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Research on System Dynamics of Urban Land Comprehensive Carrying Capacity in Xi'an City, China

Yusi Teng[1,2,*] and Weili Xia[1]

[1]*School of Management, Northwestern Polytechnical University, No. 127 Youyi West Road, Xi'an, P.R. China*

[2]*Faculty of Humanities and Foreign Languages, Xi'an University of Technology, No. 5 Jinhua South Road, Xi'an, P.R. China*

Abstract: This paper attempts to simulate the development status of Xi'an City from 2012 to 2025 with the method of Systems Dynamics (SD), in order to provide a reference for the future development of Xi'an city. On the basis of theoretical analysis and empirical analysis, in 2025, the carrying capacity indexes of 5 socio-economic development schemes from the highest to the lowest are status-continuous scheme, coordinate development scheme, economic priority scheme, resource-intensive scheme, and environmental protection scheme. According to the urban comprehensive planning of Xi'an (2008-2020), the predicted value of population scale, which is greater than the one in the status-continuous scheme, resource-intensive scheme, coordinate development scheme and environmental protection scheme, is overload; while the predicted value of GDP in the planning is also greater than the one in the status-continuous scheme and environmental protection scheme, but less than the values in the other three schemes. Therefore, during the forecast period the carrying capacity of land resources for the economic development can meet the actual requirements in Xi'an.

Keywords: Urban land use, land comprehensive carrying capacity, system dynamics (SD), Xi'an city.

1. INTRODUCTION

Land carrying capacity is a significant indicator for the population, resources and the socio-economic sustainable development within a region. The study of land carrying capacity emerged in the mid-20th century [1]. Then the carrying capacity of land and population that emphasized on calculating the productivity of land for food has positively contributed to the global socio-economic development in 1980s [2]. In 1990s, carrying threshold factors of other resources, such as water, minerals, tourism, ecology, etc., have been gradually concerned; the carrying capacity research is full of meaning for regional economic development and deployment, land-use planning and production layout [3, 4]. Since 21 centuries, the carrying capacity has become a connotation commonly referred to planning management [5]. Researchers found that a comprehensive study of carrying capacity combined with various resources rather than a single carrying threshold factor, which cannot fundamentally determine the status of a regional carrying capacity, would be more appropriate to reflect the real situation of social development [6]. The study methods of comprehensive carrying capacity has been developing from traditional methods based on the total amount of land and standards of land use per capita to the index system method stressing on the factor analysis and model approach, which focuses on simulating urban development and capacity analysis. Since the model approach can systematically integrate mechanisms and relationships of a core element together, simulate future development scenarios, as well as quantify carrying capacity, it has been affirmed by many scholars and becomes a new direction of land comprehensive carrying capacity [7, 8].

Xi'an is not only an important central city in the western region of China, but also a new starting point and a bridgehead of the Silk Road economic zone [9]. In recent years, the land comprehensive carrying capacity of Xi'an has increasingly confronted a severe challenge due to rapid economic development, expansion of urban construction and the scale of population. Whether the capacities of population and economy adapt to the threshold that land resources can carry has become a significant prerequisite for the future sustainable development in Xi'an. Currently, researches on carrying capacity of Xi'an city primarily are emphasized on single factor carrying capacity rather than on comprehensive carrying capacity, and thus the state of the regional carrying capacity cannot be fully reflected. In this paper, the fundamental factors, such as land resources, water resources and ecological environment, are taken as the object of the study. The method of system dynamics (SD) will be adopted to explore the match situation and the extent between demographic, social, economic development and land comprehensive carrying capacity, to simulate future social development scenarios, in order to provide a feasible reference for the future sustainable development planning of Xi'an city.

2. OVERVIEW OF STUDY AREA

Xi'an, also known as Chang'an, the capital of Shaanxi Province in China, is from North to South of about 116

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kilometers long and from West to East of 204 km wide, located in the center of China's geographic territory, and in the middle of the plain of the Yellow River Basin. Till the end of 2013, 9 districts and 4 counties are under the jurisdiction of the city, which covers a total area of about 10,108 square kilometers including the urban area of about 3852 square kilometers. The total population of the city amounts to 8.06 million. GDP reaches at 488.41 billion Yuan, of which the primary industry, secondary industry and tertiary industry respectively accounted for 4.5%, 43.3%, and 52. 2%. Xi'an not only has the largest population, more economic aggregate and higher degree of modernization in the Northwest of China, but also becomes an important transport hub in the Northwest [10].

3. ANALYSIS AND ESTABLISHMENT OF SYSTEM MODEL

3.1. Analysis and Establishment of System

This paper will define the entire Xi'an as the system. Starting from the relationship between resources, environment, population and economic development [11], according to the modeling purposes, the comprehensive carrying capacity of land will be divided into 4 aspects involving land carrying capacity, the carrying capacity of the population development, ecological carrying capacity and socio-economic environment carrying capacity. 9 indicators that are corresponding to 9 rate variables and many other auxiliary variables will be selected as level variables, such as GDP, total population, the proportion of tertiary industry, cultivated land area, grain yield per unit, construction land area, residential building area, the proportion of urbanization, and public green land. Relying on the software VENSIM, the system flow diagram of land comprehensive carrying capacity in Xi'an city will be built (Fig. **1**).

3.2 Establishing System Equations

System Dynamics is comprised of five equations, including level equation (L), rate equation (R), auxiliary equation (A), constant equation (C) and initial equation (N). Level equations and rate equations are the two core equations of the model.

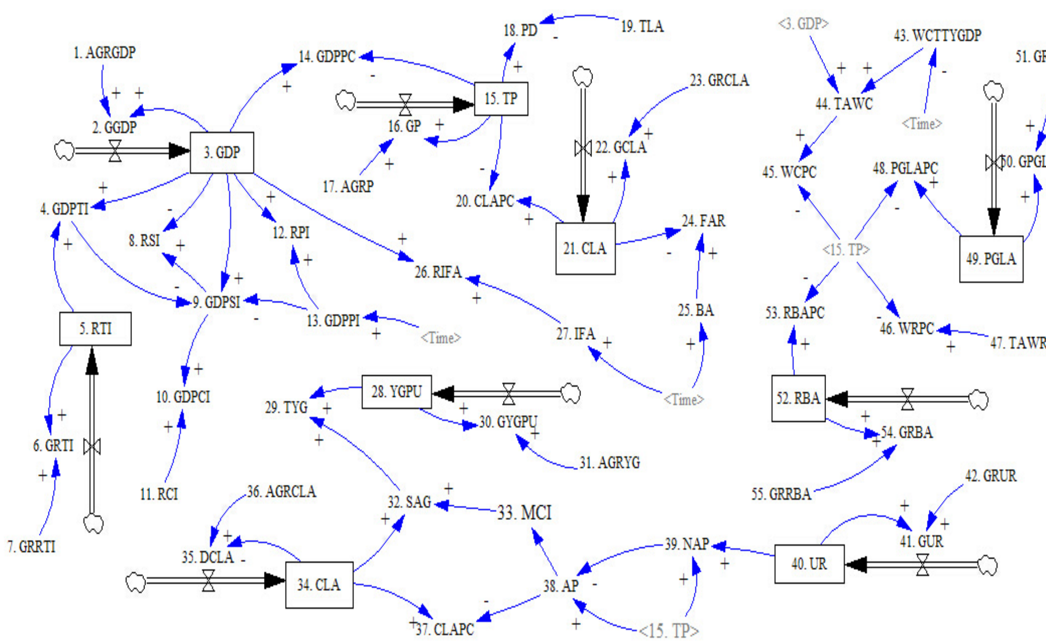

Fig. (l). The system flow diagram of comprehensive land carrying capacity in Xi'an City.
Note: Abbreviation of variables: 1. annual growth rate of GDP (AGRGDP); 2. growth of GDP (GGDP); 3. gross domestic product (GDP); 4. GDP of tertiary industry (GDPTI); 5. ratio of tertiary industry (RTI); 6. growth of ratio of tertiary industry (GRTI); 7. growth rate of ratio of tertiary industry (GRRTI); 8. ratio of secondary industry (RSI); 9. GDP of secondary industry (GDPSI); 10. GDP of construction industry (GDPCI); 11. ratio of construction industry (RCI); 12. ratio of primary industry (RPI); 13. GDP of primary industry (GDPPI); 14. GDP per capita (GDPPC); 15. total population (TP); 16. growth of population (GP); 17. annual growth rate of population (AGRP); 18. population density (PD); 19. total land area (TLA); 20. construction land area per capita (CLAPC); 21. construction land area (CLA); 22. growth of construction land area (GCLA); 23. growth rate of construction land area (GRCLA); 24. floor area ratio (FAR); 25. building area (BA); 26. ratio of investment in fixed assets (RIFA); 27. Investment in fixed assets (IFA); 28. yield of grain per unit (YGPU); 29. total yield of grain (TYG); 30. growth of yield of grain per unit (GYGPU); 31. annual growth rate of yield of grain (AGRYG); 32. sown area of grain (SAG); 33. multiple cropping index (MCI); 34. cultivated land area (CLA); 35. decrease of cultivated land area (DCLA); 36. annual growth rate of cultivated land area (AGRCLA); 37. cultivated land area per capita (CLAPC); 38. agricultural population (AP); 39. non-agricultural population (NAP); 40. urbanization rate (UR); 41. growth of urbanization rate (GUR); 42. growth rate of urbanization rate (GRUR); 43. water consumption of ten thousand Yuan GDP (WCTTYGDP);44. total amount of water consumption (TAWC);45. water consumption per capita (WCPC); 46. water resource per capita (WRPC); 47. total amount of water resource (TAWR); 48. public green land area per capita (PGLAPC); 49. public green land area (PGLA); 50. growth of public green land area (GPGLA); 51. growth rate of public green land area (GRPGLA); 52. residential building area (RBA); 53. residential building area per capita (RBAPC); 54. growth of residential building area (GRBA); 55. growth rate of residential building area (GRRBA).

Level equation (L) is the basic equation of the system dynamics model, namely:

$$L_{(t)} = L_0 + \int_0^t \left(\sum R_{in}(t) - \sum R_{(out)}(t) \right) dt \quad (1)$$

In formula 1, L (t) represents the value of level variable L at time t, L0 represents the initial value of L; Rin represents the input stream of a level variable, while Rout represents the output stream of a level variable; (ΣRin (t) -ΣRout (t)) represents a net inflow of a level variable. Integral equations above indicate that the value of a level variable at time t is equal to the sum of the initial value of a level variable and the accumulation of net flow changes affected by the time during the period [0, t].

Rate equation (R) is expressed as a function of level variable and constant variable, namely:

$$R = f\left(L, Constant\right) \quad (2)$$

4. MODEL CHECKING AND SIMULATION

4.1. Model Running and Checking

In this paper, the year 2001 is set up as a model basic point, the time interval from 2001 to 2011 as the period of verification, while 2012-2025 as the forecast period, the year 2020 and year 2025 are set up as two forecast points. The model includes 55 variables, 59 equations and three major subsystems. The system flow diagram of comprehensive land carrying capacity in Xi'an City is shown in Fig. (**1**).

Table 1. Level variable t test.

Indicators	GDP	Population	Proportion of tertiary industry	cultivated land area	grain yield per unit	construction land area	public green land	residential building area	proportion of urbanization
t value	0.859	0.711	0.100	0.642	0.257	0.737	0.616	0.876	0.910

Table 2. Five schemes evaluation program.

Index type	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Growth rate of urbanization rate	#	+	0	-	0
Growth rate of population	#	+	0	-	0
Growth rate of GDP	#	+	0	-	0
Growth rate of proportion of tertiary industry	#	+	0	0	0
Growth rate of cultivated land	#	+	-	-	0
Growth rate of grain yield per unit	#	+	-	-	0
Growth rate of construction land	#	+	-	-	0
Growth rate of residential building area	#	+	-	-	0
Growth rate of public green land area	#	-	0	+	0

Note: In the table, "#" represents the values of the status quo in 2012, "-" indicates the minimum in nearly last 10 years, "+" indicates the maximum in nearly last 10 years, "0" means the average values of the past 10 years

Then the model is activated to get simulating data.

The statistics of 11 years (2001-2011) are collected [12, 13] to compare with the simulation results by t test, which can check simulation accuracy of the model (Table **1**). Since most indicators have no significant difference by testing, it shows that the model has higher simulation accuracy, and the state of land comprehensive carrying capacity in Xi'an city can be more truly reflected by the system behavior of the model, which could be utilized to predict and to analyze the future land comprehensive carrying capacity of Xi'an city in different schemes.

4.2. Simulation of Model

According to different combinations mode of key indicators, five schemes of socio-economic development including status-continuous scheme (Scheme 1), economic priority scheme (Scheme 2), environmental protection scheme (Scheme 3), resource-intensive scheme (Scheme 4), and coordinated development scheme (Scheme 5). Under economic priority scheme, rapid economic development is regarded as the main purpose, high economic growth rate, high rate of resource consumption and inefficient investment in environmental protection as principle features. Therefore, the growth rate of urban public green land area is set as the minimum in nearly last 10 years, the rest of indicators are taking the maximum. The variable settings and their values of the other four schemes are referred to the same method. Indicator values are illustrated in Table **2** and Table **3**.

The land comprehensive carrying capacity index in Xi'an city is comprised by three parts of indicators including ecological carrying capacity indicators, economic carrying capacity indicators and social carrying capacity indicators (see Table **4**).

The values in Table **3** are respectively substituted into different systems, to simulate changes of major level variables between 2013 and 2025, to record their simulating values in 2013-2025. By formula 3 a certain carrying capacity index can be calculated.

Table 3. Five schemes index value table.

Index type	status quo value	minimum	maximum	average value
Growth rate of urbanization rate	-0.0034	0.0064	0.0326	0.0161
Growth rate of population	0.0052	0.0014	0.0231	0.0132
Growth rate of GDP	0.1304	0.1249	0.3143	0.1805
Growth rate of proportion of tertiary industry	0.0048	-0.0379	0.0499	0.0019
Growth rate of cultivated land	-0.0191	-0.0251	-0.0027	-0.0134
Growth rate of grain yield per unit	0.0567	0.0069	0.1448	0.0089
Growth rate of construction land	0.0237	0.0106	0.0821	0.0309
Growth rate of residential building area	0.0313	0.0142	0.0272	0.0192
Growth rate of public green land area	0.0377	-0.0488	0.4654	0.1167

Table 4. Main indicators of Land comprehensive carrying capacity in Xi'an city.

Ecological carrying capacity	Economic carrying capacity	Social carrying capacity
water resource per capita	GDP	total population/ population density
water consumption per capita	GDP per capita	residential building area per capita
public green land area per capita	GDP of construction industry	construction land area per capita
cultivated land area per capita		urbanization rate
water consumption of ten thousand Yuan GDP	GDP of tertiary industry	total yield of grain /grain output per capita

$$x_i = \frac{c_i}{sc}\left(i = 1,2,\ldots,n\right) \tag{3}$$

In formula 3, x_i represents the index of the i-th term indicator; c_i indicates the i-th term indicator; *sc* is the indicator of a certain standard. To eliminate the effects of different dimensions of evaluating indicators, the coefficient of variation of indicators will be used to measure the distinct degree of predicted values of the indicators.

$$V_i = \frac{\sigma_i}{\overline{x}_i}\left(i = 1,2,\ldots,n\right) \tag{4}$$

In formula 4, Vi is the coefficient of variation, also known as standard deviation coefficient of the i-th term indicator; σ_i represents the standard differential of the i-th term indicator; $\overline{x}_i$ indicates the average index of the i-th term

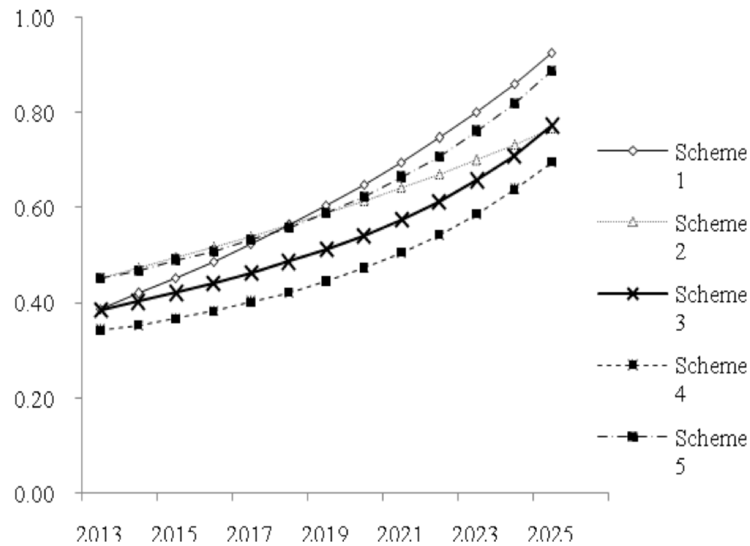

Fig. (2). Different schemes of land resource carrying capacity trend in Xi'an City.

indicator. Then the weight of each variable will be calculated by the coefficient of variation method.

$$W_i = \frac{V_i}{\sum_{i=1}^{n} V_i} \left(i = 1,2,...,n \right) \quad (5)$$

Finally, land comprehensive carrying capacity indexes under different simulated scenarios will be calculated by following formula 5:

$$Y_i = \sum_{i=1}^{n} W_i V_i \left(i = 1,2,...,n \right) \quad (6)$$

The results of the land comprehensive carrying capacity Index of Xi'an city between 2013 and 2025 under five scenarios above are shown in Fig. (**2**).

5. THE ANALYSIS OF THE SIMULATION RESULTS AND CARRYING CAPACITY POTENTIAL

5.1. Analysis of Different Schemes

Assuming that the development speed of Xi'an city in the next 13 years would maintain at the one in 2012, and the status quo values of variables would be controlled as the ones in 2012: namely the growth rate of urbanization rate is at -0.0034, growth rate of population and GDP are respectively maintained at 0.0052 and 0.1304, growth rate of the proportion of tertiary industry is at 0.0048, growth rate of grain yield per unit is at 0.0567, growth rate of cultivated land and construction land are separately at -0.0191 and 0.0237, growth rate of residential area and public green land area are controlled at 0.0313 and 0.0377. The simulation results of scheme 1 shows that its initial carrying capacity lies at a lower level, between 2012-2015 a rapid increase will be illustrated; its carrying capacity will be reached at the highest level in all schemes in 2018. It indicates that the current development mode of Xi'an city is basically reasonable, but in the long-term there is a large room for growth and it still needs further improvement.

Compared with scheme 1, the initial carrying capacity of scheme 2 will be higher than the other schemes, but after 2018, its carrying capacity index will be lower than scheme 5 and lack increasing power. It implies that scheme 2 will not accord with the fact in Xi'an due to a large consumption of resources.

Scheme 3 aims at the prior protection of ecological environment and water resources. According to the simulation result, it signifies that its initial carrying capacity is lower than the one of scheme 1, scheme 2 and scheme 5, but with the economic development it will gradually increase since 2016. However, it remains below the one of scheme 1 and scheme 5, and will be finally equivalent to the one of scheme 2.

Scheme 4 emphasizes on intensive use of natural resources by improving the scientific technology to attain more economic output with less input of resources. Through simulation results of scheme 4, it is showed that the carrying capacity is always lower than the one of other four schemes, but there is a relatively rapid upgrade of its carrying capacity index after 2020, which indicates that there will be still a high growth potential in the long run despite its low level in the prophase.

Scheme 5 attempts to balance socio-economic development speed, resource inputs and environmental change speed through a more balanced allocation of resources, environmental loss and social development, and by setting the change rate of the variables. The results of scheme 5 points out that the initial carrying capacity is higher, and the overall growth rate is relatively good. Until 2025 the carrying capacity index will be slightly lower than the one of scheme 1 and the highest annual average carrying capacity index. In this scheme the annual carrying capacity will be coordinately

Table 5. Predictive value of land resource carrying capacity in Xi'an under different schemes.

Schemes	2020		2025	
	Population (10^4 people)	GDP (10^8 Yuan)	Population (10^4 people)	GDP (10^8 Yuan)
Scheme 1	766.80	7544.24	786.95	13924.40
Scheme 2	1072.33	132251.00	1202.04	518648.00
Scheme 3	891.44	17197.20	951.85	39426.50
Scheme 4	713.56	6470.22	718.57	11469.10
Scheme 5	891.44	17197.20	951.85	39426.50

developed. Therefore, scheme 5 is the ideal mode for future development of Xi'an city.

In the light of the simulation results, the amount of population and GDP scale in Xi'an under different scenarios are predicted, their results are shown in Table **4**. It is estimated that in 2020 the population carrying capacity for Xi'an land resources will range from 713.56×10^4 people in environmental protection mode to 1072.33×10^4 people of economic priority mode, while in 2025 the number will be raised between 718.57×10^4 people in environmental priority mode and 1202.04×10^4 people in economic priority mode. It is anticipated that the GDP carrying capacity for Xi'an land resources in 2020 could range from 132251.00×10^8 Yuan in economic priority mode to 6470.22×10^8 Yuan of environmental protection model, while in 2025 the number will be increased between 518648.00×10^8 Yuan of economic priority mode and 11469.10×10^8 Yuan of environmental protection mode.

CONCLUSION

According to the urban comprehensive planning of Xi'an (2008-2020), an average annual growth rate of the resident population and GDP are respectively expected to about 3.5% and 10%. In 2020 it is anticipated that the resident population of Xi'an city will climb at 1070.78×10^4 people, GDP will reach to 10307.26×10^8 Yuan; while in 2025 resident population will increase to 1272.01×10^4 people, GDP will get to16599.95×10^8 Yuan [14]. In comparison with the predicted values of five different schemes in Table **5**, the population scale of Xi'an in 2020 will be overloaded. It is larger than the one simulated by scheme 1, scheme 3, scheme 4 and scheme 5, and less than the one of scheme 2, there is even a certain carrying space. Until 2025 its predicated values will be larger than the one of all five schemes and in the overloaded status, which is caused by following two aspects: The one is the rapid mechanical growth of population in Xi'an; the other is that some restrictive indicators referring to the "Code for urban land use classes and standards of planning construction land", such as residential building area per capita, are set up in the SD model. Actually, the residential building area per capita of Xi'an city is relatively low. Hence, the range of such indicators can be appropriately reduced referring to the actual development situation of Xi'an city, in order to improve the population carrying capacity and to meet the needs of future population development in Xi'an.

The predictive value of GDP in the planning is greater than the one of simulating values of scheme 1 and scheme 3, but less than the other three schemes. The development space of GDP respectively range from 6889.94×10^8 to 121943.74×10^8 Yuan in 2020 and in 2025 from 22826.55×10^8 to 502048.05×10^8 Yuan, which implies that the scale of future economic development of Xi'an will be confined within the carrying limits and then could satisfy the needs of economic development. Furthermore, Enhancement of technical level and application of advanced equipments have contributed to increasing the carrying capacity of land resources for the scale of economy, thus sustainable economic development will be achieved.

In accordance with the above analysis, the excessive growth of population should be appropriately controlled for the future development of Xi'an city, in order to relieve the discrepancy between population and resources. Moreover, the industrial structure and land use structure should be also adjusted to promote economical and intensive utilization of resources, to improve comprehensive carrying capacity of land resource, and to ensure stable and sustainable development of Xi'an City.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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