

Article

The Driving Role of Food and Cultivated Land Resource in Balancing the Complex Urban System of Socio-Economy and Environment: A Case Study of Shanghai City in China

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Abstract: Food is increasingly seen as a vehicle to address complex sustainability challenges, where the quantitative driving role in balancing the complex urban system of socio-economy and environment is still a gap. To fill this gap, taking Shanghai city as an example, this paper utilizes system dynamics to innovatively set three policy scenarios that aim at adjusting food security and cultivated land resources. The results confirm their positive role in socioeconomic and environmental improvement and coordinated development. In the high-rate grain yield growth scenario, the labor force ratio of the primary industry increases back to the size of 2012 (4.1%), the proportion of the primary industrial investment grows at twice the rate of the current trend, the grain yield per unit area increases back to the capacity of 1997 (798.154 t/km²), and simultaneously, the occupation of cultivated land resources by the secondary industry and the negative impact of environmental pollution on productivity are mitigated. In that case, the coordination level between the socio-economy and the environment can keep increasing. The results indicate that future urban planning should increase the input of labor force and assets in the primary industry, improve food productivity per unit area through technical means or person training, alleviate the occupation of cultivated land resources by the secondary industry, and mitigate the negative impact of environmental pollution on cultivated land productivity.

Keywords: role of food and cultivated land resource; sustainable development; coordination development; socio-economy and environment; Shanghai city



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1. Introduction

Humans have entered the urban century [1]. The scale of the urban population worldwide reached 4.22 billion in 2018 and will keep growing to 6.68 billion in 2050 [2]. Urban development simultaneously creates more than 75% of the global GDP and contributes to 75% of energy-based carbon emissions [3]. Therefore, the urban population is the protagonist in the challenge for achieving sustainable development, as it carries most human activities connected with environmental crises and resource depletion. The New Urban Agenda at the Habitat III conference emphasized the role of cities as engines for sustainable development [4]. The knowledge about a sustainable future from an urban perspective should be central, and building a global urban science is essential [5]. Therefore, research on urban-scale development is of great significance for sustainable goals and science.

Further, realizing sustainable goals is not only the independent progress of each goal but, more importantly, to combat undesirable interactions, conflicts, and impacts, which can exactly be reflected in system analysis [6]. The urban system is a complex system and seeks systematic thinking [7]. System approaches can reduce negative surprises and promote integrated planning, management, and governance [8]. Therefore, it has been a research priority for some scholars to fully connect the urban socioeconomic and environmental systems and understand their dynamic interplay and feedback [9].

Among elements in different subsystems of complex urban system models, the resource mainly covers water resources [10,11], energy resources [12], nonrenewable and renewable resources [13], land use [14,15], and land development [16]. However, rapid urban development and sprawl are also threatening agricultural sustainability [17]. Although making cities sustainable is a global determination, little attention has been paid by the government to agriculture due to the belief that the highest benefit use of land is not on agriculture; this may result from a lack of the literature on the precise role of urban agriculture in building sustainable cities [18]. Therefore, considering the cultivated land elements in the complex urban system is of great theoretical significance.

A few studies on urban development take cultivated land resources and grain output into account [19]. Tapia et al. evaluated urban sustainability in Arhus based on an indicator framework that includes urban agriculture and food security [20]. Nigussie et al. analyzed the capacity and suitability of urban farmland in Ethiopia to contribute to sustainable development [21]. Tong et al. explored the manner to optimize urban food production in Tucson, a semi-arid region [22]. Xia et al. quantified the dynamics of green infrastructure in agriculture in Zhengzhou from the perspective of ecological security and food security [23]. Clerino et al. examined the practices for the sustainability assessment of professional urban agriculture [24]. Gozdziejewicz-Biechonska et al. analyzed theoretical frameworks and practices for protecting agricultural land use [25]. These studies consider the element role of cultivated land and grain in sustainability. However, there is still a gap in their driving role in the coordinated development of complex urban systems.

Indeed, food is increasingly being regarded as a vehicle to simultaneously address economic, social, and environmental dilemmas [26]. Urban agriculture is recognized as a potential contributor to more sustainable development at the city level as it promotes food security and food sovereignty [27]. It is also lauded for its potential positive impacts on all three pillars of sustainability [18]. However, the effect of agriculture on the urban scale can be conflicting as good or bad [28]. The positive impacts include enhancing dietary diversity and improving ecosystem services and social quality [18,29,30], while the negative impacts are also stressed by some critics [27,31]. These arguments make it urgent to identify the role of food and cultivated land resources in the coordinated development of complex urban systems. In addition, although food resources for a metropolis can basically be supplied through trade with neighboring regions, the risk of public health events and natural disasters should be considered, and urban farming should be emphasized to increase food safety [32].

To sum up, this paper aims to fill the gap of the quantitative driving role of food and cultivated land resource in balancing the complex urban system of the socio-economy and the environment. Taking Shanghai city as an example, the system dynamics model is applied to simulate complex urban system development. Different scenarios are set to adjust the conditions of food and cultivated land resource and forecast the coordination level. According to the simulation results, suggestions for more sustainable and coordinated development are proposed from the perspectives of food security and cultivated land protection.

2. Methods and Study Area

2.1. System Dynamics Model

This paper applies system dynamics, which is an effective method for developing an understanding of complex systems [33]. This method can incorporate various elements of different subsystems in an integrated model, and the feedback loop can quickly seize the complex interactions [13]. In addition, scenario simulation is a good tool for policy or scheme analysis [10,34]. Due to these advantages, system dynamics has been applied in broad fields, including the urban system analysis, such as urban water–energy–food system [32], urban economy–resource–environment system [19], green urban system [35], urban social economy–water environment system [11], urban economy–society–resource–environment system [36], etc. Accordingly, this paper takes advantage of system dynamics

to analyze the food role of urban agriculture in the urban system for coordination development between the socio-economy and the environment.

2.1.1. Model Conceptualization

This paper establishes an urban system, as shown in Figure 1. Firstly, this paper focuses on the food role in the coordination development of the urban system, reflected in 77 loops. For example:

Grain security → Total population → Labor force → Output of the primary industry → Grain security (a positive loop);

Grain security → Total population → Labor force → Output of tertiary/secondary industry → natural land → Grain security (a negative loop);

Grain security → Total population → Air/Water pollution → Pollution index → Output of the primary industry → Grain security (a negative loop);

Grain security → Total population → Labor force → Output of the tertiary/secondary industry → GDP → Output of the primary industry (a positive loop);

Grain security → Total population → Air/Water pollution → Pollution index → Output of the tertiary/secondary industry → GDP → Output of the primary industry (a negative loop).

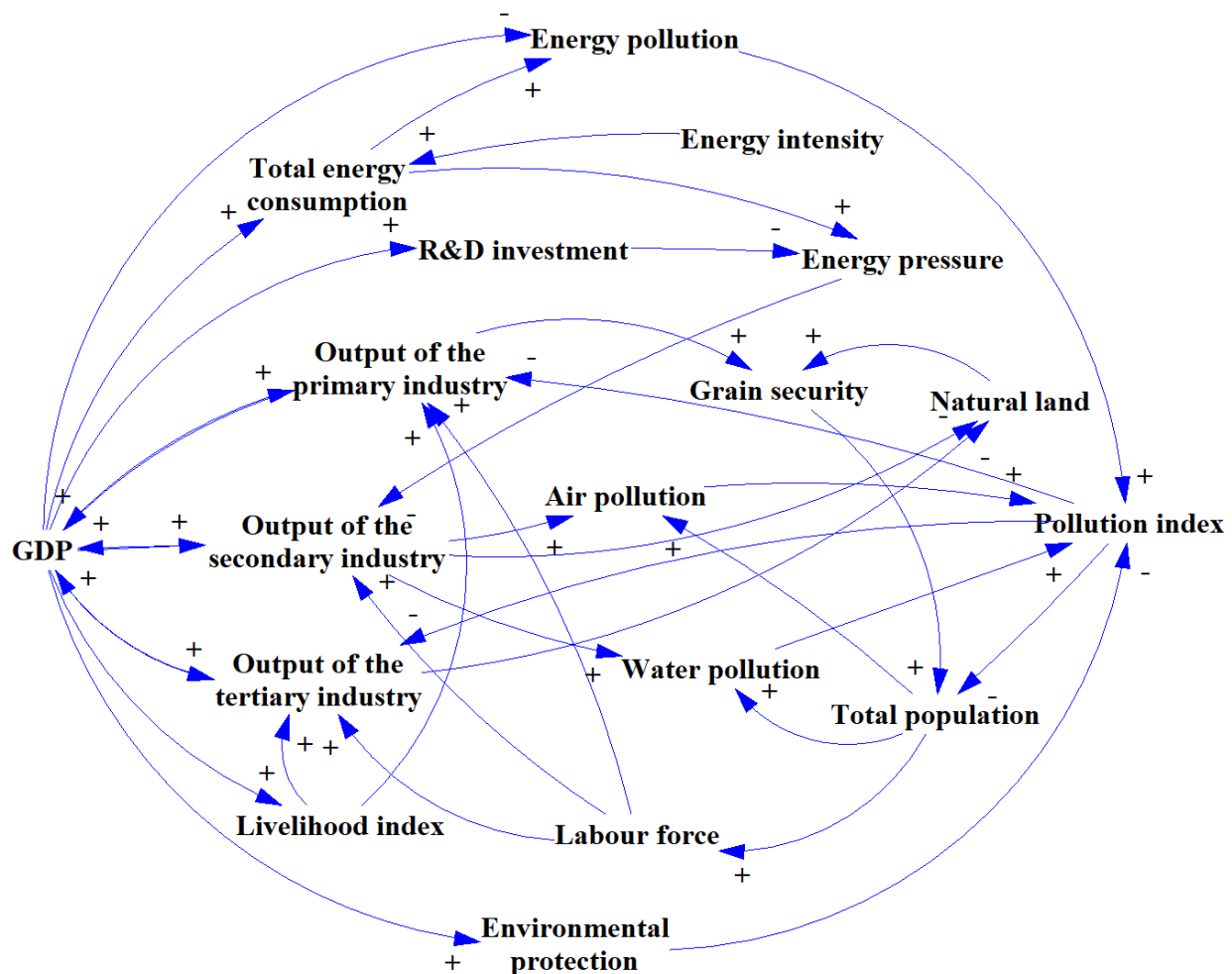


Figure 1. Causal loop diagram of the urban system.

Secondly, this paper hopes to provide a reference for promoting coordination development, considering the subsystems of the socio-economy and the environment. The socio-economy mainly covers the population, livelihood, three industries, and technology investment. The environmental subsystem investigates air and water pollution, energy consumption, and investment in protection.

2.1.2. Model Formulation

Based on the causal loop diagram, this paper further defines the urban system with various elements and interacting formulations (Appendix A). Then, the stock and flow chart of the system model is formulated, as shown in Figure 2. The model builds an urban system and aims to examine how the evolution of grain security (grain yield per capita) will influence the system coordination level. The determination methods of parameters in the interactions are shown in Appendix B.

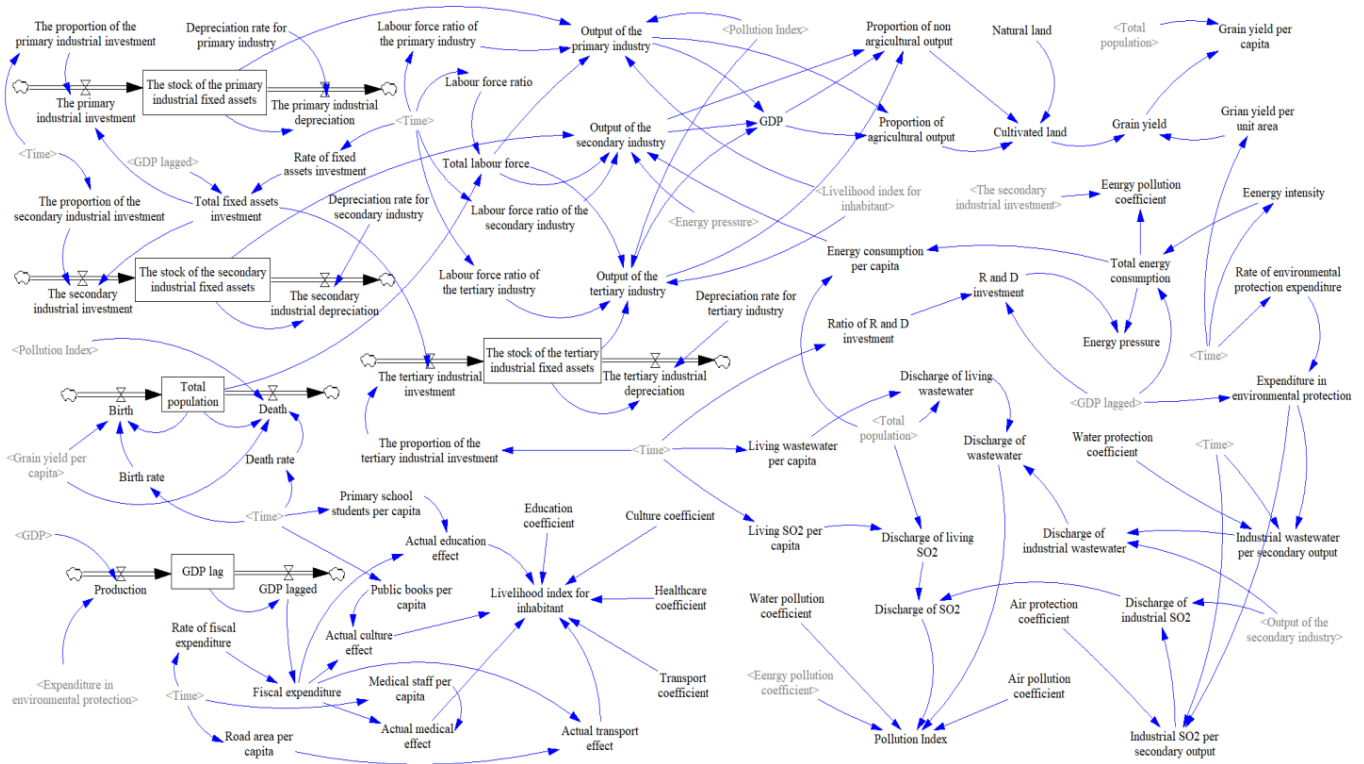


Figure 2. Stock and flow chart of the urban system.

To confirm the model's accuracy, this paper compares the simulated results with the actual data through the following formulas [19].

$$MARE = \frac{1}{N \times T} \sum_{j=1}^N \sum_{t=1}^T \left| \left(\widehat{Y}_{jt} - Y_{jt} \right) / Y_{jt} \right| \quad (1)$$

MARE represents Mean Absolute Relative Error, and a smaller value inflects a higher matching degree and a better simulation validation. Y_{it} is the actual value of indicator j at time t , and $\widehat{Y}_{jt}$ is the simulated one.

2.1.3. Scenario Settings

After establishing the urban system, the food role of urban agriculture is examined. To this end, three scenarios have been designed, as shown in Table 1. The first is the current scenario, with all variables evolving as the current trend. The second is the scenario of high protection in urban agriculture, with related parameters being adjusted to promote the growth of grain yield at a higher rate than the current value. The third scenario is low protection in urban agriculture, where the grain yield grows at a lower rate or decreases.

Table 1. Parameter setting of three scenarios to examine food role.

Parameters	Scenario 1: Current Trend	Scenario 2: Higher-Rate Grain Yield Growth	Scenario 3: Lower-Rate Grain Yield Growth
LFRP	0.012	0.041	0.006
LFRS	0.2782	0.2492	0.2842
PPII	0.008	0.026	0.002
PSII	0.1308	0.1128	0.1368
GYUA	662	800	602
REPE	0.032	0.037	0.026

Notes: LFRP: labor force ratio of the primary industry; LFRS: labor force ratio of the secondary industry; PPII: proportion of the primary industrial investment; PSII: proportion of the secondary industrial investment; GYUA: grain yield per unit area; REPE: rate of environmental protection expenditure.

2.2. Coupling Coordination Degree Model

To evaluate the coordination level between the urban socio-economy and the environment, this paper applies the coupling coordination degree model, a widely use method for complex systems with various interactions [37–39].

2.2.1. Indicator System and Data Source

Firstly, the indicator system of the urban system is established in consideration of data accessibility and previous studies [35,36,40,41], as shown in Table 2. This paper mainly collects data from Shanghai Statistical Yearbooks, and the simulation span is 1995–2030. To ensure the results are reasonable, this paper applies indicators of per capita value and converts the ones related to currency into values with 2000 as the base year.

Table 2. Indicator system of the urban system.

Subsystem	Indicators	Weight	Direction
Socio-economy	X ₁₁ : GDP per capita (¥10 thousand)	7.77%	+
	X ₁₂ : The proportion of agriculture in GDP (%)	15.93%	+
	X ₁₃ : Fixed assets investment per capita (¥10 thousand)	9.84%	+
	X ₁₄ : Fiscal expenditure per capita (¥10 thousand)	10.43%	+
	X ₁₅ : R & D expenditure per capita (¥10 thousand)	23.55%	+
Environment	X ₁₆ : Birth (10 thousand persons)	32.47%	+
	X ₂₁ : Cultivated land per capita (km ² /10 thousand persons)	11.95%	+
	X ₂₂ : Grain yield per capita (t/10 thousand persons)	21.32%	+
	X ₂₃ : Energy consumption per capita (Ton of standard coal)	11.02%	–
	X ₂₄ : Discharge of wastewater per capita (t)	13.34%	–
	X ₂₅ : Discharge of SO ₂ per capita (t)	23.62%	–
	X ₂₆ : Expenditure in environmental protection per capita (¥10 thousand)	18.74%	+

2.2.2. Performance Evaluation of Subsystems

Then, the performance of the socio-economy and environment is evaluated in the following three steps.

Step 1: The indicator values are standardized with the two formulas to eliminate the possible impacts of dimensions.

$$\text{Positive indicators : } X'_{ij} = (X_{ij} - \min\{X_j\}) / (\max\{X_j\} - \min\{X_j\}) \quad (2)$$

$$\text{Negative indicators : } X'_{ij} = (\max\{X_j\} - X_{ij}) / (\max\{X_j\} - \min\{X_j\}) \quad (3)$$

where X_{ij} and X'_{ij} represent data before and after standardization, and $\max\{X_j\}$ and $\min\{X_j\}$ represent the maximum and minimum data of indicator j .

Step 2: The weights of indicators are obtained with the entropy method.

$$\text{Proportion of indicator } j \text{ in } i\text{th year : } P_{ij} = X'_{ij} / \sum_{i=1}^m X'_{ij} \quad (4)$$

$$\text{Entropy redundancy of indicator } j: d_j = 1 - (-\frac{1}{\ln m} \sum_{i=1}^m P_{ij} \cdot \ln P_{ij}) \quad (5)$$

$$\text{Weight of indicator } j: w_j = d_j / \sum_{j=1}^n d_j \quad (6)$$

Step 3: The performance levels are obtained.

$$S_i = \sum_{j=1}^n w_j \cdot X'_{ij} \quad (7)$$

2.2.3. Coordination Evaluation of the Urban System

Finally, the coordination level of the urban system is evaluated with the coupling coordination model.

$$\text{The overall level of the urban system : } T = \beta_1 \cdot f(SE) + \beta_2 \cdot g(EN) \quad (8)$$

$$\text{The coupling degree : } C = 2 \cdot \left[\frac{f(SE) \cdot g(EN)}{(f(SE) + g(EN))^2} \right]^{\frac{1}{2}} \quad (9)$$

$$\text{The coordination level : } D = \sqrt{C \cdot T} \quad (10)$$

where $f(SE)$ and $g(EN)$ are the performance level of the socio-economy and the environment, and β_1 and β_2 represent their contributions, respectively. The values of β_1 and β_2 are both 0.5 [37].

Based on previous studies [19,37], the coordination degree can be divided into five levels, i.e., seriously unbalanced ($0 \leq D < 0.25$), slightly unbalanced ($0.25 \leq D < 0.5$), barely balanced ($0.5 \leq D < 0.75$), and superior balanced ($0.75 \leq D \leq 1$).

2.3. Study Area

Shanghai, a cosmopolitan megacity, is located at $120^\circ 52' \sim 122^\circ 12' \text{ E}$ and $30^\circ 40' \sim 31^\circ 53' \text{ N}$. It has absorbed about 25 million people with a total area of 6340.5 km². It plays a central role in multi-aspects of national development, such as the economy, technology, finance, etc. Therefore, it is significant for China and the world to study sustainable and coordinated development in Shanghai city. Since 2010, the Shanghai Municipal Government has made many efforts in farmland supplement and reclamation of inefficient construction land. However, there are still problems, such as insufficient reserve resources of agricultural land and contradiction of land use. Thus, agricultural land protection and food security are still severe.

3. Results

3.1. Model Accuracy

This paper compares the simulated results with the actual data to confirm the model's accuracy. The average relative errors of these representative indicators are all within 5%, as shown in Figure 3; these results mean that the simulation values have good agreement with the actual values [34]. Therefore, the model's behavior is reliable for simulating the development of Shanghai.

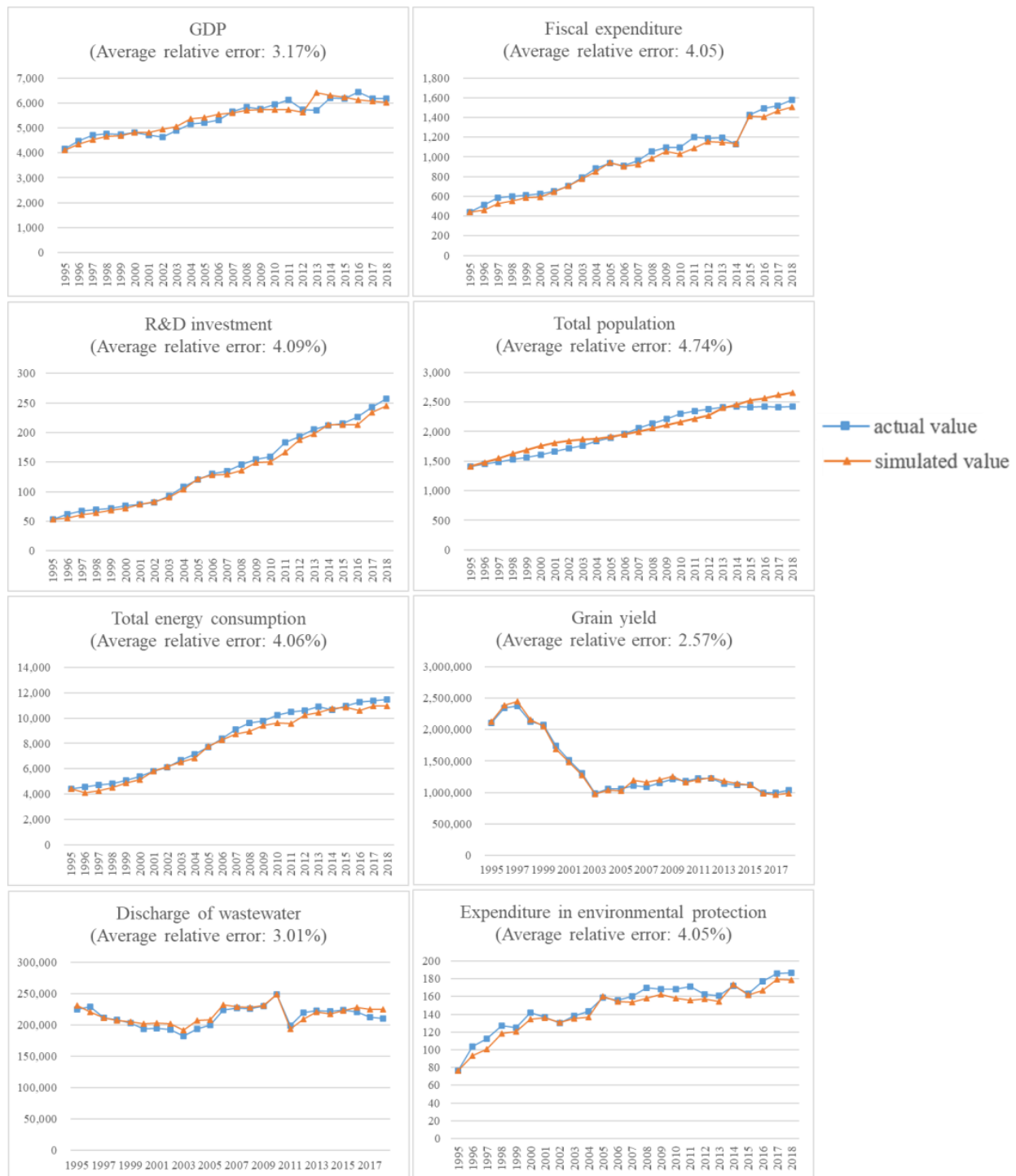


Figure 3. Average relative error of some key indicators in the model.

3.2. Model Results of Three Scenarios

3.2.1. Development of Food in Urban Agriculture

Under different scenarios, cultivated land will perform differently, as shown in Figure 4. If Shanghai follows the current development trend, agricultural land resources will be increasingly severe, and the lower-rate grain yield growth scenario will see a more serious situation. In contrast, the higher-rate grain yield growth scenario can somewhat protect cultivated land and promote resource increase at a gentle rate.

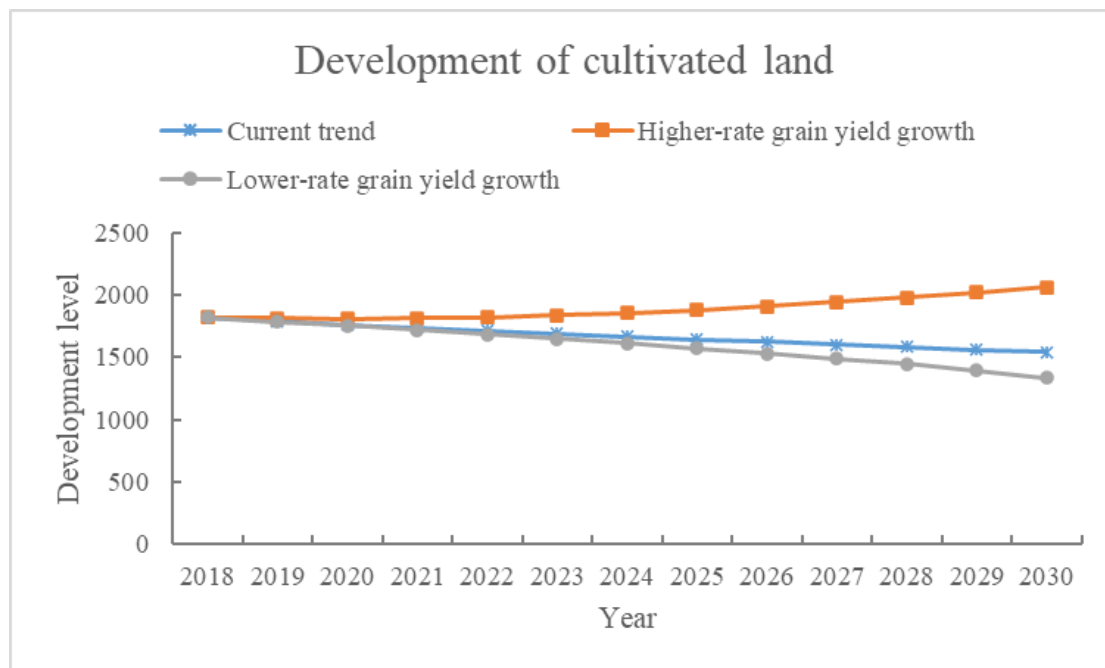


Figure 4. Development of cultivated land under three scenarios.

Similarly, the development of grain yield per capita sees the same development trends, as shown in Figure 5. Therefore, the higher-rate grain yield growth scenario that is set by this paper can protect cultivated land resources and ensure food security.

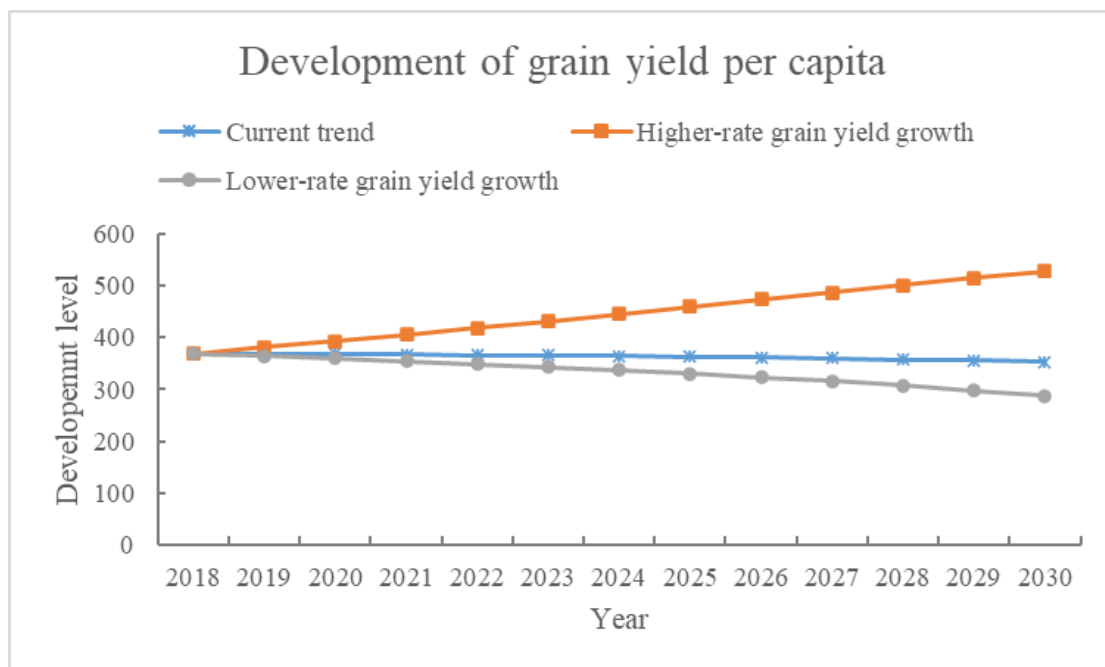


Figure 5. Development of grain yield per capita under three scenarios.

3.2.2. Socioeconomic and Environmental Performance

Under different scenarios, the performance of the socio-economy and the environment in Shanghai differs. As shown in Figure 6, the socio-economy shows an upward trend under all three scenarios during 2018–2030. The lower-rate grain yield growth scenario shows a minimum rise from 0.32 to 0.55. In contrast, the performance under higher-rate grain

yield increases significantly from 0.32 to 0.67. The results imply that ensuring food security benefits socioeconomic development, which can be explained through the indicators' weights, as shown in Table 2. The top three important indicators are birth (32.47%), R & D expenditure per capita (23.55%), and the proportion of agriculture in GDP (15.93%), contributing to over 70% of the socioeconomic growth in total. High grain yield brings high growth in agriculture and promotes population growth, resulting in a high socio-economy. Therefore, the socioeconomic performances ranks are shown below: scenario under higher-rate grain yield growth > current scenario > scenario under lower-rate grain yield growth.

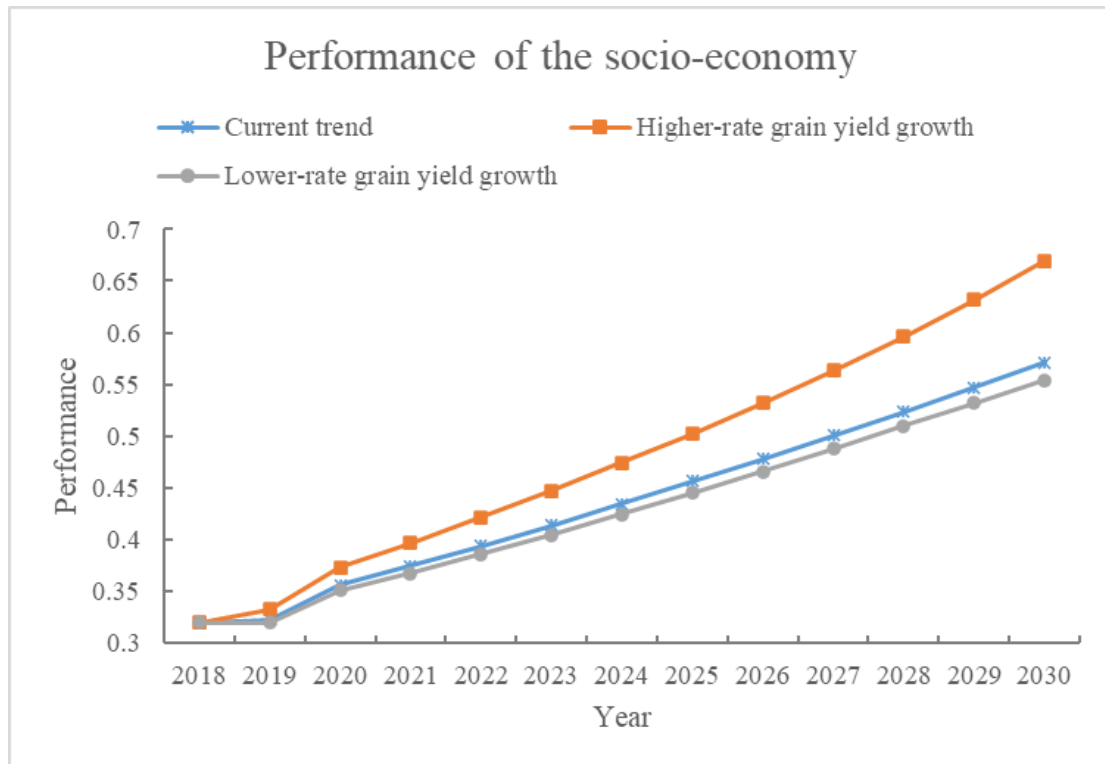


Figure 6. Performance of the socio-economy under three scenarios.

For the environment, the performance shows an opposite trend during 2018–2030, as shown in Figure 7. It will decrease sharply from 0.66 to 0.32 on the current development trend, and the situation under lower-rate grain yield growth will be even more serious. By comparison, the environmental performance can almost maintain the present level under higher-rate grain yield growth. The results imply that ensuring food security can also benefit environmental development, which can be explained through the indicators' weights in Table 2. Grain yield per capita and cultivated land per capita contribute to 23.32% and 11.95% of environmental performance, respectively; this is one-third in total. Therefore, the environmental performance ranks are shown below: scenario under higher-rate grain yield growth > current scenario > scenario under lower-rate grain yield growth.

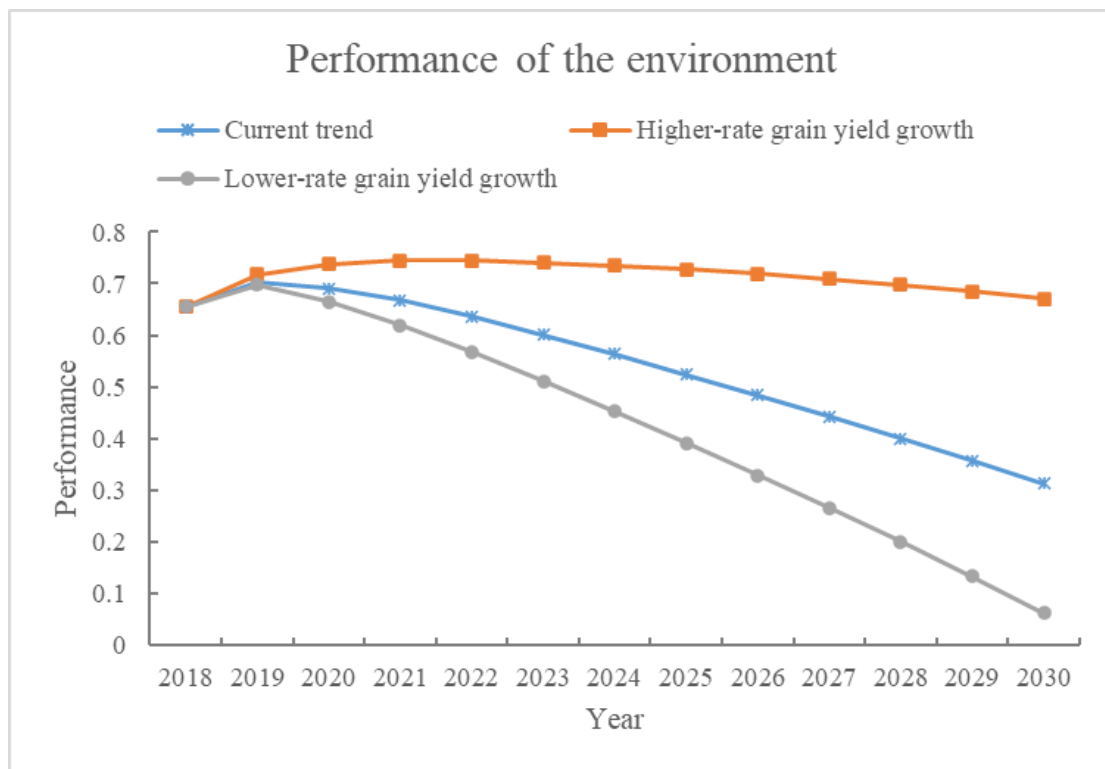


Figure 7. Performance of the environment under three scenarios.

3.2.3. Coupling Coordination Level

The coupling degrees under three scenarios are shown in Figure 8, reflecting the interacting intensity between the socio-economy and the environment. The trends under the current and higher-rate yield growth scenarios are similar, increasing from 0.2 to almost 1. In contrast, the coupling degree under lower-rate grain yield scenario growth sharply declines after 2027 to the original level.

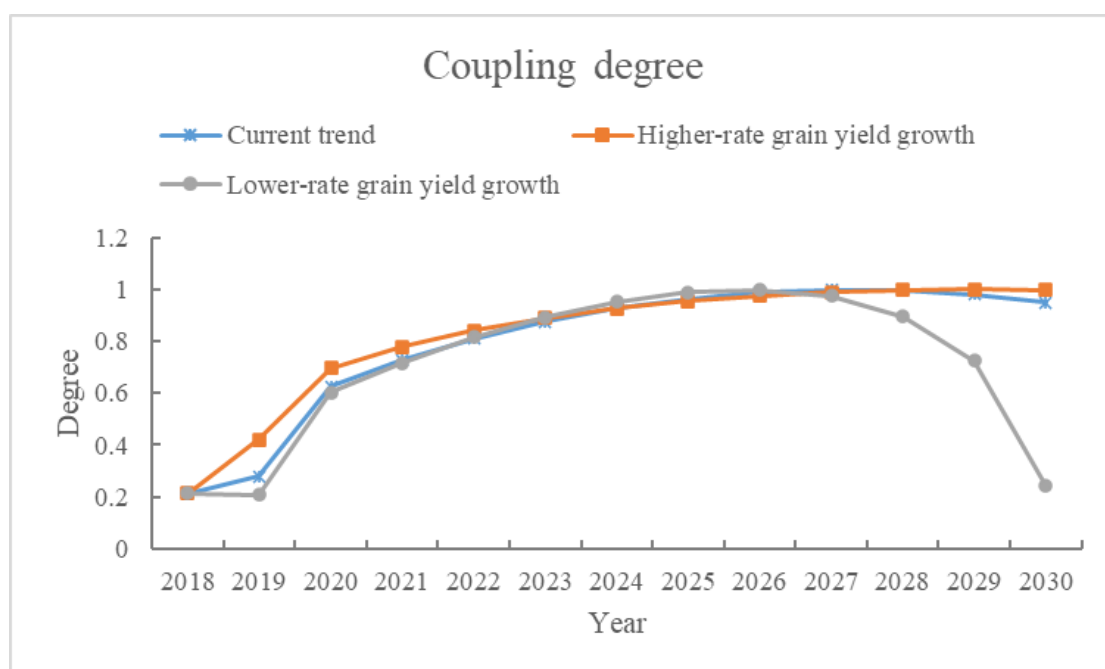


Figure 8. Coupling degree under three scenarios.

The coordination degrees under three scenarios are shown in Figure 9. In general, the coordination levels under current and higher-rate grain yield growth scenarios show an upward trend, while that of the under lower-rate grain yield growth scenario begins to decrease after 2025. Specifically, the coordination level of the current scenario increases gently from 0.3 (slightly unbalanced) to 0.7 (barely balanced). Coordination of higher-rate grain yield growth scenario is the highest and increases significantly to 0.967 (superior balanced). In contrast, that of the lower-rate grain yield growth is the lowest and first increases slowly to slightly unbalanced by 2025, and then, falls back to slightly unbalanced by 2030. These results indicate that neglecting the food role of urban agriculture will lead to uncoordinated development.

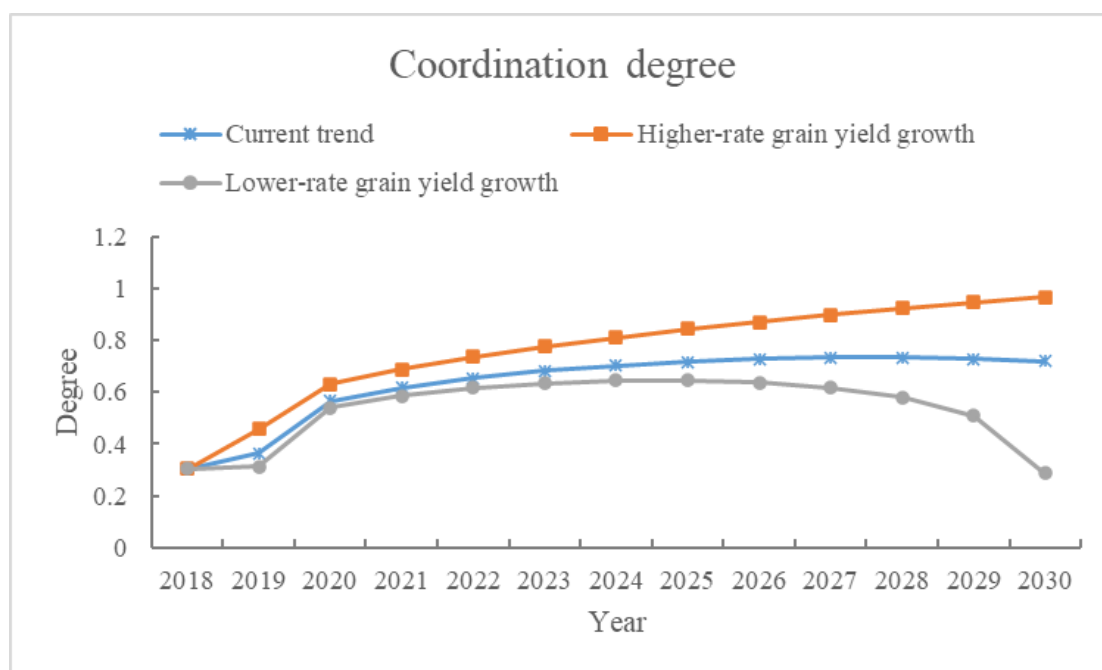


Figure 9. Coordination degree under three scenarios.

4. Discussion

Firstly, we can confirm the food role of urban agriculture in promoting the socio-economy by comparing the prediction results of different scenarios (Figure 6). The high-rate grain yield growth scenario promotes investment in the labor force and assets of the primary industry as well as improves the efficiency of food production. In addition, it alleviates the secondary industry's occupation of cultivated land resources and the negative impact of environmental damage on cultivated productivity. All these adjustments can promote the proportion of agriculture in GDP and have a positive effect on population development, which are essential aspects of the socioeconomic subsystem. These discoveries are in line with previous studies. Strengthening the development of food resources has been proven to be an optimized scenario to improve food security and GDP per capita [34]. Urban agriculture significantly benefits economic stability and physical health [42].

Secondly, we can also confirm the food role of urban agriculture in promoting the environment by comparing the prediction results of different scenarios (Figure 7). The high-rate grain yield growth scenario reduces the investment in the labor force and assets of the secondary industry as well as improves environmental protection, which can reduce pollution emissions and energy consumption. In addition, it protects the cultivated land resources and enhances food security, which has already been recognized as feasible in rich regions [27]. All these adjustments can promote the environmental subsystem. These findings align with other studies that show that more sustainable urban food systems allow energy conservation and emission reduction [42]. The results also provide quantitative

evidence for previous views that urban agriculture is essential to deal with environmental deterioration [43]. Agriculture presents the potential for meeting sustainable goals in reducing adverse environmental impacts [44].

Finally, the food role of urban agriculture in promoting coordinated development is confirmed by comparing the prediction results of different scenarios (Figures 8 and 9). The high-rate grain yield growth scenario improves the performance of the socioeconomic subsystem, mitigates the decline in environmental performance, and ensures a high coupling degree, which promotes coordinated development. These discoveries further expand the previous research results, further identifying that improving food security can benefit the development of the socioeconomic and the environmental subsystems and their coordination level.

5. Policy Implications

Based on the simulation results, this paper attaches importance to agriculture and proposes the following suggestions for Shanghai city and other metropolises worldwide with tense cultivated land resources and food security capacity to improve sustainability. Food-focused urban planning has already been recommended in some countries [45].

Firstly, increase the input of the labor force and assets in the primary industry to promote its development and improve food security. In the high-rate grain yield growth scenario, the labor force ratio of the primary industry is set to increase back to the size of 2012, rather than fall to less than half of the current level; and the proportion of the primary industrial investment will grow at twice the rate of the current growth trend. Comprehensive means, including these measures, can significantly improve the performance of socioeconomic and environmental subsystems and promote their coordinated development.

Secondly, improve food production efficiency through technical means or manual training to promote the development of the primary industry and improve food security. In the high-rate grain yield growth scenario, the grain yield per unit area is set to increase back to the capacity of 1997, much faster than the current trend, which has been proven by simulation as an effective way to improve food security.

Thirdly, mitigate the occupation of cultivated land resources by the secondary industry. In the high-rate grain yield growth scenario, the labor force ratio of the secondary industry is set to decrease at a faster rate than the actual trend; the same is true for the proportion of the secondary industrial investment. Comprehensive means, including these measures, can also significantly improve the performance of socioeconomic and environmental subsystems and promote their coordinated development.

Last but not least, strengthen environmental protection and mitigate the negative impact of environmental damage on cultivated land production. In the high-rate grain yield growth scenario, the rate of environmental protection expenditure is set to increase faster than the current trend, which has been proven by simulation as an effective way to improve food security.

6. Conclusions

This paper applies system dynamics to innovatively analyze the quantitative role of food and cultivated land resources in complex urban systems of the socio-economy and the environment. Three scenarios, the current trend scenario, low-rate grain yield growth scenario, and high-rate grain yield growth scenario, are set to adjust food and cultivated land resources to analyze their roles. The coupling coordinated degree model is applied to evaluate the coordination level.

The results confirm the positive role of food and cultivated land resources in promoting the performance of socioeconomic and environmental subsystems in Shanghai city and coordinated development. The results indicate that future urban planning should increase the input of labor force and assets in the primary industry, improve food productivity per unit area through technical means or person training, alleviate the occupation of

cultivated land resources by the secondary industry, and mitigate the negative impact of environmental pollution on cultivated land productivity.

It must be admitted that this study also has some limitations. The first limitation comes from data availability. For example, urban agriculture can also produce water pollution and play a role in promoting metabolism. However, due to the unavailability of data, these factors are not considered in the urban system. In addition to improving data quality, future research can continuously improve the representativeness of complex urban systems, such as incorporating the interactions between other elements as well as between different cities into the comprehensive system, making it more reflective of the actual development pattern.

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Data Availability Statement: Not applicable.

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

Appendix A Model Formulations

- [1] Air pollution coefficient = 0.81
- [2] Air protection coefficient = 0.2553
- [3] Birth = Birth rate $\times$ Total population $\times$ Grain yield per capita^{0.3384}
- [4] Birth rate ([(1995, 0)–(2030, 0.01)], (1995, 0.0055), (1996, 0.0056), (1997, 0.0055), (1998, 0.0052), (1999, 0.0054), (2000, 0.0053), (2001, 0.0043), (2002, 0.0047), (2003, 0.0043), (2004, 0.006), (2005, 0.0061), (2006, 0.006), (2007, 0.0073), (2008, 0.007), (2009, 0.0066), (2010, 0.0071), (2011, 0.0072), (2012, 0.0096), (2013, 0.0076), (2014, 0.0086), (2015, 0.0074), (2016, 0.009), (2017, 0.0081), (2018, 0.0067), (2030, 0.0085))
- [5] Cultivated land = Natural land $\times$ Proportion of agricultural output^{0.2342} / Proportion of nonagricultural output^{8.975}
- [6] Culture coefficient = 0.3105
- [7] Death = Death rate $\times$ Total population $\times$ (1 + Pollution index $\times$ 6.3084) / Grain yield per capita^{0.3384}
- [8] Death rate ([(1995, 0)–(2030, 0.01)], (1995, 0.0075), (1996, 0.007), (1997, 0.0068), (1998, 0.007), (1999, 0.0065), (2000, 0.0072), (2001, 0.0071), (2002, 0.0073), (2003, 0.0075), (2004, 0.0072), (2005, 0.0075), (2006, 0.0072), (2007, 0.0074), (2008, 0.0077), (2009, 0.0076), (2010, 0.0077), (2011, 0.0079), (2012, 0.0054), (2013, 0.0082), (2014, 0.0083), (2015, 0.0086), (2016, 0.0085), (2017, 0.0087), (2018, 0.0086), (2030, 0.0095))
- [9] Depreciation rate for primary industry = 0.045
- [10] Depreciation rate for secondary industry = 0.0698
- [11] Depreciation rate for tertiary industry = 0.045
- [12] Discharge of industrial SO₂ = Output of the secondary industry $\times$ Industrial SO₂ per secondary output / 1000
- [13] Discharge of industrial wastewater = Output of the secondary industry $\times$ Industrial wastewater per secondary output
- [14] Discharge of living SO₂ = Total population $\times$ Living SO₂ per capita / 1000
- [15] Discharge of living wastewater = Total population $\times$ Living wastewater per capita
- [16] Discharge OF SO₂ = Discharge of industrial SO₂ + Discharge of living SO₂
- [17] Discharge of wastewater = Discharge of industrial wastewater + Discharge of living wastewater
- [18] Education coefficient = 0.1915
- [19] Energy intensity ([(1995, 0.8)–(2030, 2.2)], (1995, 1.0581), (1996, 1.0172), (1997, 0.9991), (1998, 1.0156), (1999, 1.0713), (2000, 1.125), (2001, 1.2388), (2002, 1.3188), (2003, 1.359), (2004, 1.3919), (2005, 1.4852), (2006, 1.5712), (2007, 1.6117), (2008, 1.6427), (2009, 1.6948), (2010, 1.7256), (2011, 1.7102), (2012, 1.8409), (2013, 1.9079), (2014, 1.7114), (2015, 1.7664), (2016, 1.7471), (2017, 1.8431), (2018, 1.855), (2019, 1.7215), (2030, 2.1033))

- [20] Energy pollution coefficient = Total energy consumption $\times$ 0.63/LN (The secondary industrial investment)
- [21] Energy consumption per capita = Total energy consumption/Total population
- [22] Energy pressure = Total energy consumption $\times$ 0.01/LN (R and D investment)
- [23] Expenditure in environmental protection = GDP lagged $\times$ Rate of environmental protection expenditure
- [24] FINAL TIME = 2030
- [25] Fiscal expenditure = GDP lagged $\times$ Rate of fiscal expenditure
- [26] GDP = Output of the primary industry + Output of the secondary industry + Output of the tertiary industry
- [27] GDP lag = INTEG (Production-GDP lagged, 4151.4)
- [28] GDP lagged = GDP lag
- [29] Grain yield = Cultivated land $\times$ Grain yield per unit area
- [30] Grain yield per capita = Grain yield/Total population
- [31] Grain yield per unit area ([(1995, 370)–(2030, 800)], (1995, 725.517), (1996, 781.171), (1997, 798.154), (1998, 723.485), (1999, 715.366), (2000, 608.604), (2001, 539.629), (2002, 482.47), (2003, 383.793), (2004, 432.641), (2005, 443.995), (2006, 535.096), (2007, 530.097), (2008, 564.244), (2009, 601.483), (2010, 589.055), (2011, 610.972), (2012, 615.025), (2013, 607.181), (2014, 597.981), (2015, 590.516), (2016, 519.979), (2017, 520.772), (2018, 539.329), (2030, 762.012))
- [32] Healthcare coefficient = 0.129
- [33] Industrial SO₂ per secondary output = 53.29 $\times$ EXP (–((Time – 1995)/19.46)⁵)/(Expenditure in environmental protection^{Air protection coefficient})
- [34] Industrial wastewater per secondary output = 1411 $\times$ EXP(–0.02637 $\times$ (Time – 1995))/(Expenditure in environmental protection^{Water protection coefficient})
- [35] INITIAL TIME = 1995
- [36] Labor force ratio([(1995, 0.45)–(2030, 0.6)], (1995, 0.5617), (1996, 0.5838), (1997, 0.5639), (1998, 0.5416), (1999, 0.5113), (2000, 0.5082), (2001, 0.4763), (2002, 0.4886), (2003, 0.4946), (2004, 0.5521), (2005, 0.5333), (2006, 0.5396), (2007, 0.5334), (2008, 0.5328), (2009, 0.5239), (2010, 0.5213), (2011, 0.5126), (2012, 0.4976), (2013, 0.5923), (2014, 0.5709), (2015, 0.5527), (2016, 0.5353), (2017, 0.5217), (2018, 0.5095), (2030, 0.5316))
- [37] Labor force ratio of the primary industry ([(1995, 0.01)–(2030, 0.14)], (1995, 0.0985), (1996, 0.1204), (1997, 0.1271), (1998, 0.1244), (1999, 0.1141), (2000, 0.1077), (2001, 0.11), (2002, 0.1015), (2003, 0.0863), (2004, 0.0688), (2005, 0.063), (2006, 0.055), (2007, 0.0524), (2008, 0.0469), (2009, 0.0456), (2010, 0.034), (2011, 0.0338), (2012, 0.041), (2013, 0.037), (2014, 0.0328), (2015, 0.0338), (2016, 0.0333), (2017, 0.0309), (2018, 0.0297), (2030, 0.012))
- [38] Labor force ratio of the secondary industry ([(1995, 0.25)–(2030, 0.56)], (1995, 0.5447), (1996, 0.5226), (1997, 0.491), (1998, 0.4603), (1999, 0.4646), (2000, 0.4431), (2001, 0.3987), (2002, 0.3967), (2003, 0.4076), (2004, 0.4535), (2005, 0.4243), (2006, 0.4168), (2007, 0.4125), (2008, 0.4027), (2009, 0.3974), (2010, 0.4068), (2011, 0.403), (2012, 0.3944), (2013, 0.3501), (2014, 0.3492), (2015, 0.3377), (2016, 0.3285), (2017, 0.3136), (2018, 0.3074), (2030, 0.2782))
- [39] Labor force ratio of the tertiary industry ([(1995, 0.35)–(2030, 0.75)], (1995, 0.3568), (1996, 0.357), (1997, 0.3819), (1998, 0.4153), (1999, 0.4213), (2000, 0.4492), (2001, 0.4912), (2002, 0.5017), (2003, 0.5061), (2004, 0.4777), (2005, 0.5128), (2006, 0.5282), (2007, 0.5351), (2008, 0.5504), (2009, 0.557), (2010, 0.5592), (2011, 0.5632), (2012, 0.5646), (2013, 0.6129), (2014, 0.618), (2015, 0.6285), (2016, 0.6382), (2017, 0.6554), (2018, 0.663), (2030, 0.7098))
- [40] Livelihood index for inhabitant = LN (Fiscal expenditure $\times$ (Culture coefficient $\times$ Public books per capita + Education coefficient $\times$ Primary school students per capita + Healthcare coefficient $\times$ Medical staff per capita + Transport coefficient $\times$ Road area per capita))
- [41] Living SO₂ per capita ([(1994, 0)–(2030, 12)], (1994, 6.402), (1995, 10.792), (1996, 5.307), (1997, 4.856), (1998, 6.417), (1999, 5.888), (2000, 8.585), (2001, 10.348), (2002, 7.105), (2003, 7.627), (2004, 6.736), (2005, 7.28), (2006, 6.808), (2007, 6.463), (2008, 6.917), (2009,

- 6.317), (2010, 4.121), (2011, 1.272), (2012, 1.46), (2013, 1.778), (2014, 1.351), (2015, 2.733), (2016, 0.283), (2017, 0.241), (2018, 0.033), (2019, 0.041), (2030, 0.131))
- [42] Living wastewater per capita ([1994, 60]–(2030, 95]), (1994, 61.2117), (1995, 76.662), (1996, 78.8422), (1997, 74.6138), (1998, 77.3412), (1999, 75.0479), (2000, 75.345), (2001, 76.124), (2002, 74.257), (2003, 68.5793), (2004, 74.66), (2005, 78.6243), (2006, 89.3075), (2007, 86.7248), (2008, 84.9603), (2009, 85.6561), (2010, 91.8367), (2011, 65.6157), (2012, 72.0773), (2013, 73.5404), (2014, 73.0833), (2015, 73.3747), (2016, 76.1157), (2017, 74.6071), (2018, 74.5462), (2019, 74.1606), (2030, 77.1461))
- [43] Medical staff per capita([1995, 0.005]–(2030, 0.011]), (1995, 0.0078), (1996, 0.0075), (1997, 0.0073), (1998, 0.0071), (1999, 0.0069), (2000, 0.0067), (2001, 0.0063), (2002, 0.0059), (2003, 0.0058), (2004, 0.0055), (2005, 0.0055), (2006, 0.0056), (2007, 0.0059), (2008, 0.006), (2009, 0.0059), (2010, 0.0059), (2011, 0.0059), (2012, 0.0062), (2013, 0.0065), (2014, 0.0068), (2015, 0.007), (2016, 0.0074), (2017, 0.0078), (2018, 0.0085), (2019, 0.0084), (2030, 0.0107))
- [44] Natural land = 6341
- [45] Output of the primary industry = $0.086 / \text{Pollution index}^{0.8284} \times \text{Livelihood index for inhabitant}^{0.1163} \times \text{The stock of the primary industrial fixed assets}^{0.91} \times (\text{Labor force ratio of the primary industry} \times \text{Total labor force})^{0.5272}$
- [46] Output of the secondary industry = $0.3843 / \text{Energy pressure}^{0.4549} \times \text{Energy consumption per capita}^{0.6016} \times \text{The stock of the secondary industrial fixed assets}^{0.8047} \times (\text{Total labor force} \times \text{Labor force ratio of the secondary industry})^{0.3084}$
- [47] Output of the tertiary industry = $23.0808 / \text{Pollution index}^{0.8284} \times \text{Livelihood index for inhabitant}^{0.1163} \times \text{The stock of the tertiary industrial fixed assets}^{0.162} \times (\text{Total labor force} \times \text{Labor force ratio of the tertiary industry})^{0.7136}$
- [48] Pollution index = $\text{LN}(\text{Energy pollution coefficient} \times (\text{Air pollution coefficient} \times \text{Discharge of SO}_2 + \text{Water pollution coefficient} \times \text{Discharge of wastewater}) / (\text{Discharge of SO}_2 + \text{Discharge of wastewater}))$
- [49] Primary school students per capita([1995, 0.02]–(2030, 0.08]), (1995, 0.0776), (1996, 0.0734), (1997, 0.0688), (1998, 0.063), (1999, 0.0556), (2000, 0.049), (2001, 0.0433), (2002, 0.0393), (2003, 0.0367), (2004, 0.0293), (2005, 0.0283), (2006, 0.0272), (2007, 0.0258), (2008, 0.0276), (2009, 0.0304), (2010, 0.0305), (2011, 0.0312), (2012, 0.032), (2013, 0.0328), (2014, 0.0331), (2015, 0.0331), (2016, 0.0326), (2017, 0.0325), (2018, 0.0342), (2019, 0.034), (2030, 0.0415))
- [50] Production = GDP-Expenditure in environmental protection
- [51] Proportion of agricultural output = Output of the primary industry/GDP
- [52] Proportion of nonagricultural output = (Output of the secondary industry + Output of the tertiary industry)/GDP
- [53] Public books per capita([1995, 1]–(2030, 4]), (1995, 1.1216), (1996, 1.1392), (1997, 3.2102), (1998, 3.1493), (1999, 3.0989), (2000, 3.4191), (2001, 3.3974), (2002, 3.3959), (2003, 3.3378), (2004, 3.1891), (2005, 3.2005), (2006, 3.0866), (2007, 3.03), (2008, 2.9865), (2009, 2.9833), (2010, 2.9566), (2011, 2.9369), (2012, 3.0261), (2013, 2.9975), (2014, 3.035), (2015, 3.1337), (2016, 3.1719), (2017, 3.2146), (2018, 3.2567), (2019, 3.3208), (2030, 3.8485))
- [54] R and D investment = GDP lagged $\times$ Ratio of R and D investment
- [55] Rate of environmental protection expenditure ([1995, 0]–(2030, 0.1]), (1995, 0.01846), (1996, 0.02309), (1997, 0.02376), (1998, 0.02666), (1999, 0.02642), (2000, 0.02949), (2001, 0.02909), (2002, 0.02802), (2003, 0.02815), (2004, 0.02782), (2005, 0.03057), (2006, 0.02933), (2007, 0.02843), (2008, 0.02906), (2009, 0.02925), (2010, 0.02833), (2011, 0.02788), (2012, 0.02827), (2013, 0.02814), (2014, 0.0277), (2015, 0.02636), (2016, 0.02756), (2017, 0.03015), (2018, 0.03027), (2019, 0.02829), (2030, 0.035))
- [56] Rate of fiscal expenditure ([1995, 0.1]–(2030, 0.35]), (1995, 0.1064), (1996, 0.115), (1997, 0.1238), (1998, 0.1255), (1999, 0.1294), (2000, 0.1294), (2001, 0.1382), (2002, 0.1515), (2003, 0.1621), (2004, 0.1723), (2005, 0.1805), (2006, 0.1711), (2007, 0.1709), (2008, 0.1801), (2009, 0.1899), (2010, 0.1844), (2011, 0.1956), (2012, 0.2073), (2013, 0.2096), (2014, 0.1815), (2015, 0.2303), (2016, 0.2315), (2017, 0.2464), (2018, 0.2556), (2030, 0.3096))

- [57] Rate of fixed assets investment ($[(1995, 0.1)-(2030, 0.7)]$, (1995, 0.6361), (1996, 0.6549), (1997, 0.5707), (1998, 0.5129), (1999, 0.4397), (2000, 0.3885), (2001, 0.3794), (2002, 0.3774), (2003, 0.3604), (2004, 0.3807), (2005, 0.3852), (2006, 0.3703), (2007, 0.3462), (2008, 0.3322), (2009, 0.335), (2010, 0.2968), (2011, 0.2532), (2012, 0.2604), (2013, 0.2614), (2014, 0.2381), (2015, 0.2363), (2016, 0.226), (2017, 0.2366), (2018, 0.2334), (2030, 0.1108))
- [58] Ratio of R and D investment ($[(1995, 0.01)-(2030, 0.06)]$, (1995, 0.0129), (1996, 0.0137), (1997, 0.0144), (1998, 0.0145), (1999, 0.0151), (2000, 0.0159), (2001, 0.0168), (2002, 0.0177), (2003, 0.0189), (2004, 0.021), (2005, 0.0232), (2006, 0.0244), (2007, 0.0239), (2008, 0.0249), (2009, 0.0269), (2010, 0.0269), (2011, 0.0299), (2012, 0.0337), (2013, 0.036), (2014, 0.0341), (2015, 0.0348), (2016, 0.0351), (2017, 0.0393), (2018, 0.0416), (2030, 0.054))
- [59] Road area per capita ($[(1995, 4)-(2030, 18)]$, (1995, 4.01), (1996, 4.46), (1997, 4.91), (1998, 6.04), (1999, 8.52), (2000, 8.68), (2001, 13.6), (2002, 11.6), (2003, 12.46), (2004, 15.36), (2005, 11.78), (2006, 11.84), (2007, 15.4), (2008, 15.7), (2009, 17.54), (2010, 11.12), (2011, 11.18), (2012, 11.24), (2013, 11.3), (2014, 11.51), (2015, 11.83), (2016, 12.09), (2017, 12.34), (2018, 12.49), (2019, 12.7), (2030, 14.63))
- [60] SAVEPER = TIME STEP
- [61] The primary industrial depreciation = The stock of the primary industrial fixed assets $\times$ Depreciation rate for primary industry
- [62] The primary industrial investment = Total fixed assets investment $\times$ The proportion of the primary industrial investment
- [63] The proportion of the primary industrial investment ($[(1995, 0)-(2030, 0.012)]$, (1995, 0.0061), (1996, 0.0107), (1997, 0.004), (1998, 0.0033), (1999, 0.0044), (2000, 0.0044), (2001, 0.0035), (2002, 0.0025), (2003, 0.0018), (2004, 0.0018), (2005, 0.0017), (2006, 0.0037), (2007, 0.002), (2008, 0.0018), (2009, 0.0022), (2010, 0.0032), (2011, 0.0038), (2012, 0.0023), (2013, 0.0034), (2014, 0.0021), (2015, 0.0007), (2016, 0.0006), (2017, 0.0003), (2018, 0.0007), (2030, 0.0003))
- [64] The proportion of the secondary industrial investment ($[(1995, 0)-(2030, 0.4)]$, (1995, 0.3226), (1996, 0.3314), (1997, 0.3354), (1998, 0.3333), (1999, 0.3323), (2000, 0.3294), (2001, 0.3427), (2002, 0.332), (2003, 0.3291), (2004, 0.3275), (2005, 0.3055), (2006, 0.309), (2007, 0.3135), (2008, 0.2942), (2009, 0.2707), (2010, 0.2699), (2011, 0.2557), (2012, 0.2463), (2013, 0.2199), (2014, 0.1924), (2015, 0.1509), (2016, 0.1455), (2017, 0.1426), (2018, 0.1588), (2030, 0.075))
- [65] The proportion of the tertiary industrial investment ($[(1995, 0.6)-(2030, 1)]$, (1995, 0.6713), (1996, 0.6582), (1997, 0.6611), (1998, 0.6636), (1999, 0.6635), (2000, 0.6664), (2001, 0.654), (2002, 0.6656), (2003, 0.6692), (2004, 0.6708), (2005, 0.693), (2006, 0.6874), (2007, 0.6847), (2008, 0.7041), (2009, 0.7271), (2010, 0.727), (2011, 0.7406), (2012, 0.7516), (2013, 0.7768), (2014, 0.8057), (2015, 0.8484), (2016, 0.8539), (2017, 0.8572), (2018, 0.8405), (2030, 0.922))
- [66] The secondary industrial depreciation = The stock of the secondary industrial fixed assets $\times$ Depreciation rate for secondary industry
- [67] The secondary industrial investment = Total fixed assets investment $\times$ The proportion of the secondary industrial investment
- [68] The stock of the primary industrial fixed assets = INTEG (The primary industrial investment-The primary industrial depreciation,464.362)
- [69] The stock of the secondary industrial fixed assets = INTEG (The secondary industrial investment-The secondary industrial depreciation,8072)
- [70] The stock of the tertiary industrial fixed assets = INTEG (The tertiary industrial investment-The tertiary industrial depreciation,5501.27)
- [71] The tertiary industrial depreciation = The stock of the tertiary industrial fixed assets*Depreciation rate for tertiary industry
- [72] The tertiary industrial investment = Total fixed assets investment $\times$ The proportion of the tertiary industrial investment
- [73] TIME STEP = 1
- [74] Total energy consumption = Energy intensity $\times$ GDP lagged

- [75] Total fixed assets investment = GDP lagged $\times$ Rate of fixed assets investment
 [76] Total labor force = Total population $\times$ Labor force ratio
 [77] Total population = INTEG (Birth-Death, 1414)
 [78] Transport coefficient = 0.2399
 [79] Water pollution coefficient = 0.35
 [80] Water protection coefficient = 0.7555

Appendix B

Table A1. The Determination Methods of Parameters.

No.	Parameters	Values	Methods
1	Air pollution coefficient	Appendix A	[19]
2	Air protection coefficient	Appendix A	Regression analysis
3	Elastic coefficient of Grain yield per capita for Birth	0.3384	Regression analysis
4	Birth rate	Appendix A	Table function
5	Elastic coefficient of Proportion of agricultural output for Cultivated land	0.2342	Regression analysis
6	Elastic coefficient of Proportion of nonagricultural output for Cultivated land	8.975	Regression analysis
7	Culture coefficient	Appendix A	Regression analysis
8	Elastic coefficient of Pollution index for Death	6.3084	Regression analysis
9	Elastic coefficient of Gain yield per capita for Birth	0.3384	Regression analysis
10	Death rate	Appendix A	Table function
11	Depreciation rate for primary industry	Appendix A	[19]
12	Depreciation rate for secondary industry	Appendix A	Regression analysis
13	Depreciation rate for tertiary industry	Appendix A	[19]
14	Education coefficient	Appendix A	Regression analysis
15	Energy intensity	Appendix A	Table function
16	Elastic coefficient of Total energy consumption for energy pollution coefficient	0.63	Regression analysis
17	Elastic coefficient of Total energy consumption for Energy pressure	0.01	Regression analysis
18	Grain yield per unit area	Appendix A	Table function
19	Healthcare coefficient	Appendix A	Regression analysis
20	Industrial wastewater per secondary output	Appendix A	Regression analysis
21	Labor force ratio	Appendix A	Table function
22	Labor force ratio of the primary industry	Appendix A	Table function
23	Labor force ratio of the secondary industry	Appendix A	Table function
24	Labor force ratio of the tertiary industry	Appendix A	Table function
25	Living SO ₂ per capita	Appendix A	Table function
26	Living wastewater per capita	Appendix A	Table function
27	Medical staff per capita	Appendix A	Table function
28	Natural land	Appendix A	Constant
29	Output of the primary industry	Appendix A	Regression analysis
30	Elastic coefficient of Pollution index for Output of the primary industry	0.8284	Regression analysis
31	Elastic coefficient of Livelihood index for inhabitant for Output of the primary industry	0.1163	Regression analysis
32	Elastic coefficient of the stock of the primary industrial fixed assets for Output of the primary industry	0.91	Regression analysis
33	Elastic coefficient of the labor force for Output of the primary industry	0.5272	Regression analysis
34	Output of the secondary industry	Appendix A	Regression analysis

Table A1. Cont.

No.	Parameters	Values	Methods
35	Elastic coefficient of Energy pressure for Output of secondary industry	0.4549	Regression analysis
36	Elastic coefficient of Energy consumption per capita for Output of secondary industry	0.6061	Regression analysis
37	Elastic coefficient of the stock of the secondary industrial fixed assets for Output of the secondary industry	0.8047	Regression analysis
38	Elastic coefficient of the labor force for Output of the secondary industry	0.3084	Regression analysis
39	Output of the tertiary industry	Appendix A	Regression analysis
40	Elastic coefficient of Pollution index for Output of the tertiary industry	0.8284	Regression analysis
41	Elastic coefficient of Livelihood index for inhabitant for Output of the secondary industry	0.1163	Regression analysis
42	Elastic coefficient of the stock of the tertiary industrial fixed assets for Output of the tertiary industry	0.162	Regression analysis
43	Elastic coefficient of the labor force for Output of the tertiary industry	0.7136	Regression analysis
44	Primary school students per capita	Appendix A	Table function
45	Public books per capita	Appendix A	Table function
46	Rate of environmental protection expenditure	Appendix A	Table function
47	Rate of fiscal expenditure	Appendix A	Table function
48	Rate of fixed assets investment	Appendix A	Table function
49	Ratio of R and D investment	Appendix A	Table function
50	Road area per capita	Appendix A	Table function
51	The proportion of the primary industrial investment	Appendix A	Table function
52	The proportion of the secondary industrial investment	Appendix A	Table function
53	The proportion of the tertiary industrial investment	Appendix A	Table function
54	Transport coefficient	Appendix A	Regression analysis
55	Water pollution coefficient	Appendix A	(Xing et al., 2019)
56	Water protection coefficient	Appendix A	Regression analysis

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