sustainability

MDPI

Article

Research on the ECC of Chengdu–Chongqing's Urban Agglomeration in China Based on System Dynamics

Xiaohu Ci [1], Liping Zhang [1,2,3,*], Tongxiang Wang [1], Yi Xiao [1,2,3,*] and Jun Xia [1,2,3]

1 State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
2 Hubei Key Laboratory of Water System Science for Sponge City Construction, Wuhan University, Wuhan 430072, China
3 Institute of Water Security, Wuhan University, Wuhan 430072, China
* Correspondence: zhanglp@whu.edu.cn (L.Z.); 00011515@whu.edu.cn (Y.X.)

Abstract: The ecological carrying capacity (ECC) is a prerequisite for China's regional and green developments. Since the Chengdu–Chongqing urban agglomeration (CCUA) is an important economic area, it is important to study the development of its ECC in order to establish its green development and to promote its regionally coordinated development in China. This paper first establishes the ECC evaluation index system based on the Pressure–State–Response (PSR) model and AHP-TOPSIS. Secondly, it estimates the ECC of the CCUA between 2000 and 2018. Thirdly, it constructs a system dynamics model of the ECC and, finally, it simulates and predicts the ECC from 2021 to 2050 based on shared socioeconomic pathways. The results show that the ECC indices of 16 cities in the CCUA have increased significantly in 18 years and the annual ECC indices from 2021 to 2050 all show significant growth trends. This paper will show that the CCUA should select the most suitable development mode to be adopted in the different periods. The development should follow SSP2 from 2021 to 2025, SSP1 from 2026 to 2035, and the development characteristics of SSP5 should be referred to at levels between 2036 and 2050, based on the CCUA's overall development in accordance with SSP1.

Keywords: ecological carrying capacity; urban agglomeration; system dynamics; shared socioeconomic paths (SSPs); simulation

check for updates

Citation: Ci, X.; Zhang, L.; Wang, T.; Xiao, Y.; Xia, J. Research on the ECC of Chengdu–Chongqing's Urban Agglomeration in China Based on System Dynamics. *Sustainability* **2022**, *14*, 10896. https://doi.org/10.3390/su141710896

Academic Editor: Antonio Boggia

Received: 25 May 2022
Accepted: 17 August 2022
Published: 31 August 2022

1. Introduction

China's regional ecological environment is facing serious challenges due to population growth and urbanization [1,2]. Since the United Nations proposed the 2030 Sustainable Development Goals (SDGs) in 2015, the evaluation and prediction of the regional carrying capacity have received much attention as the basis for sustainable development [3–6]. X. W. et al. [7] analyzed the ECC of Yunyang County in the Three Gorges Reservoir area using a fuzzy integrated evaluation method. D. D. et al. [8] assessed the water resource carrying capacity in Zhangjiakou city using the ecological footprint method and system dynamics. T. W. et al. [9] constructed an ECC framework based on the Aral Sea Basin using a hierarchical analysis method and a remote sensing image technique. Although the research on the ECC of urban clusters has been more extensive, there are still some shortcomings. Existing studies on the carrying capacity mostly focus on individual elements, such as the carrying capacity of water resources [10], marine ecosystems [11], and land resources [12,13], while there are fewer studies on the comprehensive carrying capacity of multiple elements and a perfect theoretical system has not been formed. Research on the urban carrying capacity is mostly focused on individual cities [14], less on urban clusters, and the existing research is not extensive enough for the prediction of urban agglomeration. System dynamics, as a science linking nature and society, has great advantages in solving socioeconomic and resource–environmental problems and, therefore, has a wide range of applications in carrying capacity [15–17].

As the largest area in terms of population and economic development in Western China, the CCUA plays an important role in supporting national strategies, such as western development, the construction of the Yangtze River Economic Belt, and the Belt and Road Initiative. This study systematically analyzes the ECC of the CCUA based on "the comprehensive carrying capacity", which is not limited to one factor or a specific city, but takes into account social construction, foreign exchange, and rights. It also constructs an index system and acts as an extension of the existing carrying capacity research theory.

In 2019, the Central Committee of the Communist Party of China and the State Council issued a number of opinions on establishing a territorial spatial planning system and on supervising its implementation. This would establish a unified system of territorial spatial planning based on regional resources and the environmental carrying capacity. By measuring the competitiveness of industrial green development in the CCUA, Y. X. [18] found that the industrial structure of most areas in the CCUA was inefficient, it had excessive energy consumption, and had prominent human–nature conflicts; Y. L. [19] analyzed the green development efficiency of different urban agglomerations in China and found that the regional synergy of green development in the CCUA was poor and the industrial structure was outdated. The CCUA has not yet formed a reasonable green development pattern.

This paper focuses on the CCUA as the study subject, determines the index system using the PSR model and AHP-TOPSIS, evaluates the ECC of the CCUA from 2000 to 2018, and establishes a system dynamics model in order to predict the future ECC index, which refers to the mainstream research SSPs for the international prediction of future socioeconomic scenarios, assuming that the ECC performance of the CCUA is believed to be better following the sustainable development path (SSP1). Based on the studies of many research institutions and scholars, the future simulation scenario is set by combining historical data and regional characteristics. The index weights were redefined according to the predicted data in order to estimate the future ECC of the CCUA following the SSPs and provide policy suggestions and scientific support for the future planning and economic and social developments of the CCUA.

2. Research Scope and Methodology

2.1. Study Area

According to the CCUA Development Plan, approved by the State Council in 2016, the CCUA covers 27 districts (counties) in Chongqing and 15 cities in Sichuan Province. The CCUA is located in the upper Yangtze River Basin at a longitude of 102~110° E and latitude of 27~33° N and covers a total area of 185,000 km^2 (Figure 1).

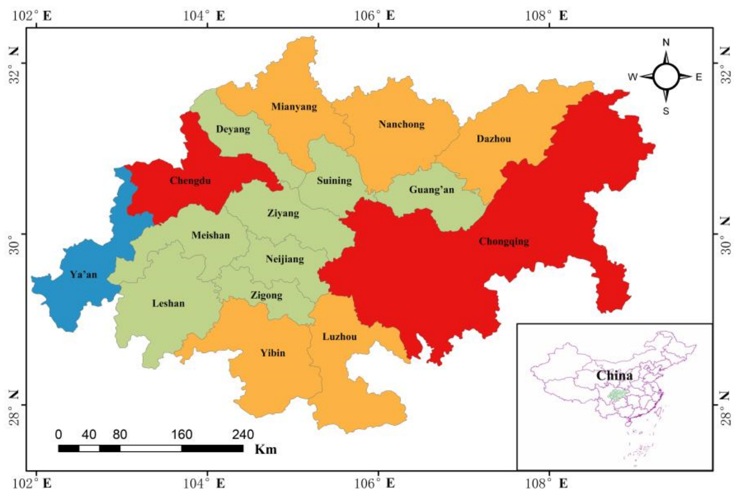

Figure 1. Map of the study area.

It is characterized by a subtropical monsoon climate, with hot summers, warm winters, and abundant precipitation. It had a population of about 95 million and a total GDP of 5.7 trillion in 2018, accounting for 6.8% and 6.4% of the country, respectively, making it the largest urban agglomeration and an important pole of economic growth in Western China [20]. At present, the CCUA has formed a "dual-core spatial structure", which forms the main axis of the Chengdu-Chongqing development, strengthening its radiation and connecting small- and medium-sized cities. The spatial development pattern of "one axis, two belts, two cores, and three districts" was formed through the development of integrated water and land transportation networks [21].

2.2. Index System and Data Sources

The pressure–state–response (PSR) model is an institutional framework based on the interaction between people and the environment, developed by the Organization for Economic Cooperation and Development (OECD) and the United Nations Environment Programme (UNEP) for the study of environmental issues [22]. Based on the principles of scientificity, representativeness, comprehensiveness, regionality, and operability, this study established the PSR model as the framework and considered various factors, such as socioeconomic, ecological, and resource endowments. It then refers to the ECC index system of other scholars and combines the characteristics of the research area to construct the ECC evaluation index system [23].

The socioeconomic data in this study are obtained from the China Urban Statistical Yearbook, the China Regional Economic Statistical Yearbook, the China Environmental Statistical Yearbook, the Sichuan Provincial Statistical Yearbook, the Chongqing Statistical Yearbook, the 2000–2018 Statistical Yearbook, the Water Resources Bulletin, the Ecological and Environmental Quality Bulletin, the Natural Resources Bulletin, and the National Economic and Social Development Statistical Bulletin of each county and city. Meteorological data were obtained from the China Meteorological Forcing Dataset (CMFD), while land use data were obtained from the CCI-LC project of the European Space Agency. The indicators were selected from authoritative data published by the local government or administration and the inter-index multicollinearity was eliminated by using the multiple linear regression method. Then, a regression analysis of the indicators was performed using SPSS software and the SD model was established. The system consists of the target, criterion, and indicator layer. In particular, the target layer represents the ECC, the criterion layer constitutes the pressure, state, and response layer, and the indicator layer consists of 27 specific indicators.

2.3. AHP-TOPSIS Method for Determining Index Weight

2.3.1. Data Standardization

In order to eliminate the effects of different magnitudes and orders of magnitude among the indicators, this study uses the extreme difference standardization method to standardize the raw data as follows:

$$\text{Positive index}: \ x'_{ij} = \frac{(x_{ij} - \min(x_{ij}))}{(\max(x_{ij}) - \min(x_{ij}))} \tag{1}$$

$$\text{Negative index}: \ x'_{ij} = \frac{(\max(x_{ij}) - x_{ij})}{(\max(x_{ij}) - \min(x_{ij}))} \tag{2}$$

where x'_{ij} is the normalized value, x_{ij} is the *i*-th value of the *j*-th indicator, and $\max(x_{ij})$ and $\min(x_{ij})$ are the maximum and minimum values corresponding to the *j*-th indicator, respectively.

2.3.2. Analytic Hierarchy Process

The analytic hierarchy process (AHP) is a multi-objective planning method that combines qualitative and quantitative analysis, due to its ability to divide complex problems into interconnected and ordered levels for the PSR model. The method is also able to reflect the analysis of people's judgments about each factor, increasing empirical reliability. Initial weights were first obtained using AHP.

1. Construction of the judgment matrix. In this study, by consulting a number of experts, all indicators in the ecological environment carrying capacity index system are scored according to importance and the relative importance is expressed by values from 1 to 9; the two-by-two comparison forms the judgment matrix. As a result, the indicator value a_{ij} and the judgment matrix A are obtained.
2. Calculate the nth product root of the elements in each row of the judgment matrix as follows:

$$W_{\mathrm{i}} = \sqrt[n]{\prod_{i=1}^{n} a_{ij}} \tag{3}$$

3. Regularization and normalization of the vector W_i as follows:

$$W'_{\mathrm{i}} = \frac{W_{\mathrm{i}}}{\sum\limits_{j=1}^{n} W} \tag{4}$$

   where W'_{i} is the weight value of the indicator.
4. The maximum eigenvalue is calculated as follows:

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i} \tag{5}$$

5. Consistency check

Calculate the consistency index, CI $= \frac{\lambda_{\max}}{n-1}$, search the table to get the random consistency index, calculate the consistency ratio, $CR = \frac{CI}{RI}$, and when $CR < 0.1$, the judgment matrix is considered to pass the consistency test.

2.3.3. TOPSIS

The entropy weighting method is an objective assignment method for a certain indicator. The entropy value is used to determine the dispersion degree of a certain indicator, i.e., the smaller the information entropy value, the greater the dispersion degree of the indicator and the greater the weight. The entropy weighting method can avoid factors of human interference in the process of assigning indicators [12], so that the evaluation results have objectivity and authenticity.

1. Data standardization

To ensure that the data are valid, the normalized values are calculated as $x''_{ij} = x'_{ij} \times 0.99 + 0.01$.

2. Calculate the entropy value of each indicator as follows:

$$\mathrm{f}_{ij} = \frac{x''_{ij}}{\sum\limits_{i=1}^{n} x''_{ij}} \tag{6}$$

$$H_j = -\frac{1}{\ln m} \sum_{j=1}^{m} f_{ij} \ln f_{ij} \tag{7}$$

   where f_{ij} is the weight of the indicator value for the *i*-th value of the *j*-th indicator and Hj is the entropy value of the *j*-th indicator.

3. Calculate the entropy weight of each index as follows:

$$\omega_j = \frac{1 - H_j}{\sum\limits_{j=1}^{n} (1 - H_j)} \tag{8}$$

where ω_j is the weight of the j-th indicator.

2.3.4. Combined Method for Weight Determination

The hierarchical analysis method is highly subjective and the weights determined by the entropy weighting method are completely determined by the relationship between the data, thus, ignoring the actual influence of the indicators and the importance that people attach to them. Accordingly, this study, based on the advantages and disadvantages of subjective and objective assignments and the research of other scientists, determined the final weights of the indicators comprehensively, which makes the assignment results more reliable and real, as well as more accurate for the quantification of the ecological environment carrying capacity. With m criterion layers and n indicator layers, each criterion layer contains $n1$, $n2$, ... , nk indicators, and the weight of the criterion layer is A = $a1$, $a2$, ... , am according to the hierarchical analysis, the weight of the indicator layer is B = $b1$, $b2$, ... , bn according to the entropy weight method, and the weight of the indicator layer is C = $c1$, $c2$, ... , cn.

1. Calculate the composite weight of the indicator layer as follows:

$$\tau_i = \frac{b_i c_i}{\sum\limits_{i=1}^{n} b_i c_i} \tag{9}$$

$$\mathrm{T} = \{\tau_1, \tau_2, \ldots, \tau_n\}$$

2. Normalization of the combined weights of the indicator layers under each criterion layer as follows:

$$\alpha_{ij} = \frac{\tau_{ij}}{\left(\sum\limits_{i=1}^{k} \tau_{ij}\right)}, k = n_{1,} n_2, \ldots, n_k \tag{10}$$

$$H = \{\alpha_{11}, \alpha_{12}, \ldots, \alpha_{1k}\ ,\ \alpha_{21}, \alpha_{22}, \ldots, \alpha_{2k}\ ,\ \ldots \alpha_{m1}, \alpha_{m2}, \ldots, \alpha_{mk}\}.$$

3. Calculate the weights of the criterion layer corresponding to the indicator layer as follows:

$$\alpha'_{ij} = \alpha_{ij} a_i, i = 1, 2, \ldots, m; j = 1, 2., \ldots, k. \tag{11}$$

$$\mathrm{H}' = \left\{\alpha_{11}{}', \alpha_{12}{}', \ldots, \alpha_{1k}{}'\ ,\ \alpha_{21}{}', \alpha_{22}{}', \ldots, \alpha_{2k}{}'\ ,\ \ldots \alpha_{m1}{}', \alpha_{m2}{}', \ldots, \alpha_{mk}{}'\right\}$$

4. Normalized calculation of the final weights as follows:

$$\omega_i = \frac{\alpha_i}{\sum\limits_{i=1}^{n} \alpha_i} \tag{12}$$

where ω_i is the weight of each indicator.

Then, the weight of each index in the ecological environment carrying capacity evaluation system is calculated and added in the column of the current ECC weight in Table 1.

Table 1. Weighting of the ECC indicators of the CCUA.

Target Layer	Guideline Layer	Weight	Indicator Layer	Current ECC Weight
ECC	Pressure layer B1	0.26	• Total population at the end of the year C1 (10,000 people)	0.013
			• GDP per capita C2 (yuan/person)	0.028
			• Total imports and exports C3 (USD billion)	0.026
			• Total energy consumption C4 (million tons of standard coal)	0.009
			• Total annual water supply C5 (million tons)	0.014
			• Total industrial wastewater discharge C6 (million tons)	0.169
	State layer B2	0.35	• GDP growth rate C7 (%)	0.031
			• Urbanization rate C8 (%)	0.022
			• Engel coefficient C9	0.023
			• Urban registered unemployment rate C10 (%)	0.015
			• Area of built-up area C11 (square kilometers)	0.086
			• Arable land per capita C12 (mu/person)	0.015
			• Energy consumption per unit of GDP C13 (tons of standard coal/million yuan)	0.020
			• Wastewater emissions per unit of industrial added value C14 (million tons/billion yuan)	0.017
			• Public green space per capita C15 (m^2/person)	0.103
			• Forest cover C16 (%)	0.004
			• The proportion of days with the air quality of grade 2 or higher to the number of days in the year C17 (%)	0.012
	Response layer B3	0.39	• Share of secondary sector in GDP C18 (%)	0.026
			• Tertiary sector share of GDP C19 (%)	0.029
			• Share of education spending in fiscal spending C20 (%)	0.021
			• Number of beds in health institutions per 10,000 people C21 (beds/10,000 people)	0.056
			• Public transportation vehicles per 10,000 people C22 (vehicles/10,000 people)	0.039
			• Road area owned per capita C23 (m^2/person)	0.061
			• Urban and rural residents' per capita disposable income ratio C24	0.023
			• The comprehensive utilization rate of industrial solid waste C25 (%)	0.105
			• Centralized sewage treatment rate C26 (%)	0.020
			• Greening coverage of built-up areas C27 (%)	0.010

3. Model Construction and Parameter Design

3.1. Model Construction

To further evaluate and predict the ECC of the CCUA and analyze its change trend, this study divided the ECC system into four subsystems, social, economic, environmental, and resource, according to the relationship between the ECC factors.

3.1.1. Model Boundary and Causal Analysis

The spatial boundary of the studied area is 16 cities in the CCUA. The time boundary is the period between 2000 and 2050 for several reasons. Firstly, many believe that China will become a strong, democratic, civilized, harmonious, and socialist modernization power by 2050. The administrative division of Chongqing was adjusted from 1995 to 2000, while the construction and migration of the Three Gorges Dam area occurred around the same time. Finally, some socioeconomic data differ greatly before and after 2000. The historical data and model simulation boundaries are the years 2000–2018 and 2021–2050, respectively. The time step is 1 year.

3.1.2. Model Construction and Testing

The system flow chart is based on the causality analysis from the previous section (Figure 2), which includes 62 variables consisting of 8 state variables (*L*), 8 rate variables (*R*), 8 constants (*C*), and 38 auxiliary variables (*A*).

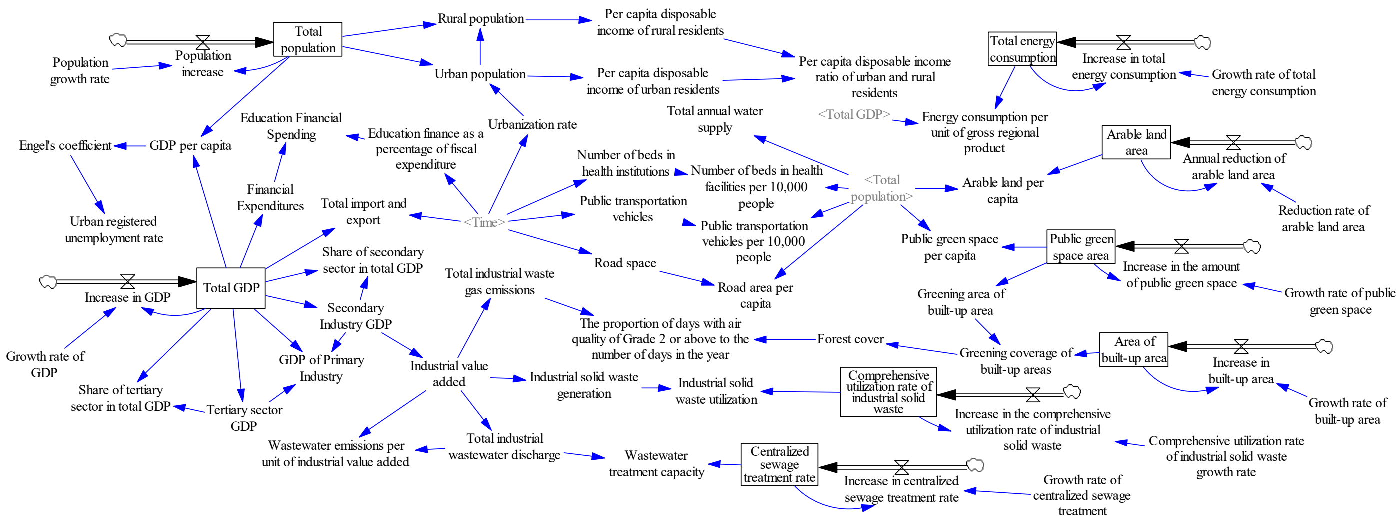

Figure 2. Ecological environment carrying capacity SD model of CCUA.

The system dynamics is modeled by the following equation.

1. State equation (*L*)

$$L(t) = L(t_0) + \int_0^t R(t)dt \tag{13}$$

where $L(t)$ is the value of the state variable L at time t and $L(t_0)$ is the value of the state variable L at time t_0.

2. Rate equation (*R*)

$$R(t) = g[L(t), a(t), e(t), c] \tag{14}$$

where $R(t)$ is the rate of change of the state variable, $a(t)$, $e(t)$ are the values of other variables related to this rate variable at time t, and c is a constant.

3. Auxiliary equation (*A*)

$$A(t) = f[L(t), A^*(t), e(t), c] \tag{15}$$

where $A(t)$ is the value of this auxiliary variable A at time t and $A^*(t)$ is the value of other auxiliary variables related to this auxiliary variable at time t.

4. Constant equation (*C*)

$$C(t) = c \tag{16}$$

where $C(t)$ is the value of the constant at time t.

According to the above formula, the model equation is established and shown in Appendix A and the SD model (Figure 2) is established by combining the logical relationship between the indicators and the actual situation and through the mathematical relationship between the variables, the regression analysis of SPSS software that was was developed by SPSS Inc and the table function in Vensim software (v.9.3.0) that was developed by Ventana Systems, Inc. (Harvard, MA, USA).

After the model was constructed, historical tests and sensitivity analysis were conducted to ensure the authenticity and validity of the model and the reasonableness and robustness of the results. The most important state variables in the system are total population, total GDP, total energy consumption, public green area, arable land area, built-up area, centralized sewage treatment rate, and comprehensive utilization rate of industrial solid waste. The historical test indicators represent the five auxiliary variables with more representative and complex feedback mechanisms: the total industrial wastewater discharge, the number of beds in health institutions, the forest coverage rate, the Engel coefficient, and the registered unemployment rate in cities. After comparing the simulated with the real data, the relative errors between them were basically less than $\pm$ 10% in all years. Somewhat larger relative errors caused by uncertainties in the individual years did not affect the response of the model to the system mechanism. Therefore, the trend of the simulated and real values was consistent in this study. Overall, all indicators passed the historical test, which further confirms the consistency between the simulation behavior of the model system and the real situation. Accordingly, it can be stated that the SD model passed the historical test. As a result, it carried out a reasonable and realistic simulation of the ECC system of the CCUA and predicted the evolution trend of the carrying capacity under different social development scenarios.

3.2. Determination of Decision Variables

Decision variables are the key elements in controlling the model behavior and the most critical factors in setting up simulation scenarios. In this study, the population growth rate, the GDP growth rate, the total energy consumption growth rate, the arable land area reduction rate, the public green space area growth rate, the built-up area growth rate, the centralized sewage treatment growth rate, and the comprehensive industrial solid waste utilization growth rate are included as decision variables because they determine the temporal cumulative effect of the most important state variables and can control the system development trend. The values of the decision variables are shown in Table 2.

Table 2. The statistical results of changes in the decision variables from 2000 to 2018.

Indicator Type	Current Value	Maximum Value	Minimum Value	Average Value
Population growth rate	0.006	0.018	0.001	0.003
Rate of GDP increase	0.075	0.248	0.075	0.143
The growth rate of total energy consumption	0.003	0.137	−0.055	0.046
The reduction rate of arable land area	−0.001	0.067	−0.045	−0.009
The growth rate of public green space	0.041	0.198	0.003	0.089
The growth rate of built-up area	0.057	0.216	0.035	0.057
The growth rate of centralized sewage treatment	0.006	0.021	−0.105	0.003
The comprehensive utilization rate of industrial solid waste growth rate	0.057	0.187	0.015	0.079

3.3. Determination of Program Parameters

Using the definitions and characteristics of the five SSPs to formulate the simulation scheme and combine the development characteristics of each indicator within its global development framework, this study calculated the trends and differences in the future development of the socioeconomic indicators of the CCUA. The results of existing studies on population, economy, energy use, resource status, environmental protection, and land use in China and the Chengdu-Chongqing region based on the SSPs [24–29] were considered to develop the simulation scheme for the CCUA under the same paths. This study especially considered the time nodes of future changes in data, such as population and economy and the degree of differences under different paths. This is combined with special national conditions, such as labor migration in China and the red line of arable land, and the "comprehensive two-child" and carbon emission policies, such as peaking CO_2 emissions by 2030 and the efforts to achieve carbon neutrality by 2060.

4. Results

4.1. Analysis of the Current State of the ECC

The three criterion layers and the overall ecological carrying capacity index of the 16 cities from 2000 to 2018 can be calculated according to the ecological carrying capacity evaluation model in the previous section (Figure 3). The ecological carrying capacity index of 16 cities in Chengdu-Chongqing urban agglomeration increased significantly over 24 years, with Chengdu and Chongqing leading the way.

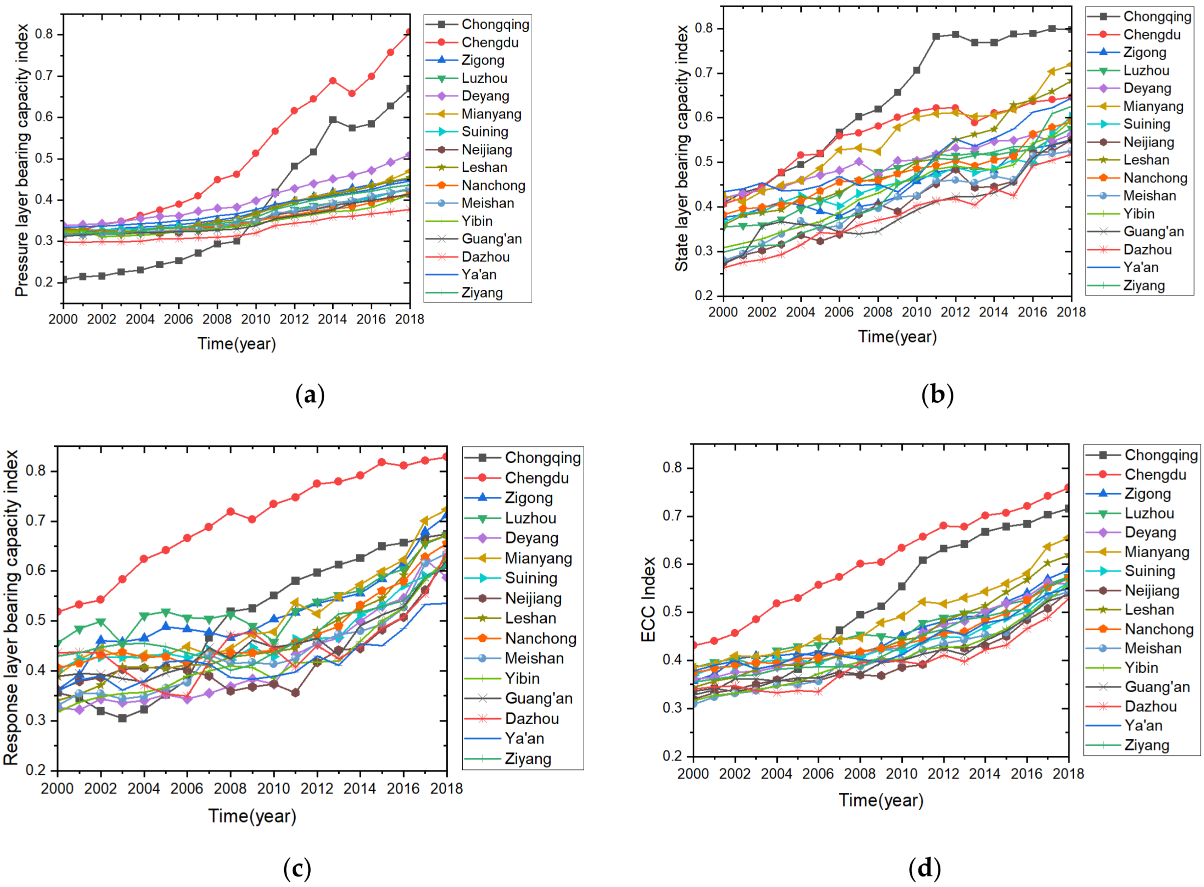

Figure 3. ECC of the CCUA from 2000 to 2018.

4.2. Analysis of the Main Indicators of the Simulation Program

The parameters in Table 3 are entered into the SD model. The predicted values of all indicators for 2021–2050 were obtained through simulation in the Vensim software. To thoroughly study the future development differences in the CCUA under each path, important representative indicators of the carrying capacity of each subsystem were selected to analyze their change trends. The indicators of the social subsystem were the total population and road surface per capita, those of the economic subsystem were the total GDP and per capita GDP, those of the resource subsystem were energy consumption per unit of GDP and arable land per capita, and those of the environmental subsystem were the green coverage of built-up areas and the total industrial wastewater discharge. Changes in each ECC index of the CCUA based on SSPs development are shown in Figure 4.

Table 3. Parameters of the simulation scheme based on the SSPs.

Indicator Type	Time	SSP1	SSP2	SSP3	SSP4	SSP5
Population growth rate	2019–2025	0.003	0.006	0.008	0.005	0.003
	2026–2030	0.003	0.006	0.008	−0.007	0.003
	2031–2035	−0.006	−0.005	0.008	−0.007	−0.0065
	2036–2050	−0.006	−0.005	−0.003	−0.007	−0.0065
Rate of GDP increase	2019–2025	0.065	0.06	0.05	0.06	0.065
	2026–2035	0.045	0.04	0.035	0.04	0.05
	2036–2050	0.03	0.03	0.02	0.02	0.04
The growth rate of total energy consumption	2019–2025	0.001	0.003	0.045	0.003	0.045
	2026–2030	−0.030	−0.020	0.045	−0.010	0.045
	2031–2050	−0.030	−0.020	−0.05	−0.010	−0.05
The reduction rate of arable land area	2019–2030	0.015	−0.001	−0.010	−0.009	−0.015
	2031–2050	0.015	0.010	−0.010	0.005	−0.015
The growth rate of public green space	2019–2050	0.100	0.041	0.003	0.041	0.003
The growth rate of built-up area	2019–2050	0.150	0.057	0.015	0.057	0.150
The growth rate of centralized sewage treatment	2019–2050	0.030	0.016	0.006	0.006	0.016
The comprehensive utilization rate of industrial solid waste growth rate	2019–2050	0.010	0.006	0.002	0.002	0.008

By analyzing the changes in the representative indicators of each subsystem in Figure 4, it was determined that the total population and total GDP in 2050 according to SSP1 will be 87.44 million and 21.50 trillion, respectively. The lowest total population was found in SSP4 with 82.65 million, while the highest total GDP was observed in SSP5 with 26.07 trillion. For all other indicators, SSP1 showed the best results, followed by SSP5, while SSP3 showed the worst results.

4.3. Analysis of Simulation Results

Considering the differences between the simulated values and the historical data and the entropy weight method based on the data calculation, the simulated values for the period 2021–2050 were finally selected in order to redetermine the index weights using the AHP-TOPSIS method.

The values of 27 indicators for 2021–2050 were obtained through the SD model simulation. The changes in the pressure, state, response layer, and the ECC index of the CCUA based on the five SSPs simulation scenarios were calculated using the ECC evaluation model (Figure 5).

It can be seen from Figure 5 that the carrying capacity indices of each criterion and target layer of the CCUA based on the five SSPs will show a continuously increasing trend from 2021 to 2050. The bearing capacity of the response layer will increase the most, while it will increase the least in the pressure layer. Furthermore, the state layer bearing capacity index of each path will vary greatly. By 2050, the bearing capacity index of the pressure layer will follow SSP5, SSP1, SSP2, SSP4, and SSP3 in order from high to low. The bearing capacity index of the state layer will follow SSP1, SSP5, SSP2, SSP4, and SSP3 in the same order. Finally, the bearing capacity index of the response layer will follow SSP1, SSP2, SSP5, SSP4, and SSP3 in the same order as the other two.

Each path is analyzed separately in this study. Firstly, SSP1 represents a sustainable development path. Its ECC index will have the highest position in 2050, rising to 0.45, which is 4.45-times higher than 0.17 in 2021. It can be seen that the growth rate of the ECC index will normally decrease with time and further development of SSP1.

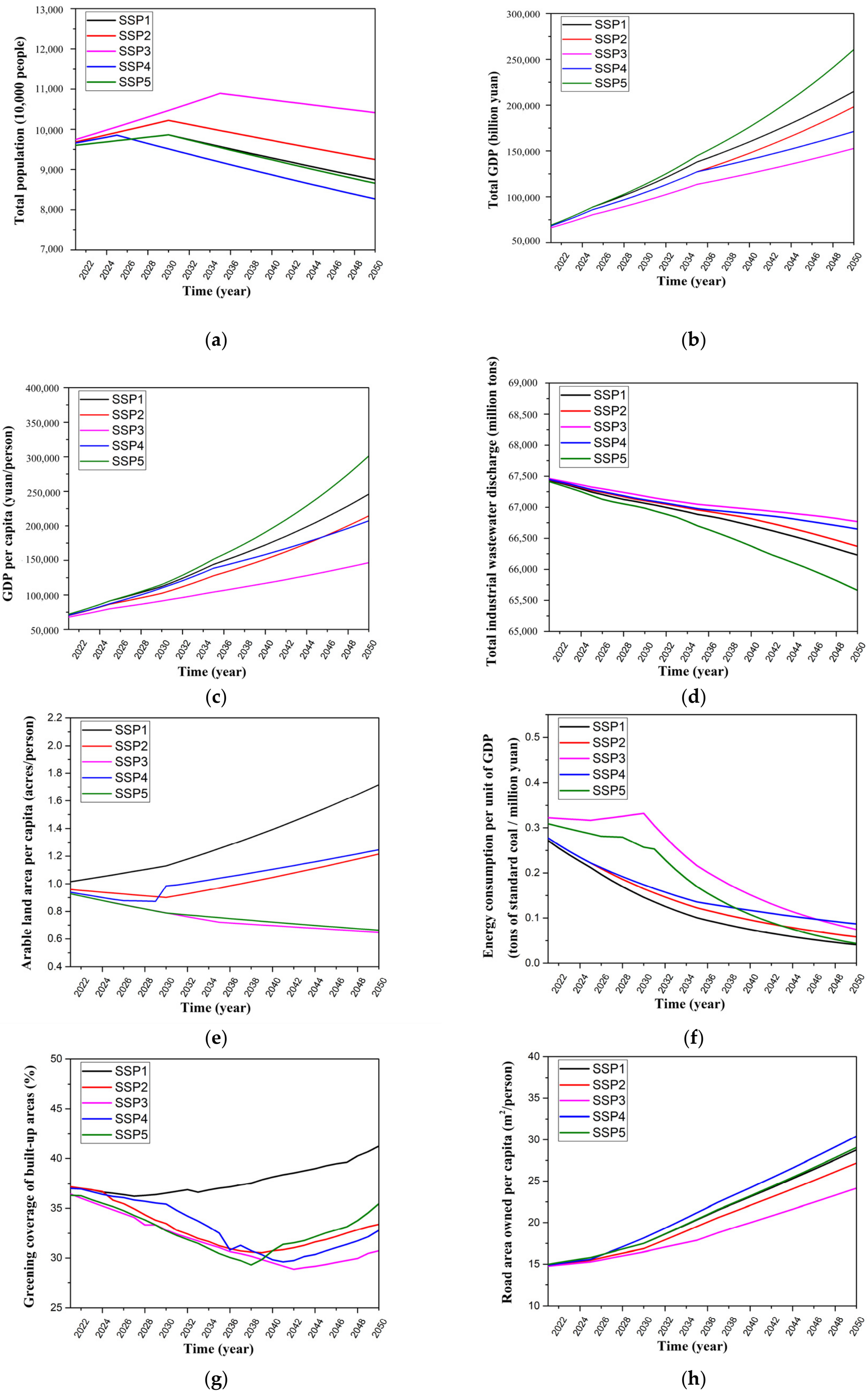

Figure 4. Changes in each ECC index of the CCUA under the SSPs.

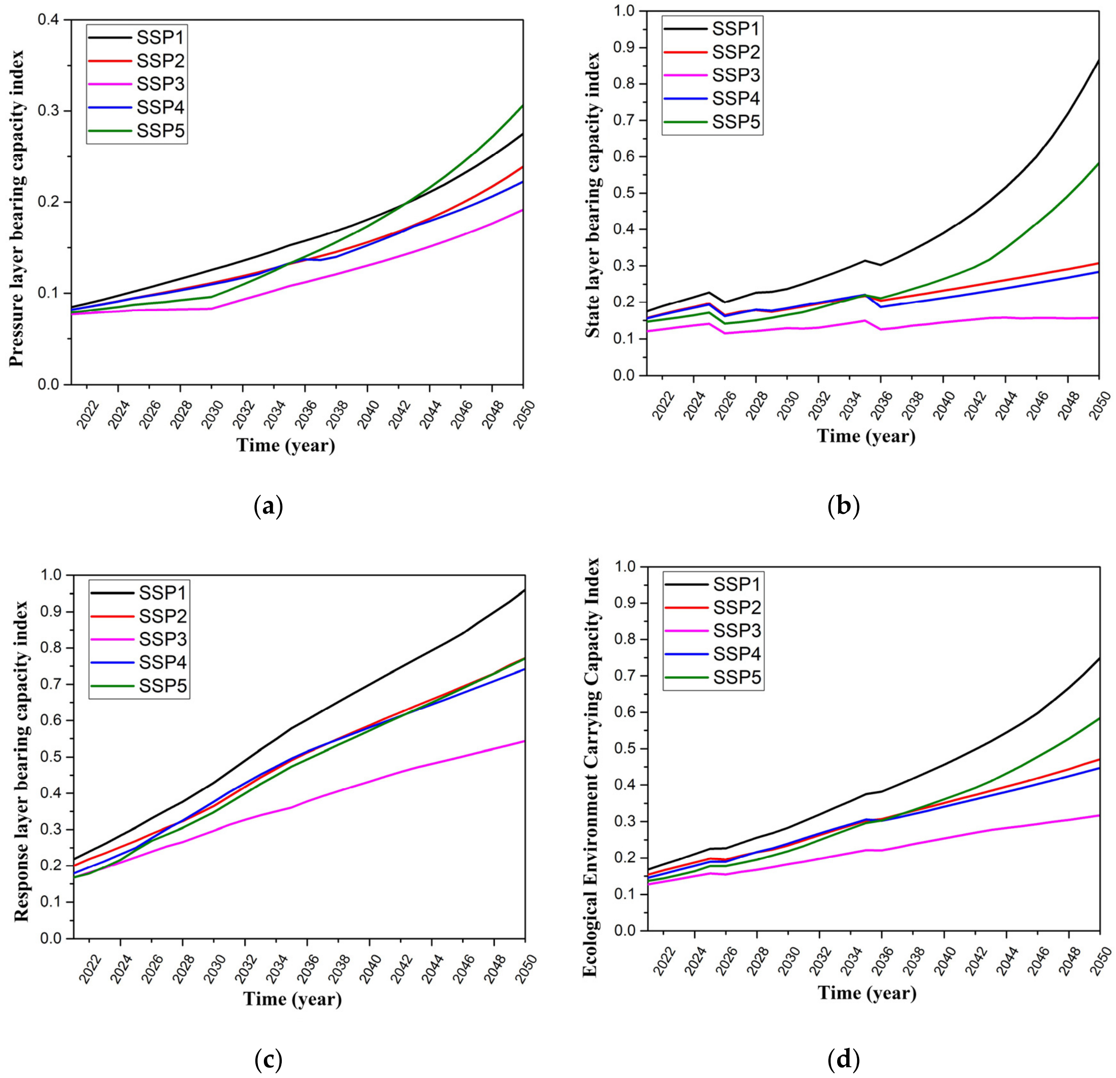

Figure 5. Changes in each criterion layer and the ECC index of the CCUA according to SSPs.

Secondly, SSP2 is an intermediate path that continues to develop and maintain the current development trend. Its ECC index will reach 0.47 in 2050, 3.06-times higher than that in 2020. It will rank third in terms of increase, with an average economic development rate, no breakthroughs in science and technology, and a continuous decrease in resources. However, SSP2 will face a certain degree of environmental pollution, representing the normal level of future development according to current trends.

SSP3 is the regional competition path. Its ECC index will reach 0.32 in 2050, increasing by 2.49-times compared to that in 2020. In addition, it will have the lowest growth rate and the worst ECC condition.

Furthermore, SSP4 is an unbalanced path. Its ECC index will reach 0.45 in 2050, increasing 3.07-times and it will rank fourth. Finally, SSP5 represents a fossil-fuel-based development path. Its ECC index will reach 5.35 in 2050, which is 4.26-times higher than that of SSP1 in 2021. It will rank second only to SSP1 and will keep increasing.

5. Discussion and Suggestions

5.1. Discussion

The ECC index of 16 cities in the CCUA has increased significantly in 18 years. Among them, Chengdu was in the leading position, increasing from 0.43 to 0.76, with an increase of 76.74%, indicating that its overall ecological bearing condition is better than other cities.

Chongqing, on the other hand, is the city with the largest increase in ECC index, from 0.34 to 0.72, an increase of 111.76%, especially from 2004 to 2011 and from 2007 onwards, significantly higher than other cities, except Chengdu; Chengdu became the first echelon, forming the "double core model" of the CCUA. The reason for this is that Chongqing has a very high growth rate in the "double core model". Accordingly, Chongqing began to develop rapidly in the "Eleventh Five-Year" Plan with its electronic information and automobile and motorcycle industries and the policies of light rail construction. The construction of the "Liangjiang New Area" strongly promoted regional economic development, with the economic growth rate remaining above 10% or even close to 20%. Mianyang has been stabilized at third position since 2009, which is in line with its status as the second largest city in Sichuan Province, while the rest of the cities are not too far apart and are at the second level overall. Among them, Dazhou has been ranked last since 2012, mainly due to high population pressure but a low level of economic development.

This study constructs an SD model and simulates and predicts the future ECC of CCUA based on SSPs' socioeconomic path. SSPs are an important component of climate change [30] that aim to accurately describe future social development paths, cover multiple development patterns in different regions of the world, and serve as a pathway to qualitatively and quantitatively describe different trends in social development without considering climate change or climate policies [31]. Therefore, SSPs can reflect future trends in socioeconomics under different development paths, which is why they have been widely used in population, energy, and economic forecasting studies [32,33]. Evaluation of ecological carrying capacity predictions through system dynamics is feasible [34].

In this study, the ECC is divided into four subsystems, namely, social subsystem, economic subsystem, environmental subsystem, and resource subsystem. We selected important representative carrying capacity indicators of each subsystem to discuss their changing trends (Figure 4). The selected indicators include total population and road area per capita of the social subsystem, total GDP and GDP per capita of the economic subsystem, energy consumption per unit GDP and arable land per capita of resource subsystem, as well as greening coverage of the built-up area and total industrial wastewater discharge of environmental subsystem.

The total population under all five SSP paths in the social subsystem shows an increasing and then decreasing trend, among which the total population under SSP3 path is the largest in 2050, reaching 104.1 million people; the road area per capita also shows an increasing trend. The total GDP and GDP per capita under each SSP path in the economic subsystem show increasing trends, which is in line with China's national development strategy, with the total GDP and GDP per capita under the SSP5 path growing the fastest.

The energy consumption per unit of GDP under each path in the resource subsystem generally shows a decreasing trend, among which the SSP3 path shows a slight increase from 2018 to 2031 and a significant decrease from 2031. The SSP5 path fluctuates and decreases from 2018 to 2031 with a smaller decrease; the changes in arable land area per capita under each path varies greatly, among which the SSP1 path shows a continuously increasing trend and accelerating growth rate. The SSP2 and SSP4 paths both show a decrease and then an increase in arable land area per capita, and SSP3 and SSP5 paths maintain a decreasing trend.

The ecological and environmental carrying capacity indices of the CCUA under the simulated development scenarios based on the five SSP paths all show a significant growth trend, indicating that the CCUA development under all five SSP paths improved the ecological and environmental carrying capacity. The growth trends of the ecological and environmental carrying capacity indices of the five simulation scenarios are relatively similar. All of them fluctuate slightly around 2025 and 2035 and become flatter, but then resume the upward trend, which is mainly caused by the different decrease magnitudes in economic growth rates at these two time points. Among them, the ECC index of CCUA under the development of the SSP1 path is always the highest, while the ECC index under the development of the SSP3 path is always at the lowest level and with the slowest growth rate. The ECC index under the development of SSP2, SSP4, and SSP5 paths is closer between 2021 and 2035 and SSP5 path is the lowest. After 2035, the ECC index under the SSP5 path increases steeply and starts to be significantly higher than SSP2 and SSP4 around 2040, which is second only to SSP1. The ECC index under the SSP2 and SSP4 paths does not increase significantly and maintains the original rate of steady increase. However, the SSP2 path starts to be higher than the SSP4 path around 2039 and the gap widens slightly but is still the closest. In summary, the ecological carrying capacity of the Chengdu-Chongqing urban agglomeration is not best developed under a single SSP1 path, but in combination with other socioeconomic paths.

5.2. Limitations and Recommendations for Future Work

The limitations of this study are worth acknowledging. First, the construction of the SD model of ecological and environmental carrying capacity system should be dynamic in the long term. Limited by the availability of data, it is simplified in variable settings and less consideration is given to the energy exchange between urban agglomerations and the outside. The structure of the model and the setting of parameters and equations should be further deepened in subsequent work. Second, the existing SSP path development forecasts are country based and less province based. This study combines the real situation of CCUA and mainly refers to domestic forecasts for Sichuan Province and Chengdu City based on SSP paths and other forecasting studies on China's future development in terms of population growth and economic development rate. The decision variables are not detailed enough and in the subsequent research, the possible development trend of CCUA should be considered more deeply and the parameter setting for the indicators can be more refined.

5.3. Suggestions

The following recommendations are proposed to enhance the ecological and environmental carrying capacity of the CCUA:

1. The future development pattern of the CCUA should be dominated by the characteristics of the SSP1 path and the development characteristics of the SSP5 path and SSP2 path should be adopted in some aspect or periods, while taking care to avoid the development characteristics of the SSP3 path.
2. According to the current actual situation, the CCUA cannot be developed according to the SSP1 path in the short term, so it is suggested that it should develop according to the SSP2 path from 2021 to 2025. Based on the basic continuation of the current development trend, it should gradually change to a sustainable development mode and continuously improve its development level.
3. Further, 2026–2035 is a critical period for China to realize socialist modernization. Based on the gradual transformation of the development mode from 2021 to 2025, this period must formally transform the development mode and truly achieve sustainable development, so that the CCUA should develop according to the SSP1 path in this period.
4. Then, 2036–2050 is the sprint stage for China to fully build a rich, strong, democratic, civilized, harmonious, and green socialist modern country. In this period, the CCUA continues to develop according to the SSP1 path, while some levels refer to the development characteristics of the SSP5 path.
5. The development characteristics of the SSP3 and SSP4 paths should be strongly avoided in the future development of the CCUA.

6. Conclusions

This paper took the CCUA as the study area. For the research, it collected various socioeconomic, precipitation, temperature, and land use data from 16 cities in the CCUA in the period of 2000–2018. Then, it established the ECC evaluation index system based on the PSR model and constructed an SD model of the ECC of the CCUA. Afterward, it set up a simulation scheme based on SSPs, simulated each ECC index of the urban agglomeration from 2021 to 2050, and selected simulation data to redefine the index weights. This study analyzed the changing trend of the ECC of the CCUA and the future carrying capacity of each criterion layer under each SSP. Lastly, it suggested policy interventions for the future development of the CCUA. The study came to the following conclusions:

1. An ECC evaluation system containing 27 indicators is constructed and AHP-TOPSIS is used to determine the index weights and evaluate the ECC of the CCUA from 2000 to 2018. The ECC indices of 16 cities in the CCUA all increased significantly in 18 years, among which Chengdu and Chongqing were in the leading positions, forming the twin core model of the CCUA.
2. This study establishes the SD model of the ECC of the CCUA, which objectively reflects the relationship between social, economic, environmental, and economic subsystems. Through the consistency test, it was found that the simulated values are within 10% of the historical data, the model can accurately respond to the evolution of the system, and the results are valid.
3. Based on SSPs' socioeconomic paths, this study obtained the ecological and environmental carrying capacity index of the CCUA in the period 2019–2050 using the SD model simulation. It was found that the ecological and environmental carrying capacity indices based on the five SSP paths all showed obvious growth trends and relatively similar curves, with slight fluctuations in 2025 and 2035. By 2050, the ecological and environmental carrying capacity indices of the paths SSP1, SSP5, SSP2, SSP4, and SSP3 are from high to low in order.
4. Through the analysis, this study believes that the CCUA should adopt the most suitable development approach in different periods, among which 2021–2025 should be developed according to the SSP2 path, 2026–2035 should be developed according to the SSP1 path, and 2036–2050 should continue to develop according to the SSP1 path based on the development characteristics of the SSP5 path at some reference levels. In addition, the SSP3 and SSP4 paths should be avoided in future CCUA development due to their poor performance in the future ecological environment carrying capacity simulation.

Author Contributions: Conceptualization, X.C., L.Z., T.W. and Y.X.; writing—original draft preparation, X.C. and T.W.; writing—review and editing, L.Z. and Y.X.; supervision, L.Z. and Y.X.; funding acquisition, Y.X. and J.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (Major Project) (No. 41890824).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Equations for the ecosystem dynamics model of the ECC.

Subsystem	System Equations
Social subsystem	• Total population = INTEG (population increase, present value of total population) • Population growth = total population × population growth rate • Urban population = total population × urbanization rate • Rural population = total population − urban population • Road area per capita = urban road area/total population • Public transportation vehicles per 10,000 people = Public transportation vehicles/total population • Number of beds in health facilities per 10,000 people = Number of beds in health facilities/total population • Per capita, disposable income ratio of urban and rural residents = per capita disposable income of urban residents/per capita disposable income of rural residents

Table A1. *Cont.*

Subsystem	System Equations
Economic subsystem	• Total GDP = INTEG (increase in GDP, the present value of total GDP) • Increase in GDP = Total GDP × Rate of GDP increase • GDP per capita = total GDP × 10,000/total population • Share of tertiary sector in total GDP = Tertiary sector GDP/Total GDP • Share of secondary sector in total GDP = Secondary Industry GDP/Total GDP • GDP of Primary Industry = Total GDP − Secondary Industry GDP − Tertiary sector GDP • Total imports and exports = IF THEN ELSE (Time > 2018, Total GDP × (0.002 × (Time - 2018)3 - 0.026 × (Time − 2018)2 + 0.393 × (Time − 2018) + 21.653)/6.5/100, 6.19 × 10^{-5} × (Total GDP $^{1.573}$)) • Fiscal expenditure on education = Fiscal expenditure × Fiscal expenditure on education as a percentage of fiscal expenditure
Resource subsystem	• Arable land area = INTEG (-Arable land reduction, the present value of arable land area) • Annual reduction of arable land area = arable land area × reduction rate of arable land area • Arable land per capita = Arable land area × 15/total population/10,000 • Built-up area = INTEG (increase in the built-up area, the present value of built-up area) • Built-up area increase = built-up area × built-up area growth rate • Total energy consumption = INTEG (increase in total energy consumption, the present value of total energy consumption) • Increase in total energy consumption = total energy consumption × growth rate of total energy consumption • Energy consumption per unit of gross regional product = total energy consumption/total GDP
Environmental subsystem	• Public green space area = INTEG (increase in the public green space area, the present value of public green space area) • Increase in public green space area = public green space area × growth rate of public green space area • Public green space per capita = public green space/total population • Greening coverage rate of built-up area = greening area of built-up area/area of built-up area × 100 • Centralized sewage treatment rate = INTEG (IFTHENELSE (centralized sewage treatment rate ≥ 1, centralized sewage treatment rate = 0.99, centralized sewage treatment rate increase), centralized sewage treatment rate present value) • Centralized sewage treatment rate increase = centralized sewage treatment rate × centralized sewage treatment rate growth rate • Sewage treatment volume = total industrial wastewater discharge × centralized sewage treatment rate • The integrated utilization rate of industrial solid waste = INTEG (IFTHENELSE (integrated utilization rate of industrial solid waste ≥ 1, integrated utilization rate of industrial solid waste = 0.99, integrated utilization rate of industrial solid waste increase), the present value of integrated utilization rate of industrial solid waste) • Increase in the comprehensive utilization rate of industrial solid waste = comprehensive utilization rate of industrial solid waste × comprehensive utilization rate of industrial solid waste growth rate • Industrial solid waste utilization = industrial solid waste generation × comprehensive utilization rate of industrial solid waste

References

1. Peng, B.; Li, Y.; Elahi, E.; Wei, G. Dynamic evolution of ecological carrying capacity based on the ecological footprint theory: A case study of Jiangsu province. *Ecol. Indic.* **2018**, *99*, 19–26. [CrossRef]
2. Mealy, P.; Teytelboym, A. Economic complexity and the green economy. *Res. Policy* **2020**, *49*, 103948. [CrossRef]
3. Delitheou, V.; Meleti, V.; Athanassopoulos, C.G.E. Green economy and smart city. *J. Reliab. Intell. Environ.* **2019**, *5*, 235–240. [CrossRef]
4. Pitkänen, K.; Antikainen, R.; Droste, N.; Loiseau, E.; Saikku, L.; Aissani, L.; Hansjürgens, B.; Kuikman, P.J.; Leskinen, P.; Thomsen, M.; et al. What can be learned from practical cases of green economy? -studies from five European countries. *J. Clean. Prod.* **2016**, *139*, 666–676. [CrossRef]
5. Borel-Saladin, J.M.; Turok, I.N. The Green Economy: Incremental Change or Transformation? *Environ. Policy Gov.* **2013**, *23*, 209–220. [CrossRef]
6. Buseth, J.T. The green economy in Tanzania: From global discourses to institutionalization. *Geoforum* **2017**, *86*, 42–52. [CrossRef]
7. Wu, X.; Hu, F. Analysis of ecological carrying capacity using a fuzzy comprehensive evaluation method. *Ecol. Indic.* **2020**, *113*, 106243. [CrossRef]
8. Dai, D.; Sun, M.; Xu, X.; Lei, K. Assessment of the water resource carrying capacity based on the ecological footprint: A case study in Zhangjiakou City, North China. *Environ. Sci. Pollut. Res.* **2019**, *26*, 11000–11011. [CrossRef]
9. Wu, T.; Sang, S.; Wang, S.; Yang, Y.; Li, M. Remote sensing assessment and spatiotemporal variations analysis of ecological carrying capacity in the Aral Sea Basin. *Sci. Total Environ.* **2020**, *735*, 139562. [CrossRef]

10. Zomorodian, M.; Lai, S.H.; Homayounfar, M.; Ibrahim, S.; Fatemi, E.; El-Shafie, A. The state-of-the-art system dynamics application in integrated water resources modeling. *J. Environ. Manag.* **2018**, *227*, 294–304. [CrossRef]
11. Ma, P.; Ye, G.; Peng, X.; Liu, J.; Qi, J.; Jia, S. Development of an index system for evaluation of ecological carrying capacity of marine ecosystems. *Ocean Coast. Manag.* **2017**, *144*, 23–30. [CrossRef]
12. Wang, D.; Shi, Y.; Wan, K. Integrated evaluation of the carrying capacities of mineral resource-based cities considering synergy between subsystems. *Ecol. Indic.* **2020**, *108*, 105701. [CrossRef]
13. Liao, S.; Wu, Y.; Wong, S.W.; Shen, L. Provincial perspective analysis on the coordination between urbanization growth and resource environment carrying capacity (RECC) in China. *Sci. Total Environ.* **2020**, *730*, 138964. [CrossRef]
14. Zhang, M.; Liu, Y.; Wu, J.; Wang, T. Index system of urban resource and environment carrying capacity based on ecological civilization. *Environ. Impact Assess. Rev.* **2018**, *68*, 90–97. [CrossRef]
15. Bu, J.; Li, C.; Wang, X.; Zhang, Y.; Yang, Z. Assessment and prediction of the water ecological carrying capacity in Changzhou city, China. *J. Clean. Prod.* **2020**, *277*, 123988. [CrossRef]
16. Wang, G.; Xiao, C.; Qi, Z.; Meng, F.; Liang, X. Development tendency analysis for the water resource carrying capacity based on system dy-namics model and the im-proved fuzzy comprehensive evaluation method in the Changchun city, China. *Ecol. Indic.* **2021**, *122*, 10732. [CrossRef]
17. Wang, Y.; Zhou, X.; Engel, B. Water environment carrying capacity in Bosten Lake basin. *J. Clean. Prod.* **2018**, *199*, 574–583. [CrossRef]
18. Xiao, Y. Analysis on the Measurement and Spatial and Temporal Evolution of the Competitiveness of Industrial Green Development in Chengdu-Chongqing City Cluster. Ph.D. Thesis, Chengdu University of Technology, Chengdu, China, 2019.
19. Liang, Y.; Liu, Y.; Yang, J. Evaluation of green development efficiency and equilibrium characteristics of urban agglomerations in China. *Econ. Geogr.* **2019**, *39*, 110–111.
20. Huang, L.; Wu, C. Study on the efficiency of green development of urban industries in Yangtze River Economic Zone and its spatial driving mechanism. *China Popul. Resour. Environ.* **2019**, *29*, 40–49.
21. Wu, C.; Huang, L. Research on the performance assessment of industrial green development in Yangtze River Economic Belt and its synergistic effect. *J. China Univ. Geosci. Soc. Sci. Ed.* **2018**, *18*, 46–55.
22. Couvet, H.L.C.K.; Weber, J. OECD pressure–state–response indicators for managing biodiversity: A realistic perspective for a French biosphere reserve. *Biodivers. Conserv.* **2009**, *18*, 1719–1732.
23. Verma, P.; Raghubanshi, A.S. Urban sustainability indicators: Challenges and opportunities. *Ecol. Indic.* **2018**, *93*, 282–291. [CrossRef]
24. Kc, S.; Lutz, W. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Glob. Environ. Change* **2017**, *42*, 181–192. [CrossRef] [PubMed]
25. O'Neill, B.C.; Kriegler, E.; Ebi, K.L.; Kemp-Benedict, E.; Riahi, K.; Rothman, D.S.; van Ruijven, B.J.; van Vuuren, D.P.; Birkmann, J.; Kok, K.; et al. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Change* **2017**, *42*, 169–180. [CrossRef]
26. Leimbach, M.; Kriegler, E.; Roming, N.; Schwanitz, J. Future growth patterns of world regions–A GDP scenario approach. *Glob. Environ. Change* **2017**, *42*, 215–225. [CrossRef]
27. Jiang, L.; O'Neill, B.C. Global urbanization projections for the Shared Socioeconomic Pathways. *Glob. Environ. Change* **2017**, *42*, 193–199. [CrossRef]
28. Dellink, R.; Chateau, J.; Lanzi, E.; Magné, B. Long-term economic growth projections in the Shared Socioeconomic Pathways. *Glob. Environ. Change* **2017**, *42*, 200–214. [CrossRef]
29. Crespo Cuaresma, J. Income projections for climate change research: A framework based on human capital dynamics. *Glob. Environ. Change* **2017**, *42*, 226–236. [CrossRef]
30. Moss, R.H.; Edmonds, J.A.; Hibbard, K.A.; Manning, M.R.; Rose, S.K.; Van Vuuren, D.P.; Carter, T.R.; Emori, S.; Kainuma, M.; Kram, T.; et al. The next generation of scenarios for climate change research and assessment. *Nature* **2010**, *463*, 747–756. [CrossRef]
31. Hallegatte, E.K.J.E.; Riahi, K.L.E.T.; van Vuuren, H.W.D.P. A new scenario framework for climate change researchthe concept of shared climate policy assumptions. *Clim. Change* **2014**, *122*, 401–414.
32. Hegre, H.; Buhaug, H.; Calvin, K.V.; Nordkvelle, J.; Waldhoff, S.T.; Gilmore, E. Forecasting civil conflict along the shared socioeconomic pathways. *Environ. Res. Lett.* **2016**, *11*, 54002–54009. [CrossRef]
33. Riahi, K.V.V.D.P. The Shared Socioeconomic Pathways and their energy, land use, andgreenhouse gas emissions implications An overview. *Glob. Environ. Change* **2017**, *42*, 153–168. [CrossRef]
34. Ying, H.; Chen, S.; Mao, Y. Research on Marine Ecological Carrying Capacity of Ningbo City in China Based on System Dynamics. *Sustainability* **2022**, *14*, 4568. [CrossRef]