Scenario Simulation For The Urban Carrying Capacity Based On System Dynamics Model In Shanghai, China

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Research Article

Keywords: Urban carrying capacity, system dynamics model, scenario simulation, coordinated equilibrium, Shanghai city

Posted Date: September 21st, 2021

DOI: https://doi.org/10.21203/rs.3.rs-886560/v1

Abstract

Shanghai, as an international metropolis, is embracing an ever-growing population and ongoing economic development, the pressure on the natural resources and the environment is continually increased. How to ease the tension among economy, resources and the environment? The sustainable green development of Shanghai has been the focus of the public and the government. Urban carrying capacity involves complex interactions among population, economy, resources and environment. Understanding how the balance among various elements is an important scientific question for sustainable green development in Shanghai. For this purpose, the balance between urban development and ecological resources was emphasized, and population carrying capacity, GDP, green ecological index and added value of secondary industry were introduced to measure urban carrying capacity. Here, the dynamic changes of the carrying population, GDP, green ecological index and the added value of the secondary industry in Shanghai during 2018-2035 were simulated using a system dynamics model including four subsystems and 65 variables from a macroscopic perspective. Five development scenarios have been employed during the simulation namely status-quo scenario, economic-centric scenario, high-tech-centric scenario, environment-centric scenario and coordinated equilibrium scenario. The simulation results indicated that the potential of carrying population will decline by 2035, and the economic and ecological indicators will also be at the low level under the status-quo scenario, which is an inferior option. While Under coordinated equilibrium scenario, the ecological environment, population growth and economic development all perform excellently, which is the best option. Therefore, the urban carrying capacity of population-economy-resources in Shanghai may be improved by increasing the investment in scientific research, rising the expenditure on environmental protection and improving the recycling efficiency of waste solid and water. The results provide insights into the urban carrying capacity of Shanghai city.

Highlights

. An system dynamics model composed of society-economy-ecology-resource subsystems was established to comprehensively evaluate urban carrying capacity in Shanghai.

. The dynamic trends of the population, economic development and green ecological index were simulated and predicted under five scenarios.

. Coordinated equilibrium scenario is the best choice for improving urban carrying capacity.

. Measures were put forward from three issues: increasing the investment in scientific research, rising the expenditure on environmental protection and improving the recycling efficiency of waste solid and water.

1. Introduction

The coordinated development of society, economy and environment has always been the key issue of regional sustainable development since the concept of sustainable development was put forward by the Commission on World and Environmental Development in 1987 (Zou and Ma,2021; Zhang et al.,2020). With the advancement in worldwide urbanization and industrialization, the contradiction between socio-economic development and population, resources and environment have become increasingly prominent, which restricts the sustainable development of the region (Bao et al.,2020; Bibri et al.,2020). Since the open door reform policy in 1978 in China, much has changed (Lin et al.,2017). One of the major changes is the tremendous improvement of social productivity and rapid economic growth (Yang et al.,2020). Another change is the rapid population growth in large cities (Shi et al.,2018). Meanwhile, many global environmental issues have emerged, such as the excessive exploitation of natural resources, the discharge of pollutants and the deterioration of human settlement environment (Li et al.,2017; Zheng et al.,2018). In order to tackle these problems, we integrate the concept of carrying capacity into the management of urban development. Urban carrying capacity (UCC) or urban comprehensive carrying capacity is an important barometer of urban sustainable development. The research topic is, however, not easy to standardize due to different meanings, principles, and focal points (Rees,1992).

Overall, the development of urban carrying capacity can be divided into three phases. In phase 1, in the twenty years of China's reform and opening up, insufficient natural resources and environmental destruction phenomenon emerges as the urban economy grows rapidly. While the researches on urban carrying capacity in this period considered urban resources and environment, economic development is still a primary issue for city builders. In phase 2, practitioners and academics began to attach great importance to the resource availability and environmental quality within a city from the late 1990s to the early 2000s. Currently, China, at its third stage of urban carrying capacity, is undergoing comprehensive development which should consider resource, environmental, economic, and social factors. Among these, social factors include not only the direct promotion effect brought by basic public facilities to the city but also the soft condition improvement.

Against this background, the research on urban carrying capacity has gained increasing attention in the scientific community. The term 'carrying capacity' was first proposed in studies of physics, demography, and biology (Plumb et al.,2009). With advances in research on UCC, previous published studies are limited to a single content, such as land carrying capacity (Zhao et al.,2019; Tang et al.,2021), water resource carrying capacity (Song et al., 2011; He et al.,2018; Yang et al.,2021), tourist environmental carrying capacity (Pu et al.,2020; Wang et al.,2020) and economy carrying capacity (Di et al.,2016).

From the perspective of the whole research process, although the connotation of carrying capacity is constantly enriched, the relative research about urban carrying capacity is still in its infancy. Generally speaking, recent studies have not formed a unified and robust basic theory and the model method is single. In respect of research methods of urban carrying capacity, those mainly focused on index evaluation method and system dynamics (SD) method (Wang et al.,2017; Zhou et al.,2017; Wang et al.,2020). Index evaluation methods, such as principal component analysis (Xing et al.,2013; Zhang et al.,2019), artificial neural networks (Luo et al.,2019), Expert evaluation method (Li et al.,2021) and fuzzy comprehensive evaluation method have been universally accepted because of its simple operation. Zhang et al.(2019) evaluated the variation trend of water resources carrying capacity on time scale using principal component analysis. However, the interpretation of principal component is fuzzy, which has weak explanatory value for real life. Artificial neural network prediction is based on relatively independent systems, which implies that the coupling between the systems is relatively challenging. The expert evaluation method has a certain level of subjectivity in determining the weight of the index. Due to the systemic, dynamics and feedback of urban carrying capacity, the traditional low-order and linear theories are not conducive to effectively solve this complex system problem. The SD method simulates the causality between factors through positive and negative feedback. It has the ability to deal with high-order, nonlinear and other complex system problems and is gradually used by scholars for the carrying capacity of water resources (Mashaly and Fernald, 2020) and land resources (Zhu et al.,2014). The biggest difference between SD and other methods is its own negative feedback system, that is, a readjustment of constraint conditions (Barati et al.,2019; Wang et al.,2021). Hence, system dynamics model is introduced to solve this problem. As a comprehensive simulation model, system dynamics model can be used to study the behavior of complex systems over time and interact with each other through feedback loops (Zomorodian et al.,2018).

In this study, five scenarios were designed based on the system dynamics model of Shanghai's comprehensive urban carrying capacity, which is composed of social subsystem, economic subsystem, ecological subsystem and resource subsystem. In addition, the population, economic development and green ecological index of each scenario were simulated and predicted. In conclusion, this paper establishes a coupling model composed of a society-economy-ecology-resource('SEER') subsystem to comprehensively evaluate urban carrying capacity, which makes up for the deficiency of single carrying capacity research. Through the green ecological index, the evaluation model of urban carrying capacity is further enriched. Five kinds of urban development scenarios, making it more comprehensive in pattern researches.

2. Materials And Methods

2.1 Study area

As our research area, we select Shanghai, which is located at the T-junction of China's coastal economic belt and the Yangtze River economic belt. As shown in Fig. 1, there are 16 districts in shanghai consisted of 9 in the suburbs and 7 districts in the downtown, covering a land area of 6833 square kilometers. According to the 2020 China seventh national census, approximately 24.87 million resident population in Shanghai, which was increased 1.85 million people against decade. From a socio-economic perspective, Shanghai's GDP ranks first among China's cities in 2020 which has nearly 2.5-fold within 10 years from 1.6 to 3.9 trillion yuan. In terms of industrial structure, the tertiary industry was the highest, accounting for 72%, while the primary industry was the least(less than 1%).

The drastic expansion of land use and environmental variations are accompanied by the increase of construction land year by year in Shanghai. Meanwhile, with the proportion of construction land over 40%, the scale of construction land is much higher than Paris and Tokyo. Whereas, the forest cover rate was only 15% in 2015, which was truly below the national average of 22% and far from the international level of forest coverage of 40–60%. It is therefore urgent and challenging to ensure the coordinated development of the society, economy, population, resources and the environment in Shanghai in the future.

2.2 Data sources

The datasets of population, social economy, ecological resources, new and high technology are used in this research. The main data sources involve the Shanghai Statistical Yearbooks (2010–2018), Statistical Communique of Shanghai National Economic and Social Development (2010–2018), the Shanghai Ecological Environment Conditions Bulletin (2010–2018), Shanghai Master Plan 2017–2035 and Statistical Yearbooks of Chinese Cities (2011–2018).

2.3 System dynamics model

The system dynamics model was proposed by Prof. Forrester to address the issues of enterprise management (Forrester and Warfield, 1971). Nowadays, system dynamics has become a comprehensive discipline based on system theory, including cybernetics, information theory, collaboration theory, structure theory and other basic disciplines. There are three main reasons why we chose to use an SD model for studying the urban carrying capacity of Shanghai. First, SD is a powerful quantitative research tool. There are currently as many as 25 functions to describe the characteristics of variables and the structure rules between variables. Second, SD specializes in complex system problems. SD pays more attention to the interconnection and interaction between subsystems and its behavior pattern over time is determined by the internal dynamic structure, which is not affected by external factors. Third, multi-scenarios simulations can be undertaken by system dynamic model. The SD model is essentially a differential equation system, through the numerical analysis to simulate the behavior of complex systems. By setting the key parameters in the SD model, the patterns of future urban development can be established. In doing so, urban carrying capacity can be described comprehensively from multiple-angles.

In this study, it is obviously unreasonable to define system boundary as the administrative boundary, because strong openness exists in Shanghai, making a continuous exchange of material, energy and information in space. When describing the urban system circulation from a macro scale, various resources circulate freely within a city which is influenced by the richness of the upper urban agglomeration and its own trade input, so it can be regarded as an equilibrium state. Vensim PLE software is selected to calculate the SD model. Based on the above analysis of urban carrying capacity, the determination of evaluation indicators should follow the following principles: comprehensiveness, universality and adaptation to local conditions. According to previous studies (Wang et al.,2021; Zhang et al.,2021; Zhao et al.,2019; Zhou et al.,2021) and data availability, the following system boundaries were determined as follows: 1) the total population that can be supported in Shanghai; 2) GDP; 3) built-up area; 4) output value of secondary industry; 5) output value of tertiary industry; 6) financial revenue; 7) total investment in environmental protection; 8) the number of graduates; 9) total amount of high-tech contracts. The above system boundaries cover population, society, economy and environment subsystems, which can reflect the current situation of urban development in Shanghai. It should be noted that the time boundary of the model is set from 2010 to 2035. The period of the historical data regulation stage is from 2010 to 2017, and the period of prediction simulation is from 2018 to 2035. Furthermore, the time step used in the simulation is 1 year and the running time of the model is 25 years.

3. Establishing The Evaluation Index System And Sd Model For The Ucc In Shanghai

3.1 SD model formulation

Urban carrying capacity is a complex and expansive system, which is impacted and restricted by many aspects. It is necessary to incorporate social subsystem, economic subsystem, environmental subsystem and resource subsystem into the research system of urban carrying capacity.

3.1.1 Social Subsystem

The social subsystem mainly reflects some basic urban elements such as urban population and represents the integration of social groups. It mainly includes the total carrying population, the number of college graduates and the residents' life index and etc. Moreover, the population change directly affects the total economic output, the amount usage of social resources and energy consumption. Changes in social resources, in turn, affect the carrying capacity of the population. This forms the corresponding feedback adjustment.

3.1.2 Economic Subsystem

Economic development is the main driving force of urbanization and an important indicator to measure urban carrying capacity. To a certain extent, it directly affects the speed of regional development, and thus determines the urban attraction and vitality. The gross domestic product is the core index of economic accounting and represents the level of regional social and economic development. Accordingly, the gross domestic product, secondary and tertiary industry output value are the vital components of the economic subsystem; in addition, the integrated development of secondary and tertiary industries is a major trend of global industrial development, and also an inevitable choice for Shanghai to continuously improve its economic strength. The steady economic growth affects the population change and the proportion of high-tech industries in today's increasingly accelerated globalization.

3.1.3 Ecological subsystem

A sound urban ecological environment provides essential support for economic development, such as water resources, pollution evolution and climate regulation. The ecological subsystem comprises green coverage rate of built-up area, urban green ecological index and so on. Specifically, a more sustainable and resilient ecological city goal was put forward in Shanghai Master Plan (2017–2035), aiming to enhance public awareness to curb pollution and polish up the eco quality.

3.1.4 Resource subsystem

The resource subsystem includes resource richness, sewage discharge and utilization rate of industrial wastewater treatment and so on. Cities tend to gather more population, and the growth of population is bound to produce dependence on and consumption of resources. The shortage of cultivated land and freshwater resources is serious, which restricts sustainable development. From all kinds of aspects, saving and optimizing the industrial structure of resources can be achieved by improving of urban governance ability, such as establishing the harmless treatment of garbage, improving the recycling rate of waste solid and wastewater. A sound resource subsystem can combine resource utilization with socio-economic development.

According to the above analysis, the SD model flowchart of Shanghai's urban carrying capacity is shown in Fig. 2. In this model, the variable located at the tail of the blue arrow represents the dependent variable, and the variable at the position of the blue arrow represents the independent variable. Variables with a square are level variables. The grey variables are shadow variables, and the other variables are constant or intermediate variables.

3.2 Evaluation index system

The SD model expresses the relationship among the directly related variables through a function called the simulation equation. The subsystems, bridged by population, economy and resources, are interlinked into a complex system that affects the urban comprehensive carrying capacity. Therefore, in order to avoid inaccurate results caused by the single-criterion evaluation method, this article adopts the multi-factor evaluation method. The evaluation indexes should reflect the actual situation of Shanghai, and also present the changes in urban population, economy, resources and environment. Based on previous research achievements and data availability, we built an evaluation index system composed of a total of 65 evaluation indexes for the urban carrying capacity in Shanghai. Due to too many evaluation indicators, the representative evaluation indicators and the formula operations between variables (in Vensim language) were listed in Table 1.

Table 1
Selection of evaluation indicators and their calculation equation of urban carrying capacity SD model at the macro scale

System level	Evaluation indicators	Calculation Equation
Social subsystem	Urban population density	Urban population/built-up area
	Social insurance expenditure	Financial revenue×0.0263
	Number of graduates per year	INTED(Number of graduates per year) + Initial Value
	Education expenditure	Financial revenue×0.038
	Resident's life index	ln(urban population density + endowment insurance + consumption level of resident + Medical insurance expenditure)
	Urban per capita level of residents	GDP×population urbanization rate/urban population
	……	
Economic Subsystem	Output value of secondary industry	INTEG(added value of secondary industry) + Initial Value
	Output value of tertiary industry	INTEG(added value of tertiary industry) + Initial Value
	Proportion of high-tech industry output value	SIN(proportion of tertiary industry)
	GDP	INTEG(GDP increment) + Initial Value
	Scientific and technological achievements	Look up
	……	
Ecological subsystem	Green coverage rate of built-up area	Constant(0.31)
	Proportion of environmental protection investment in GDP	INTEG (added value of environmental protection expenditure) + Initial Value
	Urban green ecological index	2×ln(Degree of urban construction + resident's life index + Habitat quality index + carbon emissions + financial development index)
	……	
Resource subsystem	Total resources	ln(1 + ABS(total water resources + green area of built-up area))
	Sewage discharge	EXP((7.9e-008)*energy consumption + 8)
	wastewater treatment level	Proportion of environmental protection investment in GDP*GDP*0.005 + 0.12
	……	

*Note: "With lookup" in Vensim software is a table function, which can be used to characterize non-linear relationship variables.

3.3 Multi-scenarios setting

The main purpose of this paper is to present the development trend of Shanghai's urban carrying capacity under different scenarios. From the perspective of optimizing resource allocation, improving the level of science and technology, advocating green development, optimizing industrial structure and so on, five scenarios were setting by adjusting the decision variables such as table function and constant variable in the model. For instance, GDP increment, added value of secondary industry, green coverage rate of built-up area, added value of environmental protection investment and research and experimental development expenditure ratio were selected as decision variables. Based on the current situation of urban carrying capacity and the changing trend of social economy and ecology in Shanghai, four indicators including the total population, GDP, added value of secondary industry and urban green ecological index, were selected to evaluate the carrying capacity under different scenarios.

Details of the five simulation scenarios setup using control variables are described as follows: The status quo scenario maintains the status quo social, economic, ecological and resource development mode and does not need to adjust any parameters. This status quo scenario can be used as a reference for other scenes. High-tech-centric scenario is achieved by increasing high-tech-related indicators by 20%, leaving others unchanged, such as the number of R&D employees, research and experimental development expenditure ratio and the total number of high-tech contracts, et al. For environment-centric scenario, we have raised ecological and environmental protection indicators by 20%. These indicators consist of proportion of environmental protection investment, wastewater treatment rate and harmless treatment level of garbage, etc. The economic-centric scenario increased the GDP-related variables by 20%, thus simulating the chain reaction of the variables in the system from 2018–2035. The coordinated equilibrium scenario was developed based on the high-tech-centric scenario, environment-centric and economic-centric by adjusting related indicators by 20%.

4. Simulation Results Under The Different Scenarios

4.1 Carrying population simulation

With maintaining the status quo, the total population capacity of Shanghai will gradually reach a limit after 2025, about 25 million. In this case, the growth rate of the total population tends to drop below 0.2% in 2025 and then 0.1% in 2031, basically losing the carrying potential of the population. Each of the other four scenarios will ultimately not reach the population carrying limit in 2035. Among them, the population that can be carried under the economic-centric scenario is the largest, which can reach 27.86 million in 2035. The rapid economic growth has not only improved the per capita GDP of Shanghai but also provided more jobs, causing an increase in Shanghai’s adsorbed population and the carrying population. Under the coordinated equilibrium scenario, the population growth will slow down from 2020 and eventually reach 27.36 million in 2035. The carrying population in Shanghai can reach 26.78 million and 26.39 million respectively by 2035 in the high-tech-centric and environment-centric scenario. From the perspective of the population carrying capacity, the economic-centric scenario bears the largest population, followed by the coordinated equilibrium, and the status quo is the least.

4.2 GDP simulation

As shown in Fig. 4, the GDP of Shanghai will rise continuously in either scenario, and the overall gap is not very large. Specifically, under the economic-centric scenario, the GDP value will grow quickly, by 2035, reach 8.75 trillion yuan, which is much higher than that in the status quo scenario. The explanation for this is related to the overall increase in the economic index of this development model. In the coordinated equilibrium scenario, the GDP in 2035 will reach 8.17 trillion yuan second only to that in the economic-centric scenario; and its GDP growth rate maintains 4% from 2030 to 2035, which is more healthy and stable. Moreover, the GDP in the high-tech-centric scenario and environment-centric can reach 7.95 trillion yuan and 7.63 trillion yuan respectively by 2035, with little difference. Thus, in terms of seeking more stable, healthy and potential economic development, the simulation of GDP results show that the coordinated equilibrium scenario was more effective than the above-mentioned scenario.

4.3 Green ecological index simulation

The urban green ecological index is a coupling of Shanghai's economic development index, residents' life index, degree of urban construction, carbon emissions, green coverage rate of built-up areas and so on, which is a very important intermediate variable constructed in this research. It can be seen from Fig. 5 that the urban green ecological index will gradually decrease after reaching 7.39 in 2016, and show a sharp downward trend from poor to nearly weak following the economic-centric scenario. This indicated that completely focus on economic construction without considering other factors will inevitably cause environmental pollution and reduce the quality of life of residents, which will affect the sustainable development of the city. There were similar uprising trends in the other four scenarios. In summary, the coordinated equilibrium scenario was effective in urban green ecological index and has the best performance.

4.4 Simulation of added value of secondary industry

Regardless of the scenario, the added value of the secondary industry will gradually mount, which is similar to the simulation trend of GDP (Fig. 6). In the coordinated equilibrium scenario, while its annual growth rate has gradually decreased from the initial 14.93–4.37%, the added value of the secondary industry can reach 1.80 trillion yuan by 2035. The simulation results were presented in an interleaved and similar manner under the economic-centric and high-tech-centric scenarios, which both reach 1.7 trillion yuan by 2035. In the status quo, it is only 1.4 trillion yuan in 2035, far lower than that in other scenarios. Thus, for the added value of secondary industry, coordinated equilibrium scenario was found to have the highest performance as in the previous section.

5. Discussion

The SD model of urban carrying capacity in this paper is coupled with nine typical first-order systems with nine level variables. Because of the complexity of the system, the behavior of urban carrying capacity is not limited to linear growth, exponential growth, S-shaped growth, spiral rise and damping oscillation, but the complex combination of them. Thus, the quality of the model simulation depends on whether it properly represents the real-world system (Wang et al.,2017b). Due to the large number of parameters in the model, representative indicators were extracted to test the error size between the actual and the simulation value. If all relative errors are within 10% and at least half are within 5%, we assume that the model is valid. As Table 2 shows, the total population of Shanghai, GDP and output value of the tertiary industry were employed to test the model from 2010 to 2017.

Table 2
Error test results of the SD model

Variables name		2010	2011	2012	2013	2014	2015	2016	2017
Carrying population(Ten thousand)	Historical values	2303	2347	2380	2415	2426	2415	2420	2418
	Simulated values	2303	2318	2332	2346	2360	2377	2387	2401
	Error (%)	0.00	1.24	2.02	2.86	2.72	1.57	1.36	0.70
GDP(100 million yuan)	Historical values	17437	19539	20559	22264	24068	25659	28184	30633
	Simulated values	17166	19902	21998	24277	26083	27729	29487	31526
	Error (%)	1.55%	1.86%	7.00%	9.04%	8.37%	8.07%	4.62%	2.92%
Output value of the tertiary industry(100 million yuan)	Historical values	9833	11143	12199	13786	15276	17275	19663	21191
	Simulated values	9618	11300	13139	15099	16170	17309	18520	19821
	Error (%)	2.19%	1.41%	7.71%	9.52%	5.85%	0.20%	5.81%	6.47%
Note: Source of historical values: Shanghai Statistical Yearbooks (2011–2018).									

Through comparison, it was found that the relative errors of the three indicators from 2010 to 2017 all met the requirements of the pre-design, and the relative errors of the data were less than 5%, accounting for 57% of the total checked data. Therefore, the system dynamics model has high accuracy and is suitable for the simulation of urban carrying capacity in Shanghai.

The status quo scenario sustains the current development situation. In this scenario, the population simulation result in 2035 will be within the range of about 25 million planned in the Shanghai Master Plan 2017–2035. However, the current development model restricts the large-scale development of the future economy and society. In addition, by 2035, GDP, the added value of secondary industry and other indicators are the lowest compared to other scenarios, but the basic economic, social and ecological development of Shanghai will barely be maintained.

With other system parameters unchanged, under the economic-centric scenario, the level of urban economic development is adjusted from the perspective of per capita disposable income and industrial structure and so on. Simulation results revealed that Shanghai's GDP and the added value of secondary industry are in the forefront, but the green ecological index has been declining since 2018. There is a contradictory trend between ecological and economic. This means that the post-2018 carrying capacity is inadequate because it is unable to provide suitable ecological functions for the humans in Shanghai. The development of the secondary industry is needed to considerable energy and resources, while huge pollution emissions were generated (Ehrlich et al.,2007). Consequently, the secondary industry has an important impact on China's ecological environment.

The high-tech-centric scenario focuses on increasing investment in high-tech industries. Natural resources in Shanghai are not abundant. Economic development relies more on the tertiary industry, in which the proportion of tertiary industry and the proportion of tertiary industry employees are both gradually increasing year by year (Xu and

Tan.,2021). The extensive economic growth model has been replaced by a "post-industrial" model dominated by modern services, supplemented by high-end manufacturing and high-tech industries. In this scenario, the secondary and tertiary production and GDP will increase significantly.

Environment-centric scenario not only ensures economic development but also has a small impact on the environmental load, which belongs to a good sustainable carrying state. More and more attention has been paid to the strengthening effect of solid waste treatment, ecological environment restoration, sewage treatment and environmental protection equipment manufacturing on ecological resource carrying capacity (Sanjuan-Delmás et al.,2021).

The combination of multiple scenarios in coordinated equilibrium scenario produces a marked improvement in the urban carrying capacity. All indicators are excellent. This indicates that urban carrying capacity is the result of the comprehensive effects of society, economy and ecology. In conclusion, the coordinated equilibrium scenario greatly contributed to the harmonious development of society, economy and ecology.

Furthermore, there remain certain limitations in this research:

1. The urban carrying capacity is a complex, multi-factor system. Although this study involves as many relevant influencing factors as possible, it still cannot cover all. Some influencing factors, such as land subsidence on carrying population, have been simplified or not taken into account.
2. Four indicators represented the level of urban carrying capacity of urban population, economy and ecology. In subsequent studies, land change can be integrated into the model to realize the simulation of urban land change.

Research on urban carrying capacity involves economics, environmental management and resource management. With more advanced datum and methods, researchers will get more scientifically sound results. For more comprehensive studies in the future, SD models can be combined with fuzzy comprehensive evaluation method or other relevant models (Wang et al.,2021).

6. Conclusions And Policy Implications

The system dynamic model is an important method for studying complex social-economic-environmental systems and has a reputation as a laboratory of complex socio-economic systems. Based on the SD method, the model of the urban carrying capacity of four mutually restricted subsystems in Shanghai was established. The development of urban carrying capacity (including carrying population, GDP, green ecological index and the added value of secondary industry) were simulated and analyzed under five scenarios in 2018-2035, and the results were also consistent with the historical status of the Shanghai Statistical Yearbook, confirming the reliability of the model.

Table 3 displays the simulation ranking results of the four indicators in five simulation scenarios by 2035. The simulations show that if maintains the status quo social development mode, the carrying population size, economic development and green ecological index will have increased, however, the population carrying potential and ecological environment construction have gradually slowed down over the next fifteen years. The simulation results in the status quo of the indicators are all poor from Table 3. Meanwhile, the growth rate of economy is faster than the population size, which is likely to lead to a drop in the competitiveness and attractiveness of urban development and is not conducive to the healthy development of urban economy. Note that the economic-centric scenario is obviously not feasible that the green ecological index ranks fourth (worst), showing a downward trend and causing environmental pollution and the decline of residents' living standards. Furthermore, in the environment-centric scenario, while it is possible to improve the urban ecological environment from the third ranking, it is still not conducive to the overall development of Shanghai from the perspective of economic development and population relations. In the high-tech scenario, the green ecological index and the added value of the secondary industry rank second, and its total population and GDP rank third, which is the suitable development scenario. In addition, compared to the above four scenarios, the optimal scheme is the coordinated equilibrium scenario, in which the green ecological index, the added value of the secondary industry, the total population and GDP all have top-ranked results.

Table 3 Ranking of indicators simulation results under five scenarios in 2035

Scenarios	Ranking results			
	Carrying population	GDP	Green ecological index	Added value of secondary industry
Status quo	5	5	4	5
economic-centric	1	1	5	3
high-tech	3	3	2	2
environment-centric	4	4	3	4
coordinated equilibrium	2	2	1	1

Therefore, it is not feasible to promote the sustainable urban development of Shanghai by only relying on environmental governance or accelerating economic development. Through comparative analysis, it is found that the simulation results of major variables of coordinated equilibrium scenario are better than other scenarios. This represents a rapid, ecological and coordinated systematic development model, which mainly benefits from the coordinated and unified development of environmental governance, resource utilization and economic benefits.

With the advantages of the coastal area, convenient geographical location and open policy orientation, the economic aggregate of Shanghai is far ahead in China for a long time. However, due to historical and other reasons, there is still room for Shanghai's economic scale to rise compared with global typical cities from various aspects. It is the obligatory way for Shanghai to build a global outstanding city to keep the harmonious development of market economy, scientific and technological innovation and ecological environment. The proportion of R&D expenses in GDP in 2018 exceeded 4% for the first time, which is comparable to that in Paris. However, R&D investment in Shanghai was about 100 billion yuan less than that in Shenzhen, which has more high-tech enterprises. Hence, it is necessary to make a series of science and technology policies to support innovation to synchronize economic development. Shanghai enterprises should be encouraged to invest in R&D, and close coordination between government and enterprises should be emphasized to avoid investment dispersion. And we should pay attention to industrial innovation in the suburbs, which is a relatively weak point in Shanghai.

In addition, the protection of ecological environment is also an important indicator of urban competitiveness. From 2010 to 2019, the forest coverage rate of Shanghai showed an overall increasing trend. In 2019, the total forest area of Shanghai was 1.67 million mu, accounting for 17.59%, an increase of 5% compared with that of 2011. By 2020, Shanghai plans to build 70,000 mu of woodland, with a forest coverage rate of more than 18%. The overall atmospheric environment of Shanghai is not serious across the country in China, but there were still some improvements that needed to be made. For example, in Zhongshan Street of Songjiang district, there are large garbage dumps and small and medium-sized polluting enterprises, so the dilution capacity of air pollutants is poor and the heat island effect is high. Making green vegetation laid along the walls of surrounding buildings and restricting screening and regulating the emission indicators of enterprises with polluting enterprises are good solutions to increase large areas of ecological green space and improve environmental quality. Nevertheless, adhering to the spatial layout structure of "multi-center, wedge green, green belt around the city" and the goal of harmonious coexistence between humans and nature can greatly promote the positive development of urban environment.

Over recent years, with respect to the problems of garbage treatment and classification, compulsory garbage classification was pioneered in Shanghai, with the first local law on garbage sorting (Zhao et al.,2021). This implementation gain plenty of achievement in Shanghai. By the end of October 2019, the daily recycling volume of recyclable materials has reached 5,960 tons , and the amount of wet garbage has exceeded 8,710 tons, an increase of 4.6 times and 1 time as compared with October 2018, respectively. The daily discharge of hazardous waste was 1 ton, a nine-fold increase compared with the average daily discharge in 2018. Additionally, strengthening the construction of social governance capacity and creating a market for waste classification and resource utilization may greatly promote the utilization rate of resources and the urban carrying capacity. In order to build Shanghai into an excellent global city, a city of innovation, humanity and ecology, and a modern international metropolis with global influence, it must take the road of coordinated equilibrium development.

Declarations

Funding: This research was supported by the one of key projects for Shanghai General Land Use Planning Revision (2015(D)-002(F)-11).

Acknowledgement:

Conflicts of Interest：The authors declare no conflicts of interest relevant to this study.

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Figures

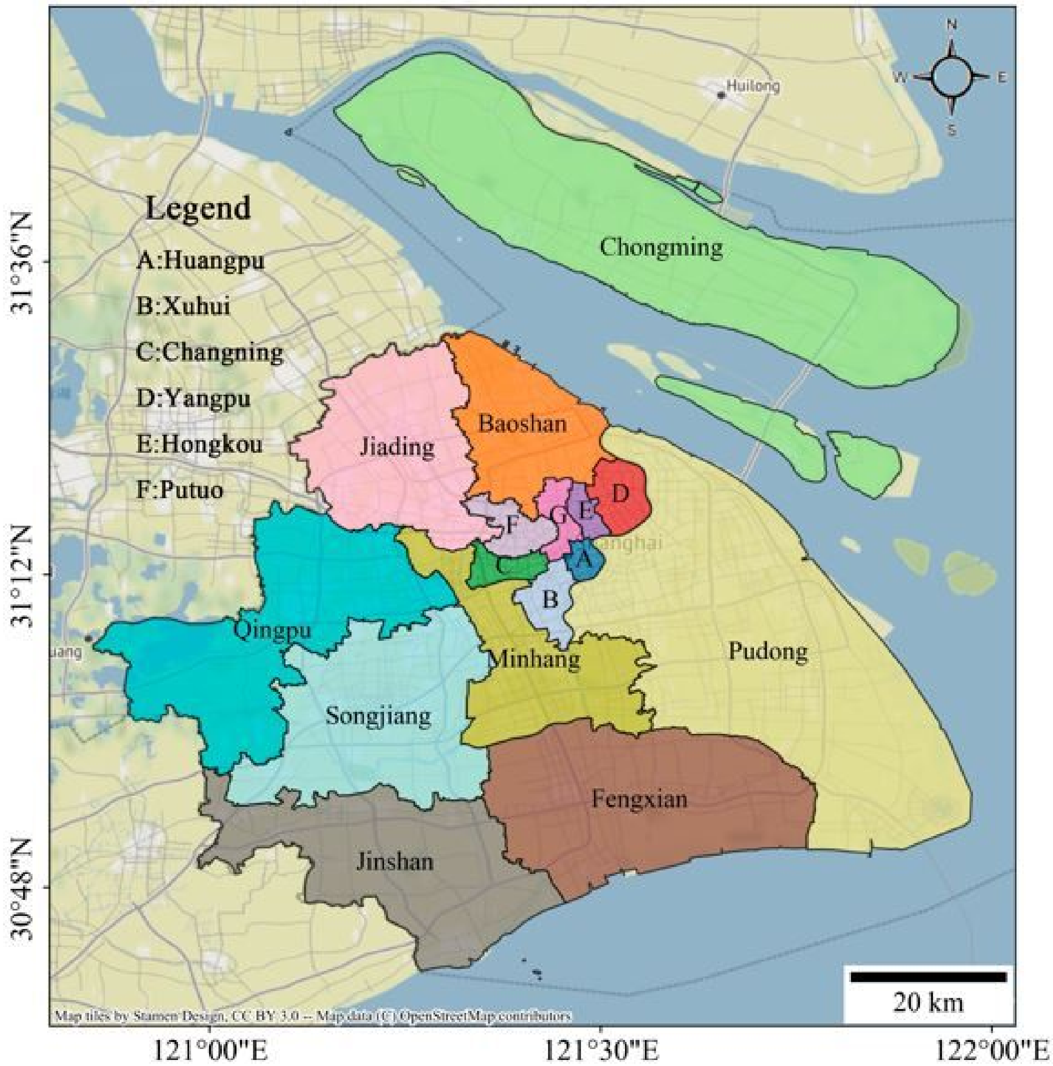

Figure 1

Geographic location of Shanghai.

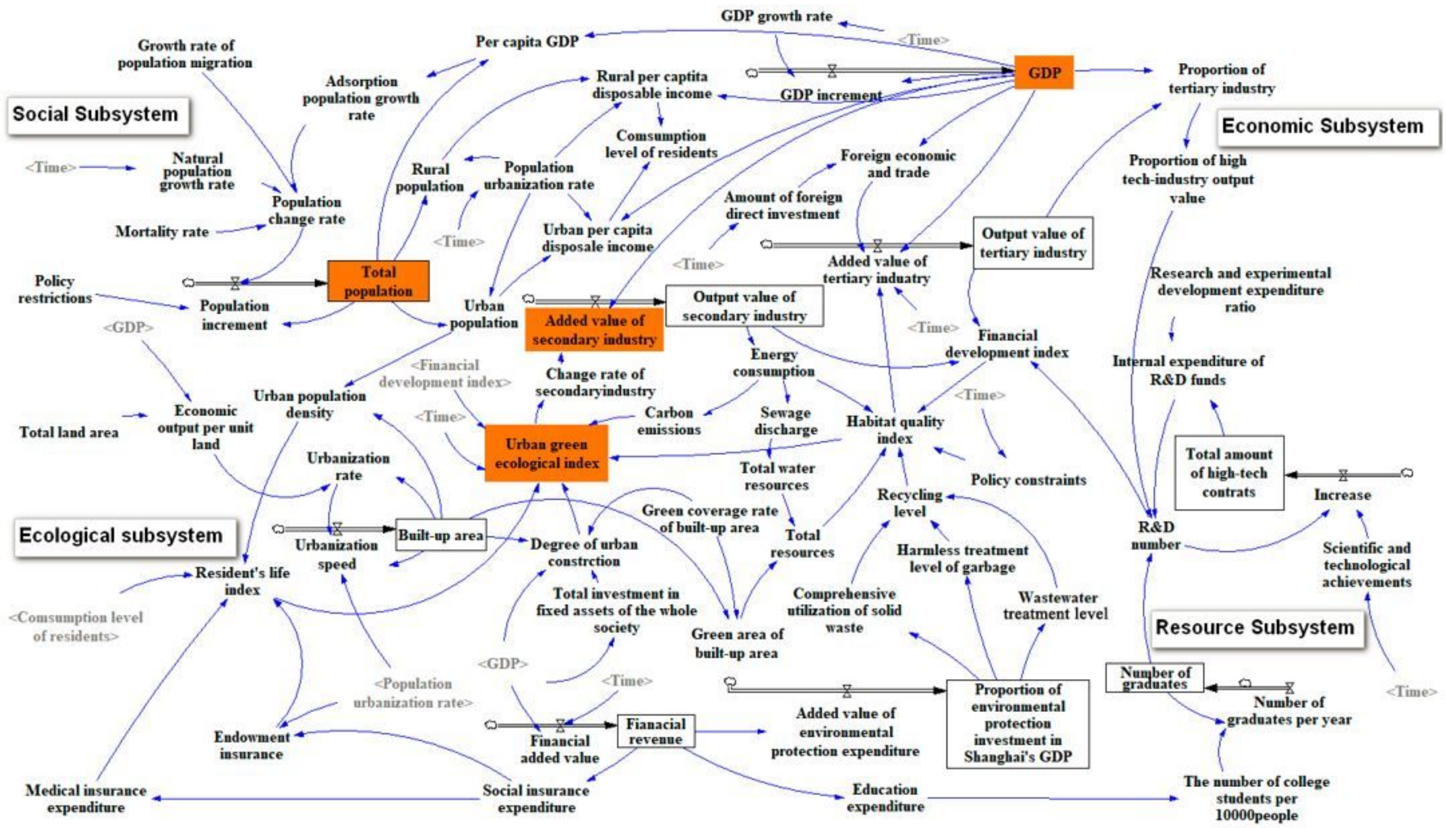

Figure 2

SD model flowchart of urban carrying capacity in Shanghai.

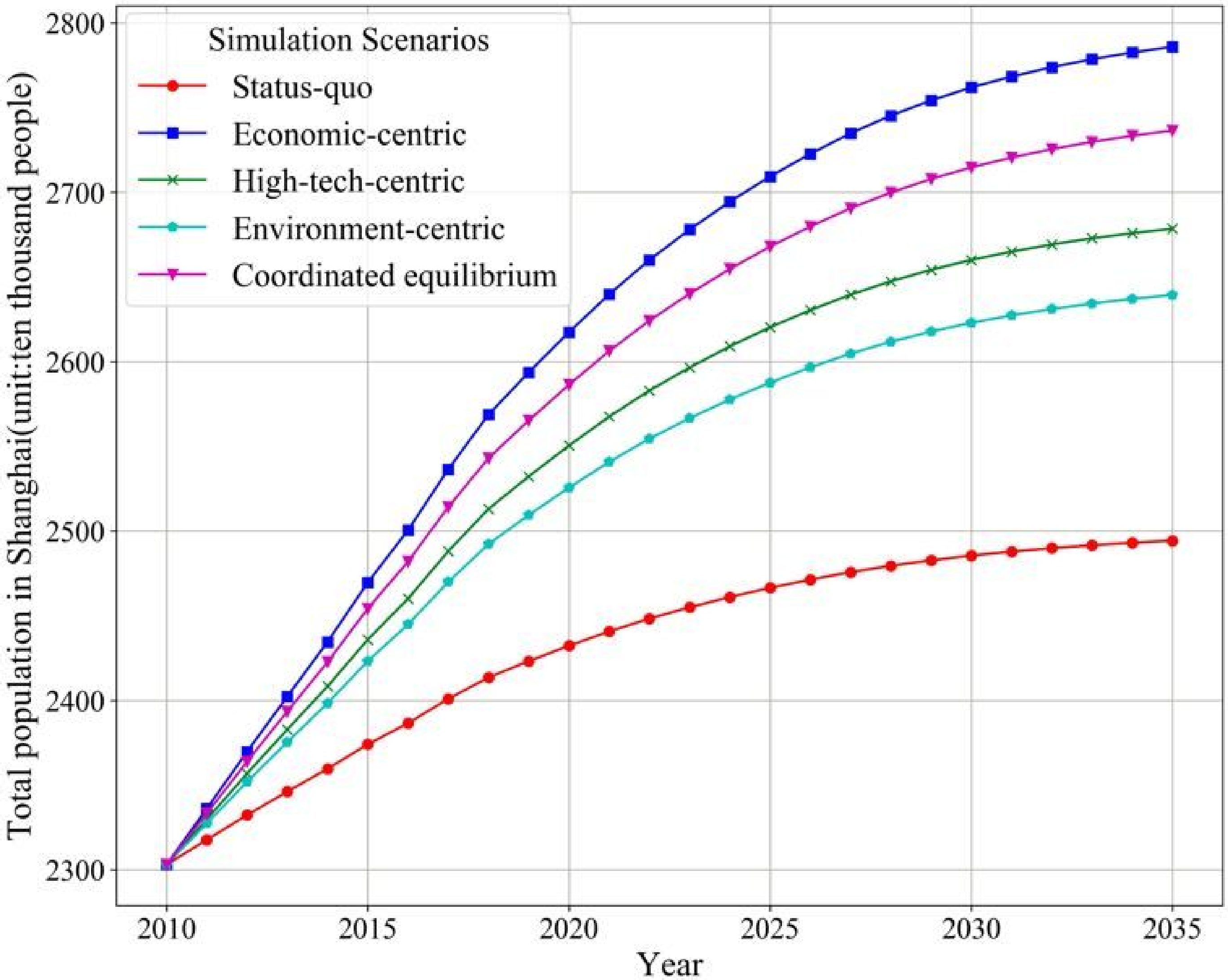

Figure 3

The dynamic trends for the total population in different scenarios.

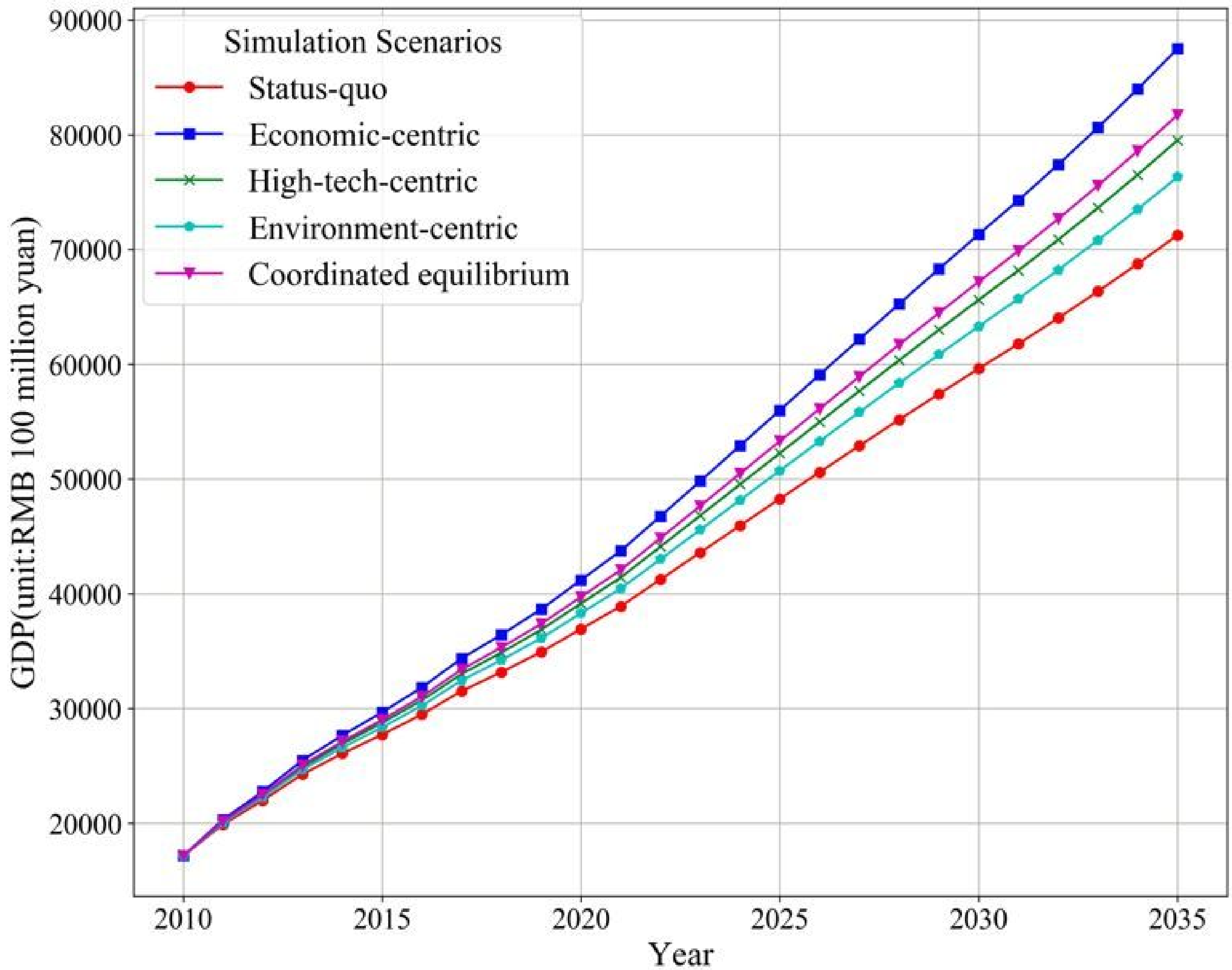

Figure 4

The dynamic trends for the GDP in different scenarios.

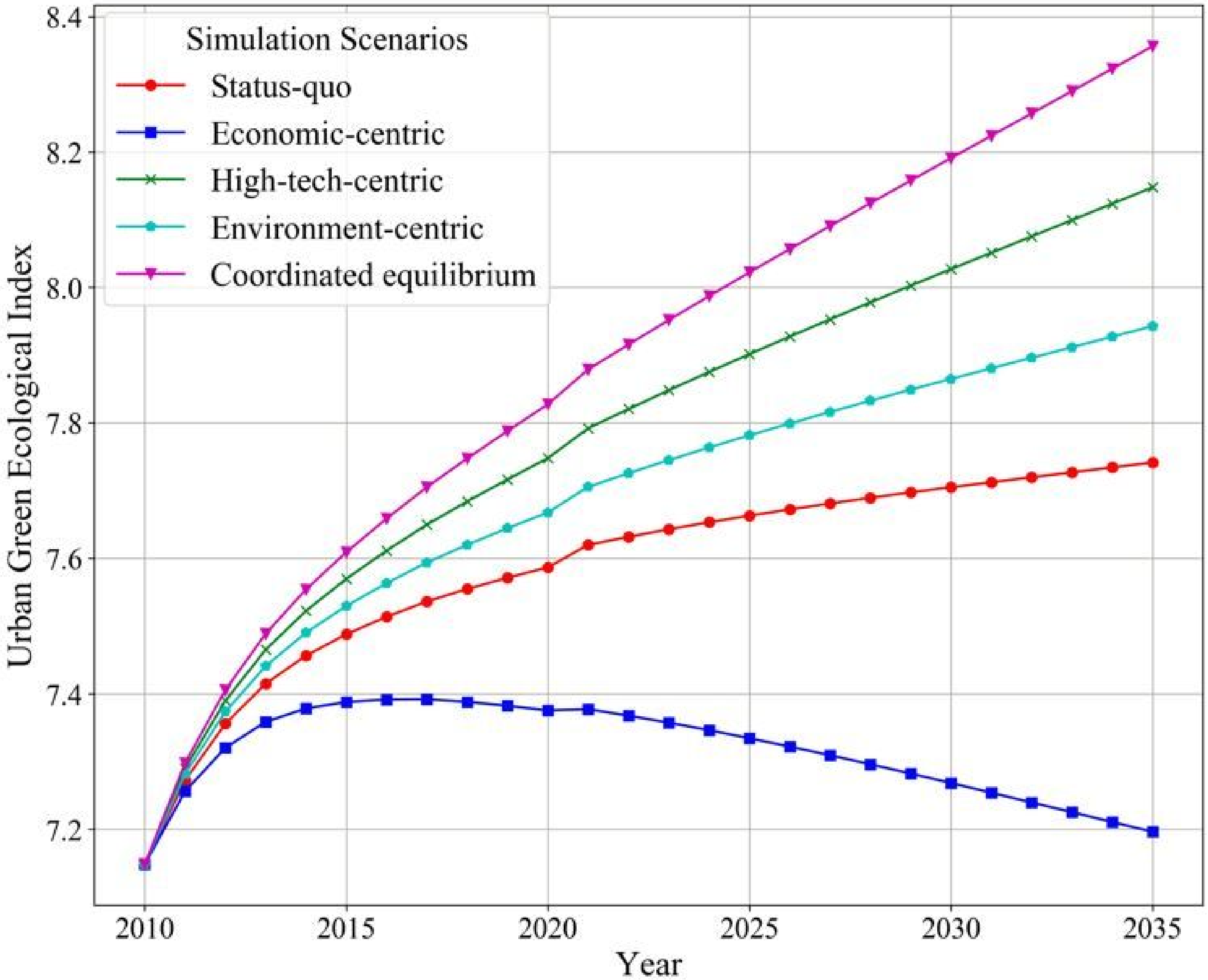

Figure 5

The dynamic trends for the green ecological index in different scenarios.

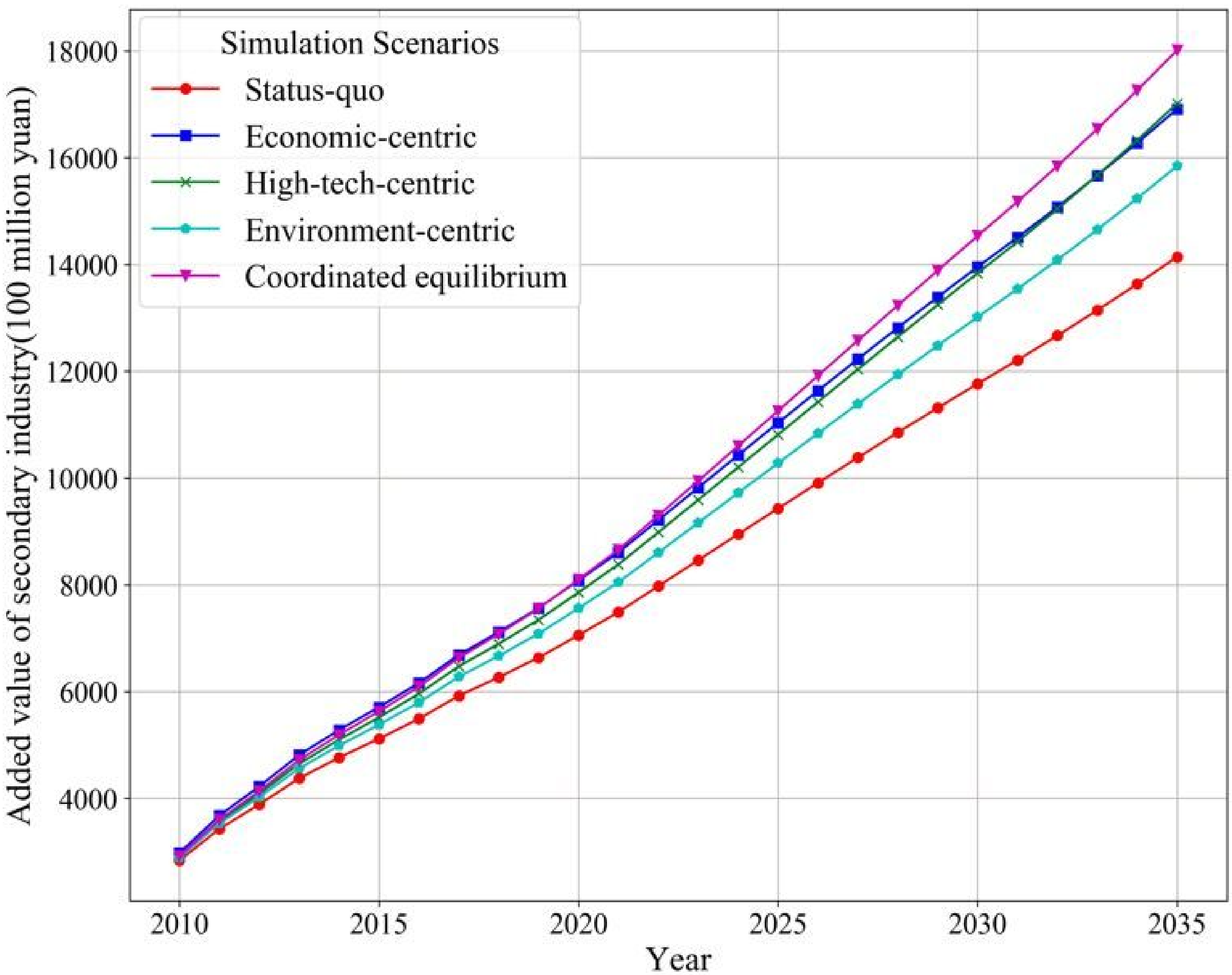

Figure 6

The dynamic trends for the added value of secondary industry in different scenarios.