weight of water resources in the relative natural resources carrying capacity, W_2 is the weight of cultivated area in the relative natural resources carrying capacity, and W_3 is the weight of energy resources in the relative natural resources-carrying capacity:

$$C_{re1} = I_{re1} \times Q_{re1} \quad (2)$$

where C_{re1} means the relative environmental resource carrying capacity. Q_{re1} is the total amount of industrial wastewater discharged into the study area. I_{re1} is the environmental resource-carrying index which has the following calculation formula: $I_{re1} = P_0/Q_{re10}$, P_0 is listed as above and Q_{re10} is the total industrial wastewater discharge of the reference area:

$$C_{re2} = I_{re2} \times Q_{re2} \quad (3)$$

where C_{re2} means the relative economic resource-carrying capacity. Q_{re2} is the regional GDP of the research region. I_{re2} is the economic resources-carrying index which has the following calculation formula: $I_{re2} = P_0 \times Q_{re20}$; P_0 is listed as above and Q_{re20} is GDP of the reference area:

$$C_{rs} = W_4 C_{rc} + W_5 C_{rh} \quad (4)$$

The above formula is to calculate the relative social resource-carrying capacity. In the formula, C_{rs} means the relative social resource-carrying capacity that is the sum of C_{rc} and C_{rh}. C_{rc} denotes social consumer goods resources and C_{rh} denotes human capital resources. $C_{rc} = I_{rc} \times Q_{rc}$, $C_{rh} = I_{rh} \times Q_{rh}$. Q_{rc} is the social consumable total retail sales in the research area, Q_{rh} is the number of people with a high school education or above in the research area. From the above two formulas, they can be calculated: $I_{rc} = P_0/Q_{rc0}$, $I_{rh} = P_0/Q_{rh0}$. Among them, I_{rc} is the social consumer goods resources-carrying index and I_{rh} is human capital resources-carrying index. P_0 is listed as above. Q_{rc0} is the social consumable total retail sales in the reference area and Q_{rh0} is the number of people with a high school education or above in the reference area. W_4 is the weight of social consumer goods resources and W_5 is the weight of human capital resources in relative social resources-carrying capacity:

$$C_s = W_6 C_{rwle} + W_7 C_{re1} + W_8 C_{re2} + W_9 C_{rs} \quad (5)$$

Among them, C_s means the relative comprehensive resource-carrying capacity. W_6, W_7, W_8, and W_9 are respectively the weights of natural resources, environmental resources, economic resources, and social resources in the relative carrying capacity on comprehensive resources. According to the specific situation of Guiyang city (Ni and Wang 2012; Li et al. 2016) and previous literatures (Dai et al. 2019; Noronha et al. 2019; Al-mulali et al. 2015), the weights could be set as: $W_1 = 0.4$, $W_2 = W_3 = 0.3$, $W_4 = W_5 = 0.5$, $W_6 = W_8 = 0.3$, $W_7 = W_9 = 0.2$.

Evaluation methods of relative resource-carrying capacity mainly included the following three types: (1) When the actual population of the research area (P) is larger than the population that resources can support (C_s), that is $P\text{-}C_s > 0$, overload. (2) When the actual population of the research area (P) is less than the population that resources can support (C_s), that is, $P\text{-}C_s < 0$, surplus. (3) When the actual population of the research area (P) is equal to the population that resources can support (C_s), that is, $P\text{-}C_s = 0$, critical. The formula of overloading rate (or surplus rate) is $R = P_0/P$. R is the relative resource overload rate (or surplus rate), and P_0 is the actual overpopulation: $P_0 = P - C_s$.

Results

Overview on the case city

Guiyang, the capital city of Guizhou province, is one of typical karst cities in southwest China. The location information is illustrated in Fig. 1 (Wang et al. 2019). The total urban area is 8034 km ^{2}, which accounts for 4.56% of the province's total area and the population was 4.69 million in 2018. Guiyang city is located in the eastern slope zone of Yunnan-Guizhou plateau in central Guizhou province, east longitude 106°07′-107°17′, north latitude 26°11′ to 27°22′. Guiyang is a typical area of karst geomorphology, and its unique geographical environment makes it a fragile region of ecologic environment. Karst area reaches 6803 km^2, occupying 85% areas in total of Guiyang. Besides, the area of rocky desertification and potential rocky desertification reaches 51%, and the soil erosion is very severe. Guiyang is endowed with natural resources, with an annual total water resources of 4.68 billion cubic meters, theoretical reserves of 1.307 million kW of water resources, a forest coverage rate of 41.78%, a garden area of 9.26%, and a forest land of 34.01%.

Models comparison before and after improvement

For the traditional relative resource-carrying capacity model, regional GDP, cultivated area, industrial wastewater discharge, and social consumable total retail sales were seen as relative economic resource-carrying capacity, relative natural resource-carrying capacity, relative environmental resource-carrying capacity, and relative social resource-carrying capacity, respectively. While for the improved relative resource carrying capacity model, water and energy resources were included in relative natural resource carrying-capacity, and human capital resources were incorporated into relative social resource-carrying capacity. Analysis results before and after model improvement showed that (Table 1 and Table 2) on the basis of analyzing the traditional relative resource-carrying capacity model and taking the whole country as the reference area, relative resource comprehensive-carrying capacity of

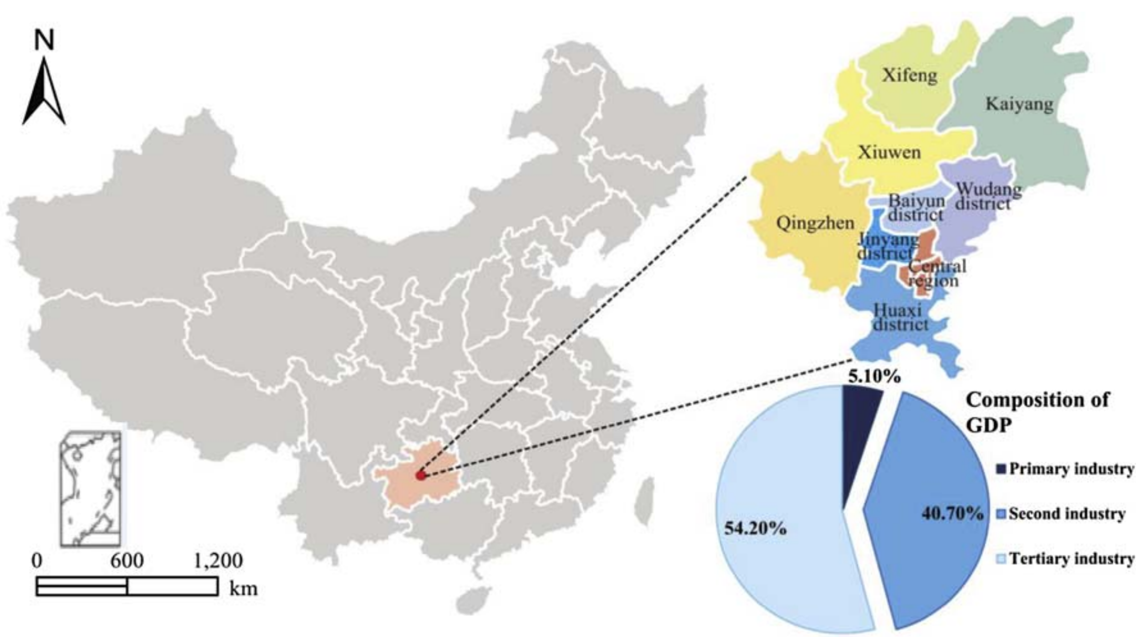

Fig. 1 Geographical information of Guiyang City in China

Table 1 Comparison of comprehensive resource carrying capacity in Guiyang from 2003 to 2017, taking the whole country as the reference area

Year	P	Traditional model				Modified model			
		C_s	P′	R	Type of carrying state	C_s	P′	R	Type of carrying state
2003	348.70	289.48	59.00	0.169	Overload	327.85	20.85	0.060	Overload
2004	350.85	285.32	65.53	0.187	Overload	322.06	28.79	0.082	Overload
2005	353.09	282.33	70.76	0.200	Overload	313.47	39.62	0.112	Overload
2006	355.14	279.18	75.96	0.214	Overload	310.96	44.18	0.124	Overload
2007	356.77	259.61	97.16	0.272	Overload	284.78	71.99	0.202	Overload
2008	372.75	244.14	128.61	0.345	Overload	263.97	108.78	0.292	Overload
2009	396.79	243.27	153.52	0.387	Overload	264.06	132.73	0.335	Overload
2010	432.46	249.27	183.19	0.424	Overload	270.11	162.35	0.375	Overload
2011	439.33	254.21	185.12	0.421	Overload	273.99	165.34	0.376	Overload
2012	445.17	271.55	173.62	0.390	Overload	293.37	151.80	0.341	Overload
2013	452.19	293.53	158.66	0.351	Overload	342.59	109.60	0.242	Overload
2014	455.60	325.95	129.65	0.285	Overload	379.44	76.16	0.167	Overload
2015	462.18	341.98	120.20	0.260	Overload	388.56	73.62	0.159	Overload
2016	469.68	411.73	57.95	0.123	Overload	427.35	42.33	0.090	Overload
2017	480.20	426.59	53.61	0.112	Overload	443.36	36.84	0.077	Overload
Average	411.39	297.21	114.17	0.276	Overload	327.06	84.33	0.202	Overload

Guiyang had been in a state of overload, with an average overload population of 1 million from 2003 to 2017, while taking Guizhou province as the reference area, the relative resource comprehensive-carrying capacity of Guiyang had been in a state of surplus, with an average surplus population of 3 million from 2003 to 2017. Relative resource comprehensive-carrying capacity of Guiyang was also in an overload state on the basis of analyzing the improved model when taking the whole country as the reference area, but the average overload population was about 0.8 million. While the relative resource comprehensive-carrying capacity of Guiyang was in a surplus state on the basis of analyzing the improved model when taking the entire province as the reference area, and the average surplus population was also about 3

Table 2 Comparison of comprehensive resource carrying capacity in Guiyang from 2003 to 2017, taking Guizhou province as the reference area

Year	P	Traditional model				Modified model			
		Cs	P′	R	Type of carrying state	Cs	P′	R	Type of carrying state
2003	348.70	875.76	−527.06	−1.51	Surplus	864.27	−515.57	−1.48	Surplus
2004	350.85	881.82	−530.97	−1.51	Surplus	868.41	−517.56	−1.48	Surplus
2005	353.09	822.97	−469.88	−1.33	Surplus	819.70	−466.61	−1.32	Surplus
2006	355.14	796.97	−441.83	−1.24	Surplus	791.03	−435.89	−1.23	Surplus
2007	356.77	769.51	−412.74	−1.16	Surplus	754.74	−397.97	−1.12	Surplus
2008	372.75	660.40	−287.65	−0.77	Surplus	638.33	−265.58	−0.71	Surplus
2009	396.79	625.19	−228.40	−0.58	Surplus	601.19	−204.40	−0.52	Surplus
2010	432.46	621.34	−188.88	−0.44	Surplus	596.32	−163.86	−0.38	Surplus
2011	439.33	572.47	−133.14	−0.30	Surplus	539.96	−100.63	−0.23	Surplus
2012	445.17	571.71	−126.54	−0.28	Surplus	546.26	−101.09	−0.23	Surplus
2013	452.19	573.87	−121.68	−0.27	Surplus	586.56	−134.37	−0.30	Surplus
2014	455.60	596.21	−140.61	−0.31	Surplus	602.72	−147.12	−0.32	Surplus
2015	462.18	609.50	−147.32	−0.32	Surplus	598.64	−136.46	−0.30	Surplus
2016	469.68	740.14	−270.46	−0.58	Surplus	704.07	−234.39	−0.50	Surplus
2017	480.20	755.34	−275.14	−0.57	Surplus	716.61	−236.41	−0.49	Surplus
Average	411.39	698.21	−286.82	−0.74	Surplus	681.92	−270.53	−0.71	Surplus

Table 3 Relative resource-carrying capacity of Guiyan from 2003 to 2017, taking the whole country as the reference area

Year	C_{rwle}	C_{re1}	C_{re2}	C_{rs}	C_s	P	P′	R
2003	261.077	356.545	376.522	326.287	327.85	348.70	20.85	0.060
2004	237.595	321.491	381.395	360.342	322.06	350.85	28.79	0.082
2005	233.206	304.268	375.290	350.345	313.47	353.09	39.62	0.112
2006	230.723	280.791	375.597	364.526	310.96	355.14	44.18	0.124
2007	226.004	213.084	341.309	359.865	284.78	356.77	71.99	0.202
2008	214.114	132.220	338.209	359.152	263.97	372.75	108.78	0.292
2009	202.089	131.936	349.310	361.258	264.06	396.79	132.73	0.335
2010	198.210	133.280	369.078	366.340	270.11	432.46	162.35	0.375
2011	190.210	115.188	388.643	386.507	273.99	439.33	165.34	0.376
2012	190.858	122.488	434.417	406.444	293.37	445.17	151.80	0.341
2013	274.181	147.030	483.817	428.915	342.59	452.19	109.60	0.242
2014	292.028	193.965	536.913	459.806	379.44	455.60	76.16	0.167
2015	261.330	183.600	586.905	486.866	388.56	462.18	73.62	0.159
2016	319.222	278.832	587.332	498.070	427.35	469.68	42.33	0.090
2017	316.931	333.900	594.378	515.944	443.36	480.20	36.84	0.077
Average	243.185	216.575	434.608	402.044	327.061	411.39	84.33	0.202

million. When taking the whole country as the reference area, whether based on the traditional model analysis or the improved model analysis, relative resource overload ratio had the same trend, they had been positive, and their numerical values showed a trend of increasing first and then decreasing. When taking the entire province as the reference area, whether based on the traditional model analysis or the improved model analysis, relative resource surplus ratio had the same trend, they had been negative, and their absolute values showed a trend of decreasing first and then increasing. Furthermore, there were some differences between the two models, indicating that the contribution rate of energy resources to natural resources was high, and the contribution rate of human capital resources to social resources was low. Hence, when analyzing the carrying capacity of regional resources, advantages and disadvantages of resources should be considered properly. Or else, population-carrying capacity calculated by the models would change greatly, which would have a negative impact on the understanding of sustainable development in the study area.

Taking the whole country and the entire province as reference areas respectively to analyze the improved model

Relative comprehensive resource-carrying capacity

From Table 3 and Fig. 2, it can be seen that when taking the whole country as the reference area, relative comprehensive resource-carrying capacity of Guiyang was in an overload status from 2003 to 2017, and the size of overload population showed a trend of increasing first and then decreasing. Overall, relative comprehensive resource-carrying capacity of Guiyang was still in overload status when taking the whole country as the reference area. The average comprehensive resource-carrying capacity was 3 million people, and the overload rate and overload scale had been decreasing in recent years. In Table 3, the overload scale decreased from 1.65 million people at the highest level in 2011 to 0.36 million people in 2017, which meant that with the development of social economy and population increase, relative comprehensive resource-carrying capacity in Guiyang gradually increased.

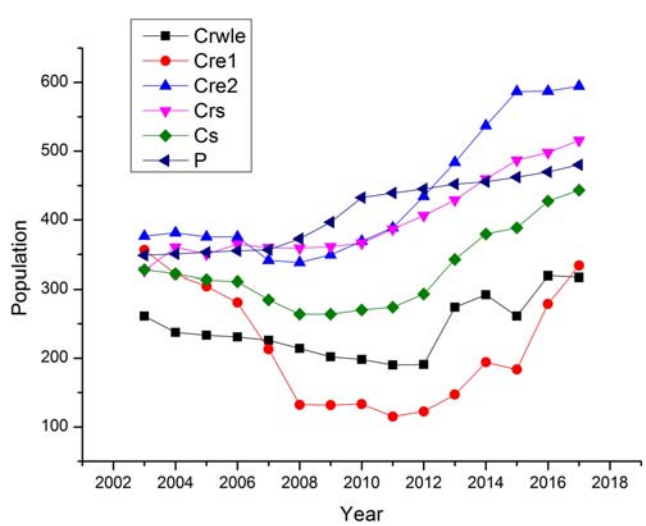

Fig. 2 Each kind of relative resource-carrying capacity of Guiyang, taking the whole country as the reference area

Table 4 Relative resource-carrying capacity of Guiyang from 2003 to 2017, taking the entire province as the reference area

Year	C_{rwle}	C_{re1}	C_{re2}	C_{rs}	C_s	P	P′	R
2003	311.473	1344.35	1074.136	898.592	864.271	348.70	− 515.57	− 1.48
2004	320.174	1318.66	1091.643	905.667	868.410	350.85	− 517.56	− 1.48
2005	328.299	1251.99	990.786	867.888	819.701	353.09	− 466.61	− 1.32
2006	317.798	1181.11	951.352	870.337	791.034	355.14	− 435.89	− 1.23
2007	293.497	1183.80	873.390	839.549	754.736	356.77	− 397.97	− 1.12
2008	271.516	738.03	819.163	817.593	638.328	372.75	− 265.58	− 0.71
2009	251.105	617.27	815.960	788.073	601.188	396.79	− 204.40	− 0.52
2010	242.711	585.48	848.094	759.905	596.319	432.46	− 163.86	− 0.38
2011	221.548	333.65	840.908	772.454	539.958	439.33	− 100.63	− 0.23
2012	241.189	299.19	868.835	767.075	546.260	445.17	− 101.09	− 0.23
2013	335.927	346.09	902.987	728.335	586.559	452.19	− 134.37	− 0.30
2014	351.072	309.77	946.465	757.506	602.716	455.60	− 147.12	− 0.32
2015	307.360	326.70	971.430	748.337	598.644	462.18	− 136.46	− 0.30
2016	356.264	817.66	953.625	737.872	704.073	469.68	− 234.39	− 0.50
2017	351.631	917.11	934.022	737.481	716.610	480.20	− 236.41	− 0.49
Average	300.104	771.391	925.520	799.778	681.920	411.39	− 270.53	− 0.71

From Table 4 and Fig. 3, it can be seen that when taking the entire province as the reference area, relative comprehensive resource-carrying capacity of Guiyang was in an surplus state from 2003 to 2017, and the absolute surplus population size showed a trend of decreasing first and then increasing. Overall, the relative comprehensive resource-carrying capacity of Guiyang City was still in surplus state when taking the entire province as the reference area. The average comprehensive resource-carrying capacity was 7 million people, and the absolute surplus rate and surplus scale had been increasing in recent years. In Table 4, the surplus scale decreased from 5 million people at the highest level in 2003 to 1 million people in 2011, then it increased to 2.36 million in 2017, which meant that with the development of social economy and population increase, relative comprehensive resource-carrying capacity in Guiyang gradually increased.

Average contribution rate of each resource-carrying capacity to population-carrying capacity

From Fig. 4, it can be seen that when taking the whole country as the reference area, carrying capacities of economic and social resources accounted most for population-carrying capacity in Guiyang, while carrying capacities of natural and environmental resources were always overload from 2003 to 2017. Carrying capacities of environmental resources and natural resources were both lower than the actual population while carrying capacities of economic resources and social resources were both higher than the actual population in Guiyang. During the period from 2003 to 2017, the contribution rate of natural resources-carrying capacity was basically below 21%, the contribution rate of environmental resources decreased first from 27% in 2003 to 10% in 2012, then increased to 19% in 2017. The average contribution rate of economic resources and the average contribution rate of social resources increased to 33.4% and 31.3% respectively. At the end of 2017, the carrying capacity of economic resources was 5944 thousand people, natural resources 3169 thousand people, environmental resources 3339 thousand people, and social resources 5159 thousand people. Among these four resource-carrying capacity indicators, natural and environmental resource-carrying capacities were always lower than the actual population-carrying capacity, and the other two kinds of resource carrying capacities were both higher than the actual population carrying capacity, which revealed that

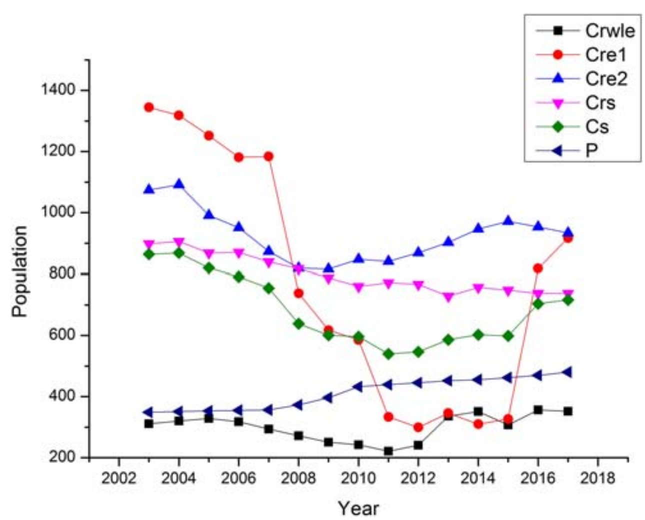

Fig. 3 Each kind of relative resource carrying capacity of Guiyang, taking the entire province as the reference area

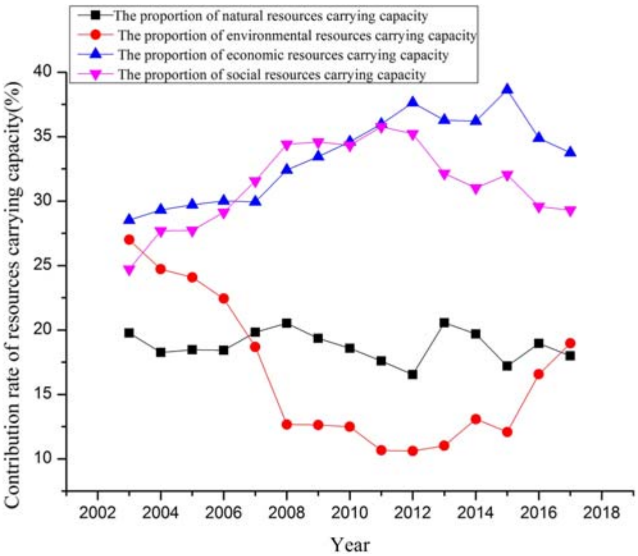

Fig. 4 Evolution of relative resource-carrying capacity of Guiyang, taking the whole country as the reference area

economic and social resources were main carriers of the social population. From 2003 to 2017, the relative carrying capacity of natural resources on the population had been stable at about 20%, and the relative carrying capacity of environmental resources on the population dropped first and then rose.

From Fig. 5, it can be seen that when taking the entire province as the reference area, carrying capacities of economic and social resources contributed the most stable for the population-carrying capacity, while natural resource-carrying capacity was always overload from 2003 to 2017, and the environmental resource-carrying capacity showed dramatic changes, which decreased first, then increased. The carrying capacity of natural resources was always lower than the actual population while carrying capacities of economic resources

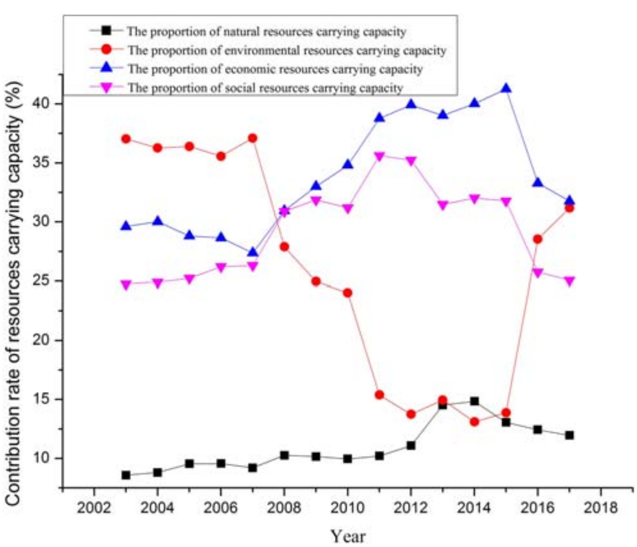

Fig. 5 Evolution of relative resource carrying capacity of Guiyang, taking the entire province as the reference area

and social resources were both higher than the actual population, and environmental resource-carrying capacity was higher than the actual population most of the time except that the 5-year period (2011-2015) was below the actual population. During the period from 2003 to 2017, the contribution rate of natural resource-carrying capacity had been below 15%, and the contribution rate of relative environmental resources decreased first from 37% in 2003 to 13% in 2014, then increased to 31% in 2017. The average contribution rate of economic resources and the average contribution rate of social resources increased to 33.8% and 29.2% respectively. At the end of 2017, the carrying capacity of social resources was 7375 thousand people, economic resources 9341 thousand people, natural resources 3516 thousand people, and environmental resources 9171 thousand people. Among these four resource carrying capacity indicators, natural resource-carrying capacity had been always lower than the actual population-carrying capacity, the environmental resource-carrying capacity was higher than the actual population-carrying capacity most of the time, and the other two kinds of resource carrying capacities were both higher than the actual population carrying capacity, which revealed that economic and social resources were main carriers of the social population. From 2003 to 2017, the relative carrying capacity of natural resources on the population had been below at 15%, and the relative carrying capacity of environmental resources on the population dropped first and then rose.

Development trend of natural resources and social resources

Whether the whole country or the entire province was taken as the reference area, natural resource-carrying capacity was both overloaded. When the whole country was taken as the reference area, it can be seen that energy resource-carrying capacity was the largest, followed by the carrying capacity of cultivated area, and the carrying capacity of water resource was the least. When the entire province was taken as the reference area, it can be seen that energy resource-carrying capacity was the largest, followed by the carrying capacity of cultivated area, and the carrying capacity of water resource was the least. In both reference area cases, energy resource-carrying capacity was relatively rich, much higher than the actual population, showing that energy resources had played an important role in the sustainable development. However, carrying capacities of water resources and cultivated area were obviously insufficient, especially the carrying capacity of water resources was well below the actual population, and they were always in deficit, indicating that water resources and cultivated area were main factors that restricted the sustainable development.

When it came to the social resource carrying capacity, the social resource carrying capacity had been in different state. When the whole country was taken as the reference area, it can be seen that the social resource-carrying capacity was in a state of overload from 2003 to 2013, the carrying capacity of social consumer goods resources was larger than the carrying capacity of human capital resources from 2003 to 2017. Carrying capacities of social consumable resources and human capital resources had been continuously increasing from 2003 to 2017, both of them were always lower than the actual population-carrying capacity from 2003 to 2013, and then larger than the actual population carrying capacity from 2014, showing that social consumable goods resources had played a crucial part in the sustainable development. When the entire province was taken as the reference area, it can be seen that social resource-carrying capacity was in a state of surplus from 2003 to 2017, and the carrying capacity of social consumer goods resources was larger than the carrying capacity of human capital resources from 2003 to 2017. The carrying capacity of social consumable resources had been stable from 2003 to 2017, while the carrying capacity of human capital resources showed a declining trend from 2003 to 2007 and was lower than the actual population-carrying capacity from 2010 onwards, showing that social consumable goods resources had played a crucial part in the sustainable development, human capital resources in Guiyang had been lost.

Relative resource-carrying capacities of each city, county, and district in Guiyang

Local natural conditions and resources had played an important and positive role in the whole session of regional economic development. Taking Guizhou province as the reference area, relative resource-carrying capacity states of a total of one city, six districts, and three counties in Guiyang were calculated from 2003 to 2017 (Table 5).

From Table 5, it can be seen that other districts and counties were in the state of surplus, except that Qingzhen was overloaded after 2010 and Xiuwen was overloaded in 2010, 2011, and 2012. According to calculation results, the surplus state of urban districts and counties could be divided into three groups: the first group was Yunyan district, Nanming district, and Huaxi district with a surplus of more than 0.2 million people, which formed the main city of Guiyang. These districts all had extreme surplus capacities because comprehensive-carrying capacity brought by the rapid economic development was far greater than the actual population-carrying capacity. Environmental resource-carrying capacity, economic resource-carrying capacity, and social resource carrying capacity of these districts were far higher than relative natural resource-carrying capacities, and natural resource-carrying capacity was in an overloaded status. This was very clear that natural resources of these three districts were the short board for the population-carrying capacity, and the government should provide policy guidance. It was necessary to take protection of water and land resources into consideration and increased energy efficiency while developing the economy, to lessen dependence on natural resources and improved natural resource-carrying capacity.

The second group was Baiyun district, Guanshanhu district, Wudang district, Kaiyang county, Xifeng county with a surplus of less than 0.1 million people after 2010, which are located in the suburbs of Guiyang. These districts all had slight surplus capacities because carrying capacities of natural resources and social resources in these districts were the same

Table 5 The overloading/surplus state of relative resource carrying capacity of each city, county, and district in Guiyang, taking Guizhou province as the reference area

Year	Yunyan District	Nanming District	Huaxi District	Baiyun District	Guanshanhu District	Wudang District	Qingzhen City	Kaiyang County	Xifeng County	Xiuwen County
2003	− 38.24	− 52.42	− 49.33	− 14.62	− 13.28	− 17.87	− 12.55	− 20.32	− 17.63	− 11.56
2004	− 37.86	− 50.63	− 48.76	− 13.89	− 12.94	− 15.62	− 13.78	− 21.35	− 15.68	− 10.59
2005	− 37.12	− 49.66	− 48.22	− 13.77	− 13.52	− 15.86	− 11.34	− 19.68	− 16.25	− 9.86
2006	− 36.95	− 48.27	− 46.38	− 14.05	− 11.08	− 14.73	− 9.87	− 18.06	− 13.66	− 9.63
2007	− 36.78	− 47.80	− 45.10	− 12.92	− 10.50	− 13.90	− 9.64	− 16.04	− 12.79	− 8.58
2008	− 36.82	− 42.72	− 45.65	− 13.00	− 10.51	− 14.02	− 9.18	− 15.87	− 12.80	− 8.39
2009	− 33.79	− 40.22	− 43.50	− 12.13	− 9.66	− 13.15	− 6.58	− 13.67	− 11.52	− 6.80
2010	− 17.36	− 24.86	− 28.63	− 6.90	− 4.87	− 7.58	4.94	− 2.24	− 4.51	0.77
2011	− 15.45	− 23.21	− 27.37	− 6.40	− 4.44	− 7.24	5.82	− 1.73	− 4.13	1.23
2012	− 17.41	− 25.14	− 29.02	− 6.94	− 4.88	− 7.63	5.38	− 1.98	− 4.44	0.99
2013	− 19.95	− 27.84	− 32.13	− 7.92	− 5.76	− 8.89	3.38	− 4.54	− 5.99	− 0.50
2014	− 24.17	− 31.74	− 34.92	− 8.93	− 6.55	− 9.34	2.85	− 4.10	− 6.13	− 0.57
2015	− 25.47	− 33.12	− 36.35	− 9.36	− 6.92	− 8.81	2.27	− 4.82	− 6.63	− 0.98
2016	− 22.32	− 30.32	− 34.13	− 8.53	− 6.20	− 9.20	3.64	− 3.97	− 5.98	− 0.24
2017	− 24.53	− 34.18	− 35.67	− 10.32	− 7.12	− 9.61	4.83	− 4.58	− 6.33	− 0.64

as the actual population, while carrying capacities of environmental resources and economic resources were in surplus. So, it was clear that the government should give rein to advantages of natural and economic resources, developing the economy with great efforts and sparing no effort to strengthen environmental protection. At the same time, it was necessary to be less detrimental to the environment by protecting and making better use of natural resources. The government should also bring in needed personnel and strengthen the construction of social resources.

The third group was Qingzhen city and Xiuwen county with slight overload comprehensive-carrying capacity which were located in the suburbs of Guiyang. Qingzhen was the most overpopulated region with an overload of nearly 50,000 people in 2017. The comprehensive carrying capacity of Xiuwen was surplus from 2003 to 2009, then overload from 2010 to 2012, and surplus again after 2013. Compared with other districts and counties, especially Xiuwen, the economic development lagged behind, and the comprehensive strength was not strong. Thus, it could be seen that Qingzhen city was in a serious state of overload, and various resource-carrying capacities were lower than the actual population-carrying capacity. The government needed to develop regional economy, attract investment, increase economic power, and introduce talents, to promote the development of this region.

Discussion

From the above calculation results of Guiyang's relative resource-carrying capacities, it can be seen that: firstly, when taking the whole country as the reference area, the comprehensive carrying capacity was always in the state of overload from 2003 to 2017, and the comprehensive bearing capacity first decreased and then increased, reflecting that the development of Guiyang was always lower than the national average in the recent 15 years. However, its comprehensive bearing capacity had been on the increase and the overload state had been on the decrease as a whole since 2008. Secondly, when taking the entire province as the reference area, the comprehensive carrying capacity was always in the state of surplus from 2003 to 2017, and the comprehensive bearing capacity first decreased and then increased, reflecting that Guiyang is the capital of Guizhou province, the comprehensive development level was far higher than the average level of Guizhou province in the recent 15 years, and the sustainable development was relatively good.

Whether taking the whole country or the entire province as the reference area, relative carrying capacities of economic resources and social resources presented an obvious trend of rising and were always in a state of surplus. Relative carrying capacities of natural resources and environmental resources also presented a trend of rising, but they were always in a state of overload. Economic resources- and social resources-carrying capacities made a great contribution to the comprehensive carrying capacity, but natural resource-carrying capacity still played a leading role, indicating that cultivated land area was a relatively weak factor in the development of Guiyang. The cultivated land area was relatively small, and per-capita cultivated land area was far less than the national average level. Relative resource-carrying capacity had been in an overloading state when taking the whole country as the reference area, but when taking the entire province as the reference area, it had been in a surplus state, indicating that with the economic growth and the export of labor force population, Guiyang had effectively alleviated the pressure of local resource-carrying capacity, and still had great potential for development in the future.

Moreover, when taking the whole country as the reference area, contribution rates of carrying capacities of social consumer goods and human resources to the carrying capacity of social resources both showed an increasing trend. The carrying capacity of human resources was smaller than that of social consumer goods, the contribution of which the carrying capacity of social resources had slowly increased. This indicated that with the increase of human resources year by year, the bearing capacity of social resources had steadily increased its contribution to the relative total bearing capacity and improved the contribution of the social resources-bearing capacity to the population-carrying capacity. When taking the entire province as the reference area, the contribution rate of the carrying capacity of social consumer goods to the carrying capacity of social resources had changed little from 2003 to 2017, and the contribution rate of the carrying capacity of human resources to the carrying capacity of social resources had slowly declined from 2003 to 2017, and human resource-carrying capacity was less than the bearing capacity of social consumer goods. This indicated that with the decrease of human resources year by year, the bearing capacity of social resources had presented a trend of declining, and its contribution to the relative total bearing capacity had also showed a trend of declining, thereby hindering the contribution of social resources-bearing capacity to the population-carrying capacity.

In addition, it can be known from the analysis of the relative resource-carrying capacity of each district in Guiyang city that the economy of main urban areas was developed and the comprehensive bearing capacity was in an exceeding surplus condition, while the economy of suburb areas was underdeveloped and the comprehensive bearing capacity was only in a slight surplus condition. This unbalanced regional development was also a key issue in Guiyang's sustainable development strategy.

Sustainable development strategies

This study analyzed carrying capacities of economic resources, social resources, natural resources, and environmental resources in Guiyang; it could be seen that when taking Guizhou province as the reference area, the comprehensive bearing capacity was in a state of surplus from 2003 to 2017. However, when taking the whole country as the reference area, the comprehensive bearing capacity presented an obvious overload situation from 2003 to 2017. The reason was that the comprehensive strength of Guizhou was lower than the national average level, and it was an underdeveloped province. This result was consistent with the actual situation, indicating that the research method of relative resource-bearing capacity had certain scientific nature. It could also be seen that analyzing the comprehensive carrying capacity status could highlight the problems existing in the sustainable development when taking the whole country as the reference area. There were 10 districts in Guiyang; each district had different resource-bearing capacity and industrial structure, which offered decision evidence for Guiyang to seek differentiated transition and upgrading paths.

The central problem of sustainable development was that the development should be coordinated with the resource-carrying capacity. In view of this, the following suggestions were put forward: (1) The government should pay more attention to the rational development and the efficient use of resources, constantly improve the resource-bearing capacity, and build a guarantee system for sustainable use of resources and a security system for strategic reserves of important resources, to provide resources guarantee for the sustainable socio-economic development. (2) The government should increase protection of arable land resources and water resources. With the continuous development of social economy, protecting cultivated land resources and water resources can improve the bearing capacity of natural resources and increase the contribution rate of natural resources in comprehensive bearing capacity, to effectively improve the overload state of current natural resource-carrying capacity. To reduce the contradiction between supply and demand of water resources, it is necessary to take outside water diversion into consideration after fully considering water conservation and rational allocation of local water resources. (3) Enterprises should accelerate the industrial restructuring, transform the economic growth mode, increase resource utilization rate, and boost the economic development by scientific and technological progress. (4) The government should pay more attention to the reasonable control of the total population and distribution and make reasonable planning and migration adjustment on the population distribution, such as through the industrial transfer and other channels to transfer population in the overload district. And it also can relieve the population pressure by carrying out the population migration from Guiyang to the inside and outside of Guizhou province step by step. (5) Sustainable development was a complex system involving the social economy, resources, and the environment, which cannot be achieved only by solving issues in an aspect. The sustainable development goal of coordinated and balanced development could be achieved through carrying out comprehensive analysis, deep understanding and overall coordination on interactions and mutual relations of subsystems in the sustainable development. (6) In terms of regional differences, economic levels of main urban areas were generally higher than that of suburb areas in Guiyang, and relative resource carrying capacities were obviously higher than that of suburb areas. Therefore, to accelerate suburban economic development and bridge the economic gap between urban areas and suburb areas had played a vital part in the sustainable development in the future. Furthermore, regional interventions need to be encouraged and local legislation should incorporate harmonized principles, policies, strategies, laws, and other agreements to enhance implementation (Juma et al., 2014).

Conclusion

With the purpose of facilitating a balanced development of the environment, resources, and the population, this study analyzed the resource-carrying capacity of Guiyang. On the basis of the existing resource-carrying capacity framework, this study revised the corresponding resource-carrying capacity model. Natural resources were composed of three indicators (energy resources, water resources, and land resources). Human capital resources were incorporated into social resources.

1. When taking the whole country as the reference area, whether based on the traditional relative resource-carrying capacity model or the improved model, the relative comprehensive resource-carrying capacity of Guiyang had been in an overloaded state. Carrying capacities of economic and social resources accounted most for population-carrying capacity, while carrying capacities of natural and environmental resources were always overload from 2003 to 2017.
2. When taking the entire province as the reference area, whether based on the traditional relative resource-carrying capacity model or the improved model, the relative comprehensive resource-carrying capacity of Guiyang had been in a surplus state. The carrying capacity of natural resources was always lower than the actual population while carrying capacities of economic resources and social resources were both higher than the actual population, and environmental resource-carrying capacity was higher than the actual population most of the time except that the 5-year period (2011-2015) was below the actual population.
3. When taking Guizhou province as the reference area, relative resource-carrying capacity states of a total of one city, six districts, and three counties in Guiyang were

calculated from 2003 to 2017. During the study period, all the other districts and counties were in the state of surplus, except that Qingzhen was overloaded after 2010 and Xiuwen was overloaded in 2010, 2011, and 2012.

4. It can be seen from the above discussion that the resource-carrying capacity had four dimensions (including social resources, natural resources, economic resources, and environmental resources), which had different impacts on the comprehensive resource-carrying capacity of Guiyang.

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References

Ait-Aoudia MN, Berezowska-Azzag E (2016) Water resources carrying capacity assessment: the case of Algeria's capital city. Habitat Int 58: 51–58. https://doi.org/10.1016/j.habitatint.2016.09.006

Al-mulali U, Tang CF, Ozturk I (2015) Does financial development reduce environmental degradation? Evidence from a panel study of 129 countries. Environ Sci Pollut Res 22:14891–14900. https://doi.org/10.1007/s11356-015-4726-x

Arrow K, Bolin B, Costanza R et al (1995) Economic growth, carrying capacity, and the environment. Science 268(5210):520–521. https://doi.org/10.1126/science.268.5210.520

Bao CY, Cui ZJ (2005) Study on the relative resource carrying capacity and sustainable development of Henan province. Academic Journal of Zhong zhou 01:90–92

Bishop AB, Fullerton HH, Crawford AB (1974) Carrying capacity in regional environment management. Conserv Pract (1):17–24. https://doi.org/10.1111/j.1526-4629.2000.tb00156

China statistical yearbook (2003-2017) http://www.stats.gov.cn/tjsj/ndsj/

China urban statistical yearbook (2003-2017) http://tongji.cnki.net/knss55/navi/Home Page.aspx?id=N2017060038&name=YZGCA&floor=1

China regional statistical yearbook (2003-2017) http://tongji.cnki.net/kns55/navi/Hom ePage.aspx?id=N2013010085&name=YZXDR&floor=1

Dai D, Sun M, Xu X, Lei K (2019) Assessment of the water resource carrying capacity based on the ecological footprint: a case study in Zhangjiakou City, North China. Environ Sci Pollut Res 26:11000. https://doi.org/10.1007/s11356-019-04414-9

Fiala N (2008) Measuring sustainability: why the ecological footprint is bad economics and bad environmental science. Ecol Econ 67(4): 519–525. https://doi.org/10.1016/j.ecolecon.2008.07.023

Fu YP, Ma SC (2016) Urban resource and environmental carrying capacity and its evaluation-a case study of 15 sub-provincial cities in China. Urban Probl (2):36–40. https://doi.org/10.13239/j.bjsshkxy.cswt.160204

Gober P, Wentz EA, Lant T, Tschudi MK (2011) WaterSim: a simulation model for urban water planning in Phoenix, Arizona, USA. Environ Plann B Plann Des 38(2):197–215. https://doi.org/10.1068/b36075

Guizhou statistical yearbook (2003-2017) http://stjj.guizhou.gov.cn/tjsj_35719/sjcx_3 5720/gztjnj_40112/

Guiyang statistical yearbook (2003-2017) http://www.tongjinianjian.com/tag/%E8%B 4%B5%E9%98%B3%E7%BB%9F%E8%AE%A1%E5%B9%B4%E9%89%B4

Holling CS (1986) The resilience of terrestrial ecosystems: local surprise and global change. W.c.clark & R.e.munn. Sustainable Development of the Biosphere

Huang CF, He LZ (2011) Model modifications and empirical analysis of the relative carrying capacity of resources. Resour Sci 33(1):41-49

Huang NS, Kuang YQ (2000) The carrying capacity of resources and the problems of sustainable development in Guangdong province. Econ Geogr (2):52–56. https://doi.org/10.3969/j.issn.1000-8462.2000.02.012

Jiang DP (1998) Evaluation theory and model of regional sustainable development. China Popul, Resour & Env S, 23–26

Johnston P, Everard M, Santillo D, Robert KH (2007) Reclaiming the definition of sustainability. Environ Sci Pollut Res Int 14:60–66. https://doi.org/10.1065/espr2007.01.375

Juma DW, Wang HT, Li FT (2014) Impacts of population growth and economic development on water quality of a lake: case study of Lake Victoria Kenya water. Environ Sci Pollut Res 21:5737–5746. https://doi.org/10.1007/s11356-014-2524-5

Li BZ, Ge TD, Xiao HA, Zhu ZK, Li Y, Shibistova O, Liu SL, Wu JS, Inubushi K, Guggenberger G (2016) Phosphorus content as a function of soil aggregate size and paddy cultivation in highly weathered soils. Environ Sci Pollut Res 23(7494-75):03–7503. https://doi.org/10.1007/s11356-015-5977-2

Liang L, Deng Y, Li R, Li J (2018) Modeling of sediment transport in a saltwater lake with supplemental sandy freshwater. Environ Sci Pollut Res 25:24975–24991. https://doi.org/10.1007/s11356-018-2535-8

Liu M, Wang SX, Duan L (2006) Application of environmental carrying capacity theory in Beijing urban and Fangshan district. Urban Environ Urban Ecol 6:12–14

Liu YH, Liu Y, Li XB (1998) Issues of geographical study in the era of knowledge economy. Acta Geograph Sin 4:289–294

Liu ZD, Yu XG (2002) Carrying capacity of resources and problems of sustainable development in Yangtze basin. Resour & Env in the Yangtze Basin (1):10–15

Lv YL, Si CN, Zhang SL, Sarwar S (2018) Impact of urbanization on energy intensity by adopting a new technique for regional division: evidence from China. Environ Sci Pollut Res 25:36102. https://doi.org/10.1007/s11356-018-3412-1

Mao HY, Yu DL (2001) A study on the quantitative research of regional carrying capacity. Adv Earth Sci 16(4):549–555. https://doi.org/10.3321/j.issn:1001-8166.2001.04.017

Millington R, Gifford R (1973) Energy and how we live, Australian UNESCO seminar committee for man and biosphere:Adelaide, Australia

Naimi-Ait-Aoudia M, Berezowska-Azzag E (2014) Algiers carrying capacity with respect to per capita domestic water use. Sustain cities soc, https://doi.org/10.1016/j.scs.2014.03.006 13:1–11

Ni Y, Wang W (2012) Research on relative resource carrying capacity and sustainable development of Guiyang city. Guizhou Soc Sci 12:111–113. https://doi.org/10.13713/j.cnki.cssci.2012.12.032

Noronha MD, Zanini RR, Souza AM (2019) The impact of electric generation capacity by renewable and non-renewable energy in Brazilian economic growth. Environ Sci Pollut Res 26:33236–33259. https://doi.org/10.1007/s11356-019-06241-4

Oh KS, Jeong YW, Lee DK, Lee WK, Choi JY (2005) Determining development density using the urban carrying capacity assessment system. Landsc Urban Plan 73(1):1–15. https://doi.org/10.1016/j.landurplan.2004.06.002

Outeiro L, Byron C, Angelini R (2018) Ecosystem maturity as a proxy of mussel aquaculture carrying capacity in Ria de Arousa (NW Spain): a food web modeling perspective. Aquaculture

S0044848617318525. https://doi.org/10.1016/j.aquaculture.2018.06.043
Pan ZD, Han M (2007) Region relative resources supporting capacity and sustainable development question discussion-taking Jinan Changqing area as an example. Resour Dev Market 23(2):145–147. https://doi.org/10.3969/j.issn.1005-8141.2007.02.015
Park RE, Burgess EW (1920) Introduction to the science of sociology. University of Chicago Press, Chicago
Paul S, Cipitria A, Golosnoy IO, Xie L, Dorfman MR, Clyne TW (2007) Effects of impurity content on the sintering characteristics of plasmasprayed zirconia. J Therm Spray Techn 16:798–803. https://doi.org/10.1007/s11666-007-9097-5
Pei WT, Wang XG (2017) Study on change of relative carrying capacity of resources and sustainable development of Tianshui City. Resour Dev Market (5):545-548. https://doi.org/10.3969/j.issn.1005-8141.2017.05.007
Peng ZC, Guo SL (2018) Research on the relative carrying capacity of resources based on improved model in the southwest district of China: a case study in Ya'an city of Sichuan province. Areal Res Dev 37:153–158. https://doi.org/10.3969/j.issn.1003-2363.2018.01.029
Rees WE (2008) Revisiting carrying capacity: area-based indicators of sustainability. http://dieoff.org/page110.htm. Accessed 14 Feb 2008
Rüstemoğlu H (2019) Factors affecting Germany's green development over 1990-201 5: a comprehensive environmental analysis. Environ Sci Pollut Res 26:6636. https://doi.org/10.1007/s11356-019-04132-2
Seidl I, Tisdell CA (1999) Carrying capacity reconsidered: from Malthus' population theory to cultural carrying capacity. Ecol Econ 31:395–408. https://doi.org/10.1016/S0921-8009(99)00063-4
Slesser M (1990) Enhancement of carrying capacity options—ECCO. The resource use institute, Washington, DC
Sun H, Liu YY (2014) Model extensions and empirical analysis of the relative carrying capacity of resources. China Popul Resour Environ 24:126–135. https://doi.org/10.3969/j.issn.1002-2104.2014.11.017
Wang CW (2009) Relative carrying capacity of resources and problems of sustainable development in Jining city of Shandong. Prog Geogr (3):142–146
Wang KY, Liu YF (2003) Study on the theory and method of regional sustainable development evaluation. J Dalian Univ Technol (Soc Sci) (6):52–57. https://doi.org/10.3969/j.issn.1008-407x.2003.02.011
Wang M, Zhang XP (2017) Coupling coordination degree of socio-economic development with resource and environment in Zhaotong City of Yunan Province as a fragile region. J Univ Chinese Acad Sci 6:684–691. https://doi.org/10.7523/jissn.2095-6134.2017.06.005
Wei LB, Liu YJ (2013) Study on relative carrying capacity of resources and sustainable development of Taiyuan. China Popul Resour Environ 11:54–57
Wang ZH, Yin XL, Wan L, Xu CM, Zhang MJ (2019) Dynamics of nitrogen, phosphorus, and organic pollutant losses from a small watershed in the drinking-water source protection area in Guiyang City of southern China. Environ Sci Pollut Res 26:1791–1808. https://doi.org/10.1007/s11356-018-3721-4
Yang DG, Chen SF, Niu WY (2001) A review of the four representative indicator systems for sustainable development. Sci Manag Res 19:58–61. https://doi.org/10.19445/j.cnki.15-1103/g3.2001.04.016
Yang JB, Ding H (2018) A quantitative assessment of sustainable development based on relative resource carrying capacity in Jiangsu Province of China. Int J Environ Res Public Health 15:2786. https://doi.org/10.3390/ijerph15122786
Zeng WH, Wang HD, Xue JY, Ye WH, Guan BR, Mei FQ (1991) Environmental carrying capacity: a key to the coordination of the development of population, resources and environment. China Popul Resour Environ (2):33–37
Zhu BS (1993) Discussion on regional matching model of population and economic resource carrying capacity. Chin J Popul Sci 6:8–14