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Comprehensive Measurement for Carrying Capacity of Resources and Environment of City Clusters in Central China

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Abstract: Studying the carrying capacity of resources and environment of city clusters in the central China has important practical guidance significance for promoting the healthy, sustainable and stable development of this region. According to their influencing factors and reciprocity mechanism, using system dynamics approaches, this paper built a SD model for measuring the carrying capacity of resources and environment of the city clusters in the central China, and through setting different development models, the comprehensive measurement analysis on the carrying capacity was carried out. The results show that the model of promoting socio-economic development under the protection of resources and environment is the optimal model for promoting the harmony development of resources, environment, society and economy in the city clusters. According to this model, the optimum population scale of the city clusters in 2020 is 42.80×10^6 persons, and the moderate economic development scale is 22.055×10^{12} yuan (RMB). In 1996–2020, the carrying capacity of resources and environment in the city clusters took on obvious phase-change characteristics. During the studied period, it is basically at the initial development stage, and will come through the development process from slow development to speedup development.

Keywords: carrying capacity of resources and environment; comprehensive measurement; city clusters; central China

1 Introduction

Carrying capacity of resources and environment of city clusters is the supporting capacity of the resources and environment conditions of water, land, atmosphere and so on in city clusters in a certain development stages for the population and socio-economic development, under a certain level of social development and technology advancement (Liu, 2009). It is mainly measured by the comprehensive carrying population scale and economic scale of resources and environment. The study on carrying capacity of resources and environment originated from the demographics, species biology and applied ecology (Dhondt, 1988; Cohen, 1995; Price, 1999; Seidl and Tisdell, 1999; Graymore, 2005). Since the end of the 18th century, some west scholars have established the theoretical and methodological bases on the study of carrying capacity (Malthus, 1798; Verhulst, 1838; Odum, 1953; Hardin, 1986; Slesser, 1990; Daily and Ehrlich, 1992; Meyer and Ausubel, 1999). Since the 1990s, with the deepening of the research on carrying capacity of resources and environment, more and more scholars have recognized the limitations and one-sidedness of the study on carrying capacity of the single-element of resources or environment (Fang *et al*., 2003; Fang and Lin, 2009), and discussed actively the theories and methods of comprehensive carrying capacity of resources and environment (Zhou *et al*., 2003; Feng and Liu, 2006; Chen and Hui, 2007; Lu, 2007; Tan *et al*., 2007). But, up to now, studies on the carrying capacity of resources and environment of city clusters is still weak (Liu and Fang, 2008; Liu, 2009). This paper taking the city clusters in the central China as the case, discusses the methods of comprehensive measurement of carrying capacity of resources and environment of city clusters, to make up for the shortage of relevant research.

City clusters in the central China is the core area of economic and social development and key area of ur-

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banization of Henan Province, but also the area with serious resources and environmental problems (Fang *et al.*, 2005; Liu *et al.*, 2008). According to their influencing factors and reciprocity mechanism, using system dynamics (SD) approach, this paper built a SD model for measuring the carrying capacity of resources and environment of the city clusters in the central China, and through setting different development models, the comprehensive measurement analysis on the carrying capacity was carried out. This study can improve theoretical research of regional carrying capacity, and has important practical guidance significance for promoting the healthy, sustainable and stable development of the city clusters in the central China.

2 Methods

2.1 Study area and data sources

City clusters in the central China is the denseness regions of cities with Zhengzhou as the center, including Luoyang, Kaifeng, Xinxiang, Jiaozuo, Xuchang, Pingdingshan, Luohe and Jiyuan cities. It is in the northern and central Henan Province (Fig. 1), located in 33º08′–36º02′N, and 111º08′–115º15′E. The study area is situated in the transition region from China's western plateau to the mountainous and plain regions, with various types of landforms and four rivers of the Huanghe (Yellow) River, the Huaihe River, the Haihe River, and the Changjiang(Yangtze) River. The land area of the study area is 58 700 km^2, accounting for 35.1% of the total area of Henan Province; in 2007, the total population was 39.72×10^6 persons, and the GDP was 8.6105×10^{12} yuan (RMB), respectively occupying 40.4% and 57.0% of the total of Henan Province (Liu *et al.*, 2008). About 60% of cities in Henan Province centralize in this area, and the population density reaches 665 persons/km^2. It is the core area of economic and social development and the key area of urbanization of Henan Province, but also one of the regions with larger population in the central and western China.

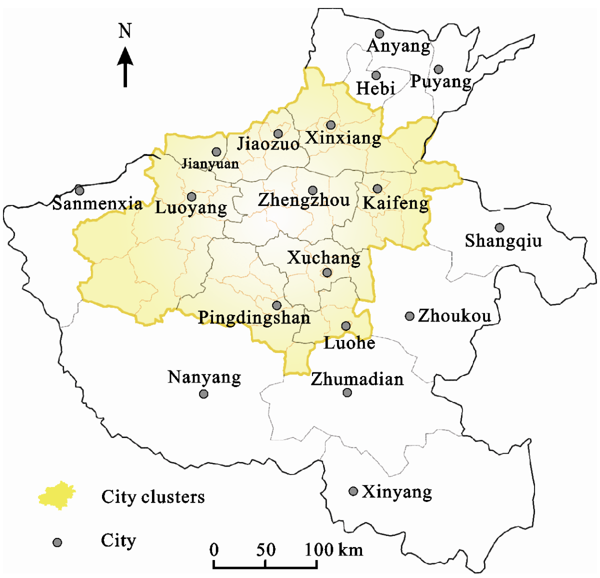

Fig. 1 Location sketch of studied city clusters in Henan Province, China

In this study, the land resources data came from the *Report of Land and Resources of Henan Province* (*1996–2006*) (National Land Agency of Henan Province, 2007); the water resources-related data from the *Henan Water Resources Bulletin* (*1996–2006*) (Cui *et al.*, 2007); the environment-related data were derived from the *Compendium of Environment Statistics of Henan Province* (*1996–2006*) (Henan Environmental Monitoring Center Station, 2007), and the *Environmental Quality Reports of Henan Province* (*1996–2006*) (Henan Environmental Monitoring Center Station, 2001a; 2006b; 2007c); and the socio-economic data came mainly from the *Henan City Statistical Yearbook* (*1996–2006*) (Editorial Board of Henan City Statistical Yearbook, 1997–2007).

2.2 Theoretical method

The high density of population and cities and towns, extroversion of resources utilization as well as the close interactions between regions determine that the carrying capacity of resources and environment of city clusters are substantively the load degrees of the rigid restricting conditions of resources and environment, such as water, land and atmosphere, for the population and socio-economic development, under certain spatial optimizing and collocating effects. So, the carrying capacity of resources and environment of city clusters are mainly influenced by concentration degrees of society and economy, supporting capacity of resources, bearing capacity of environment, integration ability of space, and evolution ability of culture. Among them, the supporting capacity of resources is carrying basis, the concentration degrees of society and economy are main carrying body, and the bearing capacity of environment is constraint condition. There are complex interactions and mutual feedback relationships between the three. And the integration ability of space and the evolution ability of culture as the important regulation factors, by influencing the supporting capacity of resources and the bearing capacity of environment, directly or indirectly affect the concentration degrees of society and economy (Liu, 2009).

According to the classical Logistic theory, combined with the basic rules of formation and evolution of city clusters, the changing course of carrying capacity of resources and environment of city clusters can be divided into initial development stage, optimizing and upgrading stage and sustainable development stage. In the initial development stage, with the gradually maturing of city clusters, the changing course of carrying capacity of resources and environment composes an S-shaped curve of Logistic, which can be divided into four stages of early development, slow development, accelerating development and stable development. With scientific and technological progress and management ability improvement, the efficiencies of resources utilization and environmental governance advance gradually, the carrying threshold (K) of the city clusters increases, and population and socio-economic development enter a new round of evolution process of Logistic curve. With such a constant succession of reincarnation, until close to the theoretical maximum carrying threshold, the city clusters enter into the optimizing and upgrading stage. At this point, the scientific and technological progress and the social development make humanity be able to deal with population, economy, resources, environmental issues harmoniously, and the population and socio-economic development will eventually maintain a certain level of dynamic balance, thus making the city clusters entering into the sustainable development stage (Liu, 2009).

2.3 SD model

According to the influencing factors of carrying capacity of resources and environment of city clusters, we divided the studied system of the carrying capacity into three subsystems of resources, environment and socio-economy, and the integration ability of space and evolution ability of culture as the adjusting parameters were involved in the analysis. Among them, the resources subsystem was concretely divided into four sub-models, i.e., the total amount of land resources, utilization of land resources, total amount of water resources and utilization of water resources; environment subsystem into the atmospheric environment capacity, atmospheric pollution, water environment capacity and water pollution; and socio-economic subsystem into population development and economic growth. According to the interaction mechanisms of the composing elements and the basic feedback loops of the system, this paper drew the causal feedback flow chart of the comprehensive measurement of carrying capacity of resources and environment of the city clusters in the central China in the software of Vensim PLE of version 5.4 (Fig. 2). In Fig. 2, there are six state variables, eight rate variables, three types of auxiliary variables, a number of constants and four functions. Among them, the three types of auxiliary variables include the variables used to help establish rate equations such as total population, per capita GDP, *etc.*; those to reflect the integration ability of space and the evolution ability of culture such as the spatial interaction strength, the proportion of investment in R & D and so on; and those to measure the carrying capacity of single element and comprehensive elements, such as the carrying population scale of resources, carrying economic scale of resources and environment and so on. Four functions are Table function, STEP (step function), IF THEN ELSE MIN (choice function) and minimum value function.

Using system dynamics model to make dynamic simulation of carrying capacity of resources and environment of the city clusters in the central China, first of all we need to identify the model parameters, namely the values of constants and table functions in the SD models. This paper, according to the historical data in 1996–2006 and using the regression analysis methods in the software of SPSS, established the equations of the system model. Then inputting the values of constants and table functions in the software of Vensim PLE of version 5.4, simulation was carried out. By selecting some variables and comparing their simulated values with the historical data we found that the changing trend of simulated values and historical data went basically consistent, and the overall error had good control, which indicated the system model had a better simulation results.

3 Results

3.1 Identifying of parameters

On the basis of testing above, this paper extended the simulation time to the years 1996–2020, a total of 25 years, and set up three programs to compare and analyze the dynamic changing laws and trends of carrying capacity of resources and environment of the city clusters in the central China.

In Program Ⅰ, we predicted the carrying capacity according to the development trends of historical data, and the values of the table functions in various forecasted years are in Table 1.

In Program Ⅱ, we emphasized resource conservation and environmental protection, and relaxed the requirements for economic growth. So we adjusted the annual growth rate of GDP respectively from 14% in 2007–2015 and 10% in 2016–2020 to 13% and 8.5%, and focused on increasing the investment proportion in environmental protection and R & D, and respectively adjusted them to 1.5 times and 2 times than program Ⅰ. Appropriately we lowered the SO_2 emission factor by consumption and the concentration of SO_2. Simultaneously we adjusted the proportion of industrial output to 90% of Program Ⅰ. The proportion of domestic water is the same with Program Ⅰ.

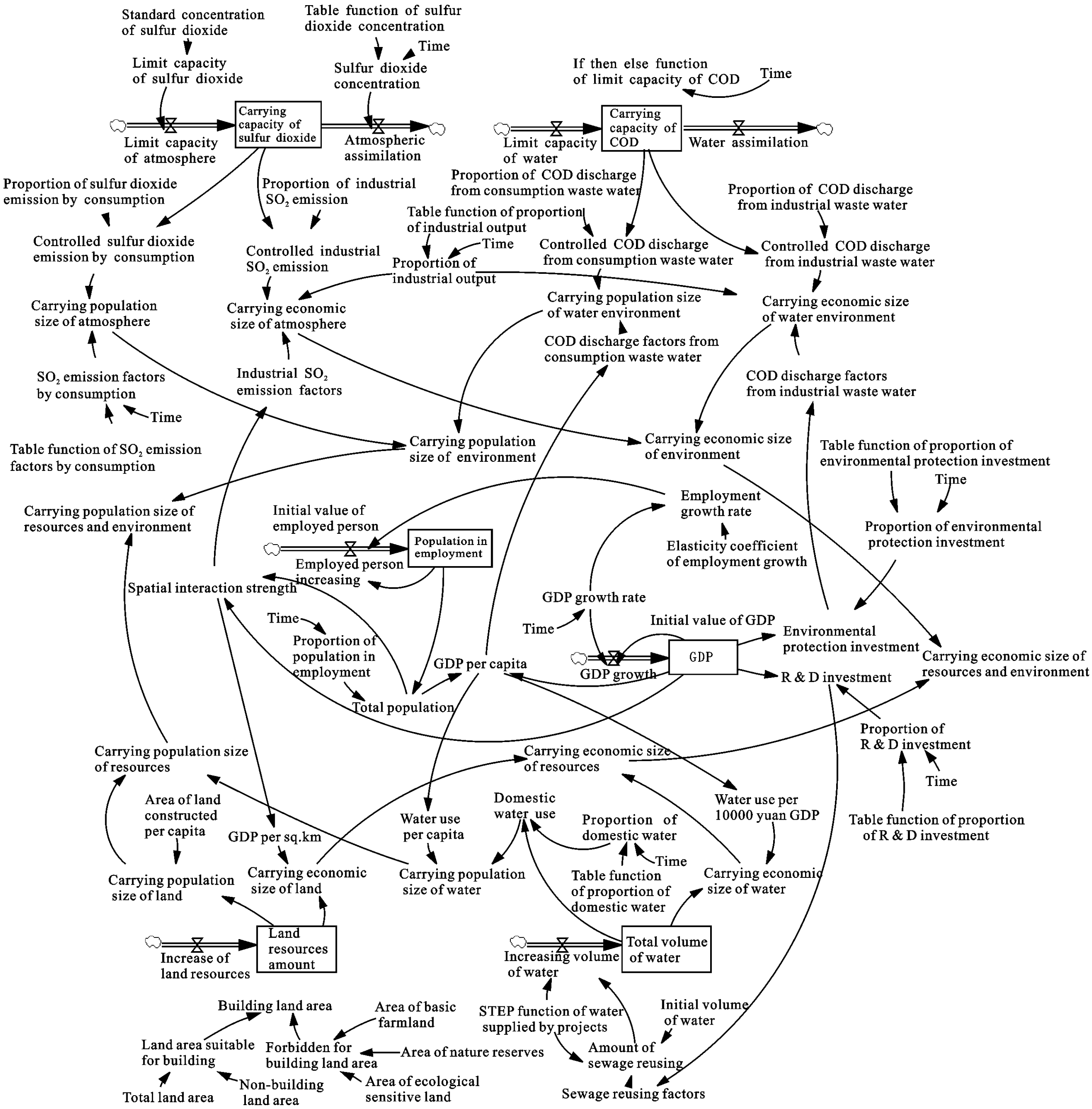

Fig. 2 Causal feedback flow chart of carrying capacity of resources and environment of city clusters in central China

Table 1 Table functions of SD models in various forecast years

Year	Proportion of investment in R & D (%)			Proportion of investment in environmental protection (%)			Proportion of domestic water (%)		
	Program Ⅰ	Program Ⅱ	Program Ⅲ	Program Ⅰ	Program Ⅱ	Program Ⅲ	Program Ⅰ	Program Ⅱ	Program Ⅲ
2007	17.95	17.95	17.95	1.57	3.14	3.14	0.33	0.49	0.49
2008	18.51	18.51	18.51	1.65	3.30	3.30	0.35	0.53	0.53
2009	19.07	19.07	19.07	1.73	3.47	3.47	0.38	0.57	0.57
2010	19.63	19.63	19.63	1.81	3.63	3.63	0.41	0.61	0.61
2015	22.42	22.42	22.42	2.22	4.45	4.45	0.53	0.80	0.80
2020	25.22	25.22	25.22	2.63	5.26	5.26	0.66	0.99	0.99
Year	SO_2 emission factor by consumption (m^3/person)			Concentration of SO_2 (mg/m^3)			Proportion of industrial output (%)		
	Program Ⅰ	Program Ⅱ	Program Ⅲ	Program Ⅰ	Program Ⅱ	Program Ⅲ	Program Ⅰ	Program Ⅱ	Program Ⅲ
2007	0.0020	0.0019	0.0019	0.055	0.054	0.054	53.21	53.22	53.22
2008	0.0021	0.0020	0.0020	0.054	0.053	0.053	54.59	54.59	54.59
2009	0.0022	0.0021	0.0021	0.053	0.052	0.052	55.31	55.31	55.31
2010	0.0023	0.0022	0.0022	0.052	0.051	0.051	56.04	56.04	56.04
2015	0.0022	0.0021	0.0021	0.046	0.045	0.045	58.79	60.00	60.00
2020	0.0017	0.0016	0.0016	0.040	0.040	0.040	57.47	59.00	59.00

In Program Ⅲ, in order to promote economic and social development under the condition of protecting resources and environment, the values of main parameters were adjusted on the basis of program Ⅰ. The growth rate of GDP is between those in Program Ⅰ and Program Ⅱ, being the geometric mean value of the two. In 2007–2015 it is 13.5%, and in 2016–2020 is 9.0%. The construction land area per capita was adjusted to 120 m^2 from 100 m^2 like in Program Ⅰ and Program Ⅱ. Proportion of domestic water and proportion of industrial output kept the same with program Ⅰ. Proportions of investment in R & D and environmental protection were the same with program Ⅱ, respectively increasing 1.0 and 0.5 times than Program Ⅰ. The SO_2 emission factor by consumption and the concentration of SO_2 were appropriately decreased.

3.2 Comparison and selection of three programs

We respectively put the parameters of the above three programs into the SD model to simulate the carrying capacity. According to the results of prediction (Table 2, Table 3), after slowing down the pace of economic development in Program Ⅱ, the level of GDP per unit area, per capita water use and the COD discharge factor from industrial waste water reduce, but water use per 10 000 yuan (RMB) GDP, industrial SO_2 emission factor and COD discharge factor from consumption waste water will improve in a certain degree (Table 2). According to the development model of Program II, the predicted total population and GDP scale of the city clusters will be lower than those of Program Ⅰ, while the comprehensive carrying population and GDP scale of resources and environment will improve in a large extent (Table 3).

In the development model of Program Ⅲ, the GDP per unit area, per capita water use and water use per 10 000 yuan (RMB) GDP of the city clusters in both 2015 and 2020 will be between those in Program Ⅰ and Program Ⅱ. Meanwhile, the second variable value mentioned above is higher than the current level (45.6 m^3/person in 2006) and the third variable value is lower than the current level (145.6 m^3/10000 yuan (RMB)), indicating that the level of per capita water use will improve and the water-use efficiency of production will greatly enhance.

The industrial SO_2 emission factor, COD discharge factor from industrial waste water and COD discharge factor from consumption waste water are close to those of program Ⅱ, far lower than the current levels (0.0241 m^3/10000 yuan (RMB), 0.0043 m^3/10000 yuan (RMB) and 0.0047 m^3/person in 2006), respectively, and show decreasing trends, indicating that the environmental stress on socio-economic development of the city clusters in the central China tends to improve gradually.

Table 2 Simulated values of variables in three programs in different forecast periods

Period	GDP per unit area ($\times 10^6$ yuan (RMB))			Per capita water use (m^3)			Water use per 10000 yuan (RMB) GDP (m^3)		
	Program Ⅰ	Program Ⅱ	Program Ⅲ	Program Ⅰ	Program Ⅱ	Program Ⅲ	Program Ⅰ	Program Ⅱ	Program Ⅲ
2015	320.61	297.89	309.08	86.5	83.1	84.8	36.0	38.5	37.2
2020	539.15	469.90	498.77	123.2	113.0	117.3	20.8	23.6	22.4

Period	Industrial SO_2 emission factor (m^3/10000 yuan (RMB))			COD discharge factor from industrial waste water (m^3/10000 yuan (RMB))			COD discharge factor from consumption waste water (m^3/person)		
	Program Ⅰ	Program Ⅱ	Program Ⅲ	Program Ⅰ	Program Ⅱ	Program Ⅲ	Program Ⅰ	Program Ⅱ	Program Ⅲ
2015	0.0130	0.0131	0.0131	0.0020	0.0015	0.0015	0.0015	0.0015	0.0015
2020	0.0125	0.0126	0.0125	0.0009	0.0002	0.0000	0.0012	0.0013	0.0013

Table 3 Comprehensive measurement results of carrying capacity of resources and environment of city clusters in central China

Period	Program	Total population ($\times 10^6$ persons)	GDP ($\times 10^{12}$ yuan (RMB))	Carrying population scale ($\times 10^6$ persons)	Carrying economic scale ($\times 10^{12}$ yuan (RMB))
2015	Ⅰ	42.36	24.562	46.75	9.253
	Ⅱ	41.89	22.891	52.08	11.294
	Ⅲ	42.13	23.714	52.08	10.206
2020	Ⅰ	43.30	40.996	53.64	20.438
	Ⅱ	42.41	35.847	69.63	24.406
	Ⅲ	42.80	37.992	66.43	22.055

With relatively better efficiency of resources utilization and environmental pollution control, the total population, GDP, carrying population scale and economic scale of resources and environment predicted in program Ⅲ are all between those in Program Ⅰ and Program Ⅱ. The development model of Program Ⅲ not only keeps the sustainable and stable growth of population and GDP, but improves the efficiency of intensive use of resources, and reduces the environmental pollution. Therefore, this kind of development model is the coordination development model of economy, society, resources and environment, and its predicted results should be used as the regulation goals of socio-economic development in the city clusters in the central China. According to the principles of optimization of economic and social development under the constraint of resources and environment, we compared the total population and GDP scale respectively with the comprehensive carrying population and economic scale of resources and environment, and considered that the appropriate population scale of the city clusters in 2020 is 42.80×10^6 persons, and the scale of economic development under the constraints of resources and environment should be 22.055×10^{12} yuan (RMB) in 2020. This prediction results are basically in accord with the population and GDP scale determined in the overall planning of the city clusters①, which proves that the prediction results have better credibility.

3.3 Dynamic change characteristics of carrying capacity

We compared respectively the carrying population scale and economic scale of resources and environment with the total population and GDP derived from Program Ⅲ (Fig. 3, Fig. 4) to explore the dynamic change rules and trends of carrying capacity of resources and environment of the city clusters in the central China. On the aspect of population development, in 1996–2020, the actual population scale shows a sustainable and stable growth state with a relatively lower growth rate, while the carrying population scale of resources and environment continues to grow as a whole with a great annual variation. Its average annual growth rate is lower before 2012 and higher after 2012. Moreover, the carrying pop-

① Project Team of Overall Planning of city clusters in the central China, 2005. The overall development planning framework of city clusters in the central China (2006–2020) ulation scale of resources and environment is lower before 2012 and greater after 2012 than the actual population, and the gaps gradually expand (Fig. 3). For the economic growth, both the actual scale of GDP and the carrying economic scale of resources and environment are growing continually in the studied period (Fig. 4), but as a whole the former is greater than the latter, except the period 2001–2004. The changes of annual growth rate of the carrying economic scale also have clear phase characteristics, which is relatively lower before 2015, and higher after 2015.

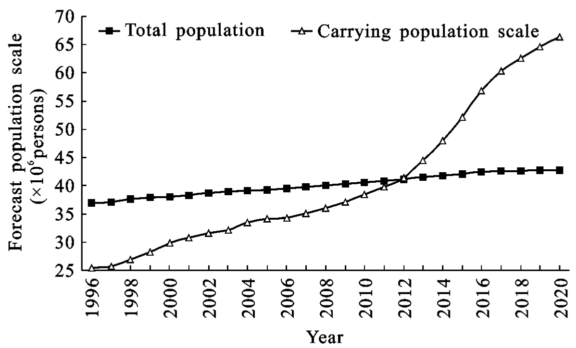

Fig. 3 Total population and carrying population scale of resources and environment of city clusters in central China in 1996–2020

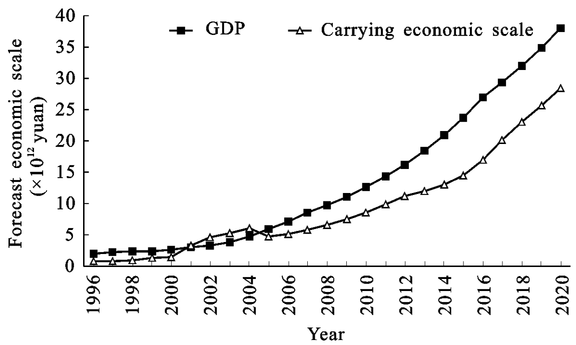

Fig. 4 GDP and carrying economic scale of resources and environment of city clusters in central China in 1996–2020

4 Discussion and Conclusions

4.1 Discussion

In this paper, we considered that except the resources, environment and socio-economic conditions, the carrying capacity of resources and environment of city clusters is also subject to the integration ability of space and evolution ability of culture. Based on the five factors and their interaction mechanism, we constructed the SD model for comprehensively measuring the carrying capacity of resources and environment of city clusters by system dynamics methodology, and predicted the carrying capacity of resources and environment of the city clusters in the central China. The predict results are basically consistent with the actual development and the confirming scale in the overall planning of city clusters in central China, having higher reliability, which indicates that the theory analysis and comprehensive measurement method had a good practicability and rationality.

4.2 Conclusions

According to the theoretical method, this paper developed a SD model, and through setting three development programs, the comprehensive measurement analysis on carrying capacity of resources and environment in the city clusters in the central China was carried out, and the main conclusions are as follows:

(1) The carrying capacity of resources and environment of the city clusters in the central China are mainly influenced by concentration degrees of society and economy, supporting capacity of resources, bearing capacity of environment, integration ability of space, and evolution ability of culture. By testing, the system model developed according to the influencing factors and their reciprocity mechanism in this paper has good simulating results.

(2) Comparing the simulation results, we found that the model of promoting socio-economic development under the protection of resources and environment is the optimal model for promoting the harmony development of resources, environment, society and economy in the city clusters in the central China. Forecasting according to this development model, the optimum population scale of the city clusters in 2020 is 42.80×10^6 persons, and the moderate economic development scale is 22.055×10^{12} yuan (RMB) in the same year.

(3) According to the comprehensive measurement analysis results, in the studied period, the carrying capacity of resources and environment of the city clusters basically present a sustainable growth state, and has obvious phases characteristics. And in most of the time in the studied period, the population and GDP scale is all greater than those of carrying scale of resources and environment, and the sustainable development state of the city clusters is not optimistic.

(4) According to the changing rules of carrying

capacity of resources and environment of the city clusters in the central China, combined with their actual change characteristics, it is considered that in the studied period the carrying capacity of resources and environment are basically at the initial development stage, and will come through the development process from slow development to speedup development.

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