

Article

A Coupling Relationship between the Eco-Environment Carrying Capacity and New-Type Urbanization: A Case Study of the Wuhan Metropolitan Area in China

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Abstract: Ongoing global urbanization is imposing tremendous pressure on the eco-environment. Research on the coupling of the eco-environment and urbanization has important significance for the sustainable development of urban metropolitan. Looking at the Wuhan Metropolitan Area, which includes nine cities, as a case study area, this paper describes an empirical study done to uncover the interactive coupling relationship between the eco-environment and new-type urbanization in the urban metropolitan area from the perspective of eco-environment carrying capacity. The eco-environment carrying capacity evaluation index system was set up using the pressure-state-response (PSR) model, and then the coupling model was built. The results indicate that the eco-environment carrying capacity in the Wuhan Metropolitan Area is generally sustainable and has three grades. The quality of new-type urbanization in the nine cities in the Wuhan Metropolitan Area shows clear spatial heterogeneity. There are five types of the coupling relationship including moderate coordinated development, elementary coordinated development, reluctant coordinated development, edge of maladjustment, and mild maladjustment between the eco-environment carrying capacity and new-type urbanization level in the Wuhan Metropolitan Area. Therefore, this paper proposes corresponding policies from the aspects of coordinating the industrial division of labor, focusing on the eco-environment carrying threshold and strengthening policy guidance.

Keywords: eco-environment carrying capacity; new-type urbanization; coupling analysis; Wuhan Metropolitan Area; China

1. Introduction

The process of urbanization, which began in North America and Western Europe, is now mainly occurring in developing nations. It is bringing major social–ecological change to humankind and especially is imposing tremendous pressure on the eco-environment [1,2]. Researchers have been sharing growing concerns about the relationship between urbanization and the eco-environment [3,4], which simultaneously has become an indispensable part of sustainability research. A growing number of studies consider urban sprawl as a land use change driver affecting the provision of ecosystem services [5–7], which produced global problems, notably climate change, air pollution, as well as food, water, and energy availability et al. [8–10]. Wachsmuth et al. [11] determined that ecological issues related to sustainability problems are generally on a regional or global scale, but current urban policies usually focus on one aspect of ecological issues in a single city. Therefore, sustainability research must shift its focus from a single city to an urban metropolitan area. In the past few decades, China has achieved rapid economic growth relying on the extensive urban development pattern, which features farmland consumption, cheap labor force supply, and environmental deterioration.

On the one hand, population gathering, resource shortage and environmental pollution have already exerted a huge pressure on the ecosystem [12]. On the other hand, economic and social development is increasingly restricted by resource availability and the environment, which hinders the process and speed of urbanization development to some extent [13]. This type of coupling relationship between the eco-environment and urbanization, characterized by the negative impact of high-speed urbanization on the eco-environment and the restricting effect of the eco-environment on the process and mode of urbanization, is particularly significant in urban metropolitan areas that are experiencing high-speed urbanization [14]. The concept of ‘New-type urbanization’, proposed in 2013 under the guidance of a sustainable development strategy, is different from China’s previous mode of urbanization. Promoting the intensive growth of resources and paying close attention to the protection of the eco-environment are its core principles. In the National Plan on New-type Urbanization (2014–2020) issued in 2014 by the National Development and Reform Commission, PRC pointed out that the current unreasonable spatial distribution and scale structure of urban in China is not well matched to the carrying capacity of resources and the environment, which increases the cost of economic society and the eco-environment. The Wuhan Metropolitan Area, also known as Wuhan “1 + 8” City Circle, is in the middle of China. This area is centered on Wuhan, the largest city in central China, and includes eight medium-sized neighbor cities, including Huangshi, Ezhou, Huanggang, Xiaogan, Xianning, Xiantao, Qianjiang, and Tianmen (Figure 1). In 2007, the State Council of the People’s Republic of China formally approved the Wuhan Metropolitan Area as the “Resources-saving and Environment-friendly Comprehensive Reform Experimental Area” that aims to explore the roadmap of new-type urbanization development and promote the coordination of population, economy, resource and eco-environment. Therefore, the interactive coupling relationship between the eco-environment and urbanization in the urban metropolitan area represented by the Wuhan Metropolitan Area is a problem worth exploring.



Figure 1. Study area.

With the recent development of interdisciplinary and comprehensive global change research, such as the International Human Dimension Programme on Global Environmental Change (IHDP) and the Millennium Ecosystem Assessment (MA), the coupling relationship between the eco-environment and urbanization has received extensive attention and has become one of the cutting-edge interdisciplinary fields of earth system science and sustainable research [15,16]. Scholars have discussed the coupling relationship between urbanization and the eco-environment from different disciplinary perspectives, such as water resources use [17], land use change [18], atmospheric environment [19,20] and biodiversity and ecosystems [21]. Most of the research has found either a completely negative

relationship between urbanization and eco-environment, or diverse relationships due to different urbanization factors or levels [4,22,23]. For example, Kumar et al. [24] found that human activities affect local water quality and threaten regional stability in the Pasig-Marikina River Basin area, and they argued that rapid urbanization is one of the reasons for river pollution. Land cover change caused by urbanization may lead to local changes, such as hydrologic processes, in water resources within the basin [25]. Henderson et al. [26], through analysis of the climatic conditions and urbanization in sub-Saharan African districts, held that climate can impact urban population and urbanization rates. The research by Galletti et al. [27] suggested that the number of types of cloud forest of Dhofar in Oman decreased due to urban expansion and grazing activities and that this change has threatened biodiversity and ecosystems. The existing literature usually uses quantitative modeling to discuss the coupling relationship between urbanization and the eco-environment [2]. Liu et al. [28] set up the evaluation index system according to a sustainable development approach and adopted an interpretive structural model and gray relational technology to assess the coupling relationship between urbanization and the eco-environment. Some scholars have attempted to use new methods, such as the STIRPAT model [29] or big data and computing models [30], to explore the coupling relationship between urbanization and the eco-environment. Research on this relationship has also attracted the attention of scholars in developing countries with high-speed urbanization. The coupling model has been extensively used in China. Zhou et al. [31] discussed the coupling relationship between regional economy, eco-environment, and tourism industry and predicted the coupling coordinative degree of these three systems in the following several years by the GM(1,1) forecasting model. However, there are many disputes about the theoretical basis of the coupling relationship and the classification of a standard of coupling degrees. For example, Chen et al. [32] measured the coupling degree of new-type urbanization and the eco-environment carrying capacity in the Yangtze River Delta Urban Metropolitan based on Leopold's earth ethics and classified the degree into three types: breaking-in stage, antagonistic stage, and moderate coordination stage. Wang et al. [33] divided the coordination pattern into eight types, including comprehensive coordination, lagging economy, and unsustainable, based on the change rate of the eco-environment, and the economic growth rate.

The impact of human activities on the eco-environment must be maintained within the boundary of the planet, which is the safe threshold and operating space of the earth's systems [34]. Threshold changes at the local or regional scale can affect functioning at the planetary level, so local or regional boundaries are necessary to be estimated in the process of urbanization [35]. On this basis, some studies identified the thresholds of ESs response to population and economic urbanization [4]. The eco-environment has a specific demographic, economic, and social carrying capacity and safe minimum standards in different regions, which is one of the essential characteristics of the eco-environment [36]. This provides a basis for analyzing the interaction relationship between the eco-environment and urbanization from the perspective of the eco-environment carrying capacity. However, as an important part of the eco-environment, the eco-environment carrying capacity has not been given appropriate consideration in the investigation of the interactive coupling relationship of the eco-environment and urbanization. Moreover, with the development of urbanization and regional economic integration in China, the circulation of population, resources, technology and other factors among cities is accelerating; thus, some regions gradually form a geographical economic circle, an industrial circle and even an ecological circle [36,37]. The interplay of human activities and the environment in the urban agglomeration area is particularly notable [12]. Therefore, it is of great practical and theoretical significance for the benign coupling of the eco-environment and urbanization in the urban metropolitan area that researchers understand the relationship between economic and social activities, natural resources, and spatial differentiation.

The paper first presents the interactive coupling relationship between the eco-environment carrying capacity and new-type urbanization from a theoretical point of view. Then, the eco-environment carrying capacity evaluation index system is set up using the pressure-state-response (PSR) model, and the coupling model is built. Next, the paper presents the results that discuss the eco-environment carrying

capacity, new-type urbanization level and the coordination degree of the Wuhan Metropolitan Area in 2016. The discussion that follows reviews the research on the coupling relationship between the two systems. Finally, the paper provides some policy recommendations and suggestions for future work.

2. The Interactive Coupling Relationship of the Eco-Environment Carrying Capacity and Urbanization

The interactive coupling effect of the eco-environment and urbanization is the process by which two systems interact and influence each other through their respective elements. On the one hand, urbanization affects the quality of the eco-environment through population, air, land, and other factors [38–40]. Specifically, with the migration of rural populations into urban areas and the concentration of nonagricultural industries in urban areas, the scale of urban development land expands continuously [41]. The consumption of water, grain, energy, land, and other environmental elements by social and economic activities has gradually increased, which has resulted in a large amount of domestic waste and industrial pollution and has caused the deterioration of the eco-environment [42,43]. In addition, the growing economic strength of the city has caused the government to promote the use of renewable energy resources and increase investment in environmental protection, which improves the environment to some extent. On the other hand, the eco-environment can also affect the development of urbanization. Environmental pollution may damage human health and lead to population migration and capital exclusion in the form of the relocation of high-tech enterprises with substantial environmental requirements and the emigration of high-quality talents [44]. The pattern that sets a priority on economic development over environmental protection often leads to a decline in the quality and stability of the environment, which will drain follow-up funds for economic development and undermine the progress that urbanization has made [35,45].

The eco-environment carrying capacity refers to the ability of an ecosystem to support the scale of economy and population, which is an important basis for measuring the coordination degree of social and economic development and the ecosystem [46,47]. The resource endowment and environmental capacity of the ecosystem in each city are finite, and development and utilization levels in each city are different; thus, the eco-environment carrying capacity is also finite and heterogeneous [48,49]. The characteristics of carrying capacity have an influence on the regional industrial structure and industrial layout, which, in turn, profoundly affect the direction and urbanization development pattern of each city. Moreover, if the impact of human activities is within the threshold of the eco-environment, the eco-environment and urbanization will support each other and achieve harmonious development. However, once the intensity and the scale of urbanization exceed the carrying capacity of the eco-environment, the environment will deteriorate, and the process of urbanization will be hindered correspondingly. In contrast, urbanization also exerts an influence on the eco-environment carrying capacity. During the early industrialization, wastewater and waste gas are wantonly discharged into local waterways and airsheds [35]. These environmental damages, caused by industrialization and urbanization, lead to a decrease in the threshold and carrying capacity of the eco-environment, which is often irreversible [48]. However, if the investment intensity of environment construction exceeds the ability of the regional economy, the process of urbanization will also be delayed due to the shortage of funds, and as a result, the eco-environment will not be sustainable without economic support (Figure 2).

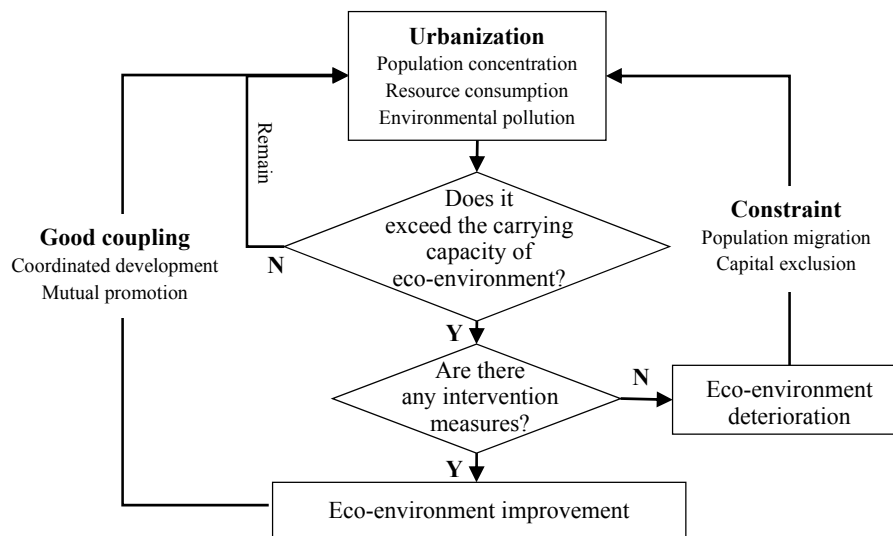


Figure 2. The coupling relationship between the eco-environment carrying capacity and urbanization.

3. Materials and Methods

3.1. Data Preprocessing

The statistical data are available from the statistical yearbook and the water conservancy annals of Hubei Province. Because the dimension and attribute of the evaluation indicators are inconsistent, the indicators should be dealt with using nondimensional processing. Min-Max normalization is the most common method, but some results of this method are equal to 0, which limits the use of the entropy method [50]. Since the efficiency coefficient method can solve this problem [51], this paper selected the efficiency coefficient method to standardize the data. Equation (1) was used as a positive indicator, and Equation (2) was used as a negative indicator.

$$X_{xj} = \frac{x_{xj} - \min\{x_j\}}{\max\{x_j\} - \min\{x_j\}} \times \gamma + (1 - \gamma) \quad (1)$$

$$X_{xj} = \frac{\max\{x_j\} - x_{xj}}{\max\{x_j\} - \min\{x_j\}} \times \gamma + (1 - \gamma) \quad (2)$$

where x_{ij} and X_{ij} are the original value and the normalized value of indicator j of region i , respectively; $\max\{x_j\}$ and $\min\{x_j\}$ are the maximum value and minimum value of indicator j , respectively. γ represents the adjustment coefficient and ranges from 0 to 1. With the growth of γ , the influence of $1 - \gamma$ gradually decreases, the distortion of the original data is smaller, and the influence of γ on the results is smaller. Therefore, this paper made γ equal to 0.9999 so that a value of 0 can be avoided and the influence of the efficacy coefficient method can be minimized.

3.2. Method

3.2.1. Index System of the Eco-Environment Carrying Capacity

Sustainable development theory, the state space method and PSR model provide a theoretical basis for the construction of an evaluation index system of eco-environment carrying capacity. The PSR model is an environmental problem analysis framework that was proposed by the Organization for Economic Cooperation and Development (OECD) and the United Nations Environment Programme (UNEP) in the late 1980s [52]. Because the PSR model can effectively reflect the causal relationship of pressure, state, and response, it is widely used in ecological security, evaluation of the eco-environment carrying capacity, and other studies [53]. The PSR model can reflect the interaction relationship

between humans and the environment. Specifically, how the resource consumption of water, soil, air, and the like exerts pressure on the eco-environment, which results in a decline in environmental quality [54]. These changes in the environment, in turn, affect human consciousness and behavior so that people will mitigate or eliminate these negative effects of human activities through environmental protection and economic policy [55]. This process forms a pressure-state-response relationship between humans and the eco-environment.

In keeping with the PSR model and relevant literature [56,57], this paper selected 17 indicators to analyze the eco-environment carrying capacity in the Wuhan Metropolitan Area (Table 1). The pressure index reflects the negative impact of human activities on the ecosystem during the process of urbanization development. This paper selected seven basic indicators (energy consumption per 10⁴ yuan worth of gross industrial out value, water consumption per 10⁴ yuan worth of GDP, discharged volume of industrial SO₂ per capita, discharge of wastewater per capita, land deterioration index, fertilizer use intensity, value of noise pollution) to address the actual ecological situation of the Wuhan Metropolitan Area. There are some environmental problems in the Wuhan Metropolitan Area, such as the loss of agricultural land, the destruction of forests, water pollution and soil pollution. Accordingly, this paper selected six indicators, including per capita water resources, per capita agricultural land and organism abundance index, to measure the current state of the eco-environment. The response index refers to the policies and measures to restore and improve the eco-environment and includes four indicators (sewage treatment rate, industrial solid waste comprehensively rate, garbage harmless treatment rate, proportion of environmental protection expenditure to GDP).

Table 1. Evaluation index system of the eco-environment carrying capacity and new-type urbanization.

System	First Grade Index	Basic Grade Index	Weight
Eco-environment Carrying capacity	Pressure	Energy consumption (tons of standard coal) per 10 ⁴ Yuan output value	0.0538
		Water consumption per 10 ⁴ Yuan worth of GDP (m ³)	0.0776
		Discharged volume of industrial SO ₂ per capita (kg/capital)	0.0606
		Discharge of wastewater per capita (ton/capital)	0.0398
		Land deterioration index (%)	0.0517
		Fertilizer use intensity (kg/hm ²)	0.0287
		Value of noise pollution (db)	0.0652
	State	Per capita water resources (m ³ /person)	0.0655
		Per capita agricultural land (m ² /capital)	0.0423
		Organism abundance index (%)	0.1100
		Vegetation cover index (%)	0.0443
		Rivers density index (%)	0.0938
		Proportion of days with good air quality (%)	0.0557
	Response	Sewage treatment rate (%)	0.0377
		Industrial solid waste comprehensively rate (%)	0.0456
		Garbage harmless treatment rate (%)	0.1023
		Proportion of environmental protection expenditure to GDP (%)	0.0252
Population urbanization	Proportion of the urban population to the total population (%)	0.0404	
	Urban population density (persons/km ²)	0.0751	
Economy urbanization	Per capita GDP (Yuan)	0.0567	
	Proportion of the value of the secondary and tertiary industry to GDP (%)	0.0302	
	Proportion of the added value of the high-tech industry in GDP (%)	0.0876	
	Proportion of foreign investment actually utilized to GDP (%)	0.0728	
Space urbanization	Proportion of built-up areas to urban areas (%)	0.0729	
	Per-unit area financial revenue (10 ⁴ Yuan/km ²)	0.1720	
	Per-unit area investment in fixed assets (10 ⁴ Yuan/km ²)	0.0892	
Social urbanization	Proportion of public security and employment expenditure to financial expenditure (%)	0.0851	
	Proportion of education expenditure to GDP (%)	0.0423	
	Numbers of sickbeds per 10 ⁴ persons	0.0281	
	Gas utilization rate (%)	0.0316	
Urban-rural integration	Ratio of urban households' to rural households' per capita disposable income (%)	0.0627	
	Ratio of urban households' to rural households' per capita consumption expenditure (%)	0.0287	
	Ratio of urban households' to rural households' Engel coefficient (%)	0.0246	

Notes: The indexes of Pressure are negative.

3.2.2. New-Type Urbanization Index System

The existing literature has analyzed the level of urbanization development from economic development, urban population growth and urban spatial expansion. New-type urbanization focuses on the living standards of people, industrial transformation and upgrading, ecological civilization, and urban and rural development [58]. To get closer to the actual situation of China, this paper measured the urbanization level of the Wuhan Metropolitan Area from the perspective of new-type urbanization. This research constructed the evaluation index system of the eco-environment carrying capacity from the three dimensions of pressure, state and response. Therefore, the environmental factors were no longer considered separately in the index system of new-type urbanization. This research measured the quality of new-type urbanization of nine cities in the Wuhan Metropolitan Area through five first-grade indexes (population urbanization, economy urbanization, space urbanization, social urbanization, and urban–rural integration) and sixteen basic indicators (proportion of the urban population to the total population, urban population density, per capita GDP, etc.) (Table 1).

First, some scholars select the indicators of numbers of students in college per 10^4 persons and numbers of sickbeds per 10^4 persons to reflect the recessive population urbanization [59]. However, this research argues that population urbanization emphasizes the process of rural population concentration in cities and towns. Many scholars agree with this view and classify these recessive indicators as reflecting social urbanization [60]. Therefore, this paper chose two indicators, urban population density and the proportion of the urban population within the total population, which together represent urban population expansion and population agglomeration. Second, new-type urbanization emphasizes the transformation of industrial structure and the driving role in economic development. This research selected four basic grade indexes to characterize economy urbanization (per capita GDP, proportion of the value of the secondary and tertiary industry to GDP, proportion of the added value of the high-tech industry in GDP, proportion of foreign investment actually utilized to GDP). Third, new-type urbanization refers to the expansion of urban areas in geographical space, which can be represented by the proportion of built-up areas to urban areas. It also refers to the input and output of land-intensive use, which can be represented by per-unit area financial revenue and per-unit area investment in fixed assets. Fourth, new-type urbanization considers the development of humankind as the core goal and aims to improve the quality of life for urban and rural residents and the level of urban public services. Accordingly, this paper selected indexes of social urbanization using social security, employment, education and medical care. Finally, new-type urbanization contributes to the narrowing of the income gap between urban and rural residents and the sharing of modernization achievements [61]. The ratio of urban households' to rural households' per capita disposable income, ratio of urban households' to rural households' per capita consumption expenditure, and ratio of urban households' to rural households' Engel coefficient were selected to measure the level of urban and rural development.

In this research, the entropy method was adopted to determine the weight of each index, shown in Table 1, and then the comprehensive index of the eco-environment carrying capacity and new-type urbanization was calculated according to the standardized value of each index (Equations (3) and (4)).

$$f(x) = \sum_{i=1}^m w_i X_i \quad (3)$$

$$g(y) = \sum_{j=1}^n w_j Y_j \quad (4)$$

where $f(x)$ stands for the general function of eco-environment carrying capacity and $g(y)$ stands for the general function of new-type urbanization. X_i and w_i are the values of indicator i of eco-environment

carrying capacity and its weight, respectively. Y_j and w_j are the values of indicator j of new-type urbanization and its weight, respectively.

3.2.3. Coupling Model

Many studies have used static coupling models, which are based on the studies of Liao [62] and Liu et al. [63], to analyze the coordination degree of two systems. However, there are many problems, including the error of equation and the inconsistency between calculation result and equation, in the application of static coupling models. Based on the above problems, this paper discusses the use of static coupling models of two systems in the existing literature. Liu et al. [63] proposed the multisystem coupling model (Equation (5)) and the coupling model for urbanization and the eco-environment based on the concept of physics coupling. They classified the coupling degree C into four stages: (1) when $0 < C \leq 0.3$, it is low-level coupling stage; (2) when $0.3 < C \leq 0.5$, it is antagonistic stage; (3) when $0.5 < C \leq 0.8$, it is break-in stage; and (4) when $0.8 < C \leq 1$, it is high-level coupling stage. However, this research finds that the coupling model of urbanization and the eco-environment is not consistent by comparing these two papers (Equations (6) and (7)). Although this inconsistency does not affect the ordering of the coupling degree, it has led to the misuse of the equation and the stage of coupling degree in some studies. From the value range and the stage of the coupling degree, the coupling degree of two systems should be measured by Equation (7). However, from the general function of the multisystem coupling model (Equation (5)), the coefficient that is equal to 2 in Equation (7) will be discussed. Meanwhile, when $k = 0.5$ in Equation (8), Equation (7) is equal to Equation (8). The previous study has shown that the value of k has a great influence on the distribution of coupling degree C [63]. When k is less than or equal to 0.5, the value of the coupling degree C is highly concentrated in $[0.8, 1]$. Therefore, the accuracy and rationality of Equation (7) need to be further explored.

$$C = \left\{ \frac{(u_1 \cdot u_2 \cdots u_m)}{\prod(u_i + u_j)} \right\}^{\frac{1}{p}} \tag{5}$$

$$C = \left\{ \frac{u_1 u_2}{[u_1 + u_2]^2} \right\}^{\frac{1}{2}} \left(0 \leq C \leq \frac{1}{2} \right) \tag{6}$$

$$C = 2 \left\{ \frac{u_1 u_2}{[u_1 + u_2]^2} \right\}^{\frac{1}{2}} = \left\{ \frac{u_1 u_2}{\left[\frac{u_1 + u_2}{2} \right]^2} \right\}^{\frac{1}{2}} \left(0 \leq C \leq 1 \right) \tag{7}$$

In accordance with the principle of the minimum of the mean square deviation, Liao [62] proposed the coupling degree and the coupling and coordination development degree to measure the synergy between economy and environment. That study also suggests that the coupling and coordination development degree is more stable than the coupling degree and that coupling and coordination development is most suitable to evaluate the coordination between the two systems in different regions or in different periods. Subsequently, many scholars have carried out extensive research on the coupling relationship of two systems [64]. Therefore, the present study measured the coupling degree and the coupling and coordination development degree of nine cities in 2016 and classified the coupling and coordination development degree into ten types, shown in Table 2, based on the research of Liao [62] (Equations (8)–(10)).

$$C = \left\{ \frac{f(x) \cdot g(y)}{\left[\frac{f(x) + g(y)}{2} \right]^2} \right\}^k \tag{8}$$

$$T = \alpha f(x) + \beta g(y) \tag{9}$$

$$D = \sqrt{C \times T} \tag{10}$$

where C represents the coupling degree and k is the adjustment coefficient ($k \geq 2$). T stands for the overall benefit of the eco-environment carrying capacity and new-type urbanization. α and β are undetermined coefficients ($\alpha = \beta = 0.5$). The coupling and coordination degree is represented by D . Considering the distribution of the coupling degree, this research made k equal to 2. As mentioned in the introduction, the eco-environment carrying capacity and new-type urbanization influence each other. They are both important in the process of urbanization development, so putting particular emphasis on one of them could damage the development of urbanization [65]. Therefore, in this paper, both α and β are made equal to 0.5.

Table 2. Criteria and types of the coupling and coordination development degree.

Type	Value Interval (D)	Subtype
The coordinated development	0.9001–1.0000	The best coordinated development
	0.8001–0.9000	The good coordinated development
	0.7001–0.8000	The moderate coordinated development
	0.6001–0.7000	The elementary coordinated development
Excess	0.5001–0.6000	The reluctant coordinated development
	0.4001–0.5000	The edge of maladjustment
Maladjustment	0.3001–0.4000	The mild maladjustment
	0.2001–0.3000	The moderate maladjustment
	0.1001–0.2000	The severe maladjustment
	0.0000–0.1000	The extreme maladjustment

4. Results

The results of the coupling model are presented in Table 3. Based on the above results, this paper analyzes the level of the eco-environment carrying capacity, the quality of new-type urbanization and the coordination of the two systems in the Wuhan Metropolitan Area in 2016.

Table 3. Comprehensive index and coupling degree of the eco-environment carrying capacity and new-type urbanization in the Wuhan Metropolitan Area.

Region	Eco-Environment Carrying Capacity $f(x)$	New-Type Urbanization $g(y)$	The Coupling Degree C	The Overall Benefit T	The Coupling and Coordination Development Degree D
Wuhan	0.4269	0.8021	0.8223	0.6145	0.7108
Huangshi	0.5352	0.3081	0.8602	0.4216	0.6023
Ezhou	0.3149	0.3512	0.9941	0.3330	0.5754
Xiaogan	0.3909	0.2431	0.8944	0.3170	0.5325
Huanggang	0.6135	0.2247	0.6161	0.4191	0.5082
Xianning	0.6770	0.1300	0.2921	0.4035	0.3433
Xiantao	0.5032	0.1905	0.6349	0.3469	0.4693
Qianjiang	0.4399	0.2773	0.8999	0.3586	0.5681
Tianmen	0.3759	0.2369	0.8998	0.3064	0.5251

4.1. Spatial Distribution Characteristics of the Eco-Environment Carrying Capacity

To clearly illustrate the spatial distribution characteristics of the eco-environment carrying capacity, this research divided the eco-environment carrying capacity into five types: (1) when $0 \leq f(x) \leq 0.2$, it is poor; (2) when $0.2 < f(x) \leq 0.4$, it is relatively poor; (3) when $0.4 < f(x) \leq 0.6$, it is average; (4) when $0.6 < f(x) \leq 0.8$, it is relatively good; and (5) when $0.8 < f(x) \leq 1$, it is good. The Jenks natural breaks classification method is a data clustering approach that finds the optimal arrangement of data sets by calculating each class's average deviation within classes and between classes [66,67]. This method was adopted to analyze the spatial differentiation characteristics of pressure, state, and response (Figure 3).

As shown in Figure 3, the eco-environment carrying capacity in the Wuhan Metropolitan Area in 2016 is relatively sustainable, with values distributed between 0.3149 and 0.6770. There were three types of eco-environment carrying capacity identified: relatively poor, average, and relatively good, which accounted for 22.61%, 30.35%, and 47.04% of the total area of the Wuhan Metropolitan Area, respectively. First, the eco-environment carrying capacities of Ezhou (0.3149), Xiaogan (0.3909), and Tianmen (0.3759) are classified as relatively poor. This indicates that social and economic activities have exerted great

stress on the environment and that local governments pay insufficient attention to the eco-environment. Second, the eco-environment carrying capacities of Wuhan, Huangshi, Qianjiang, and Xiantaos are classified as average. This suggests that the impact of human activities on the eco-environment in these regions remains within the threshold of the ecosystem. The resources and the environment can meet the needs of the current regional economic development. Third, the eco-carrying capacities identified as relatively good, including Huanggang and Xianning, are the most widely distributed.

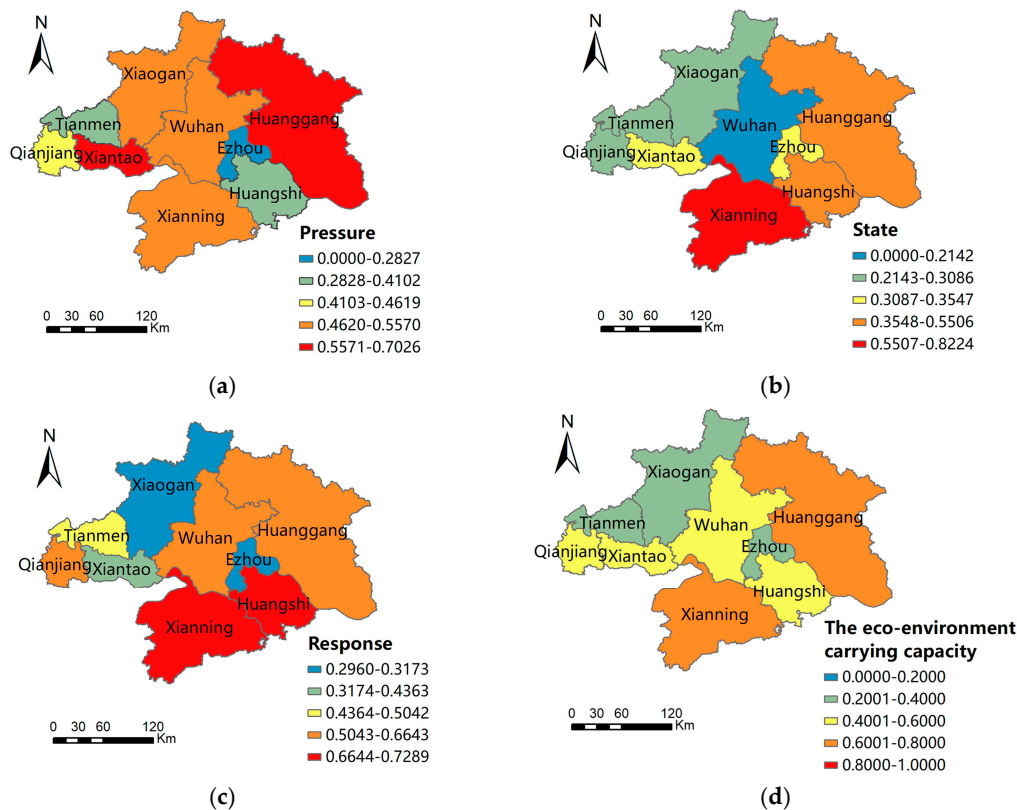


Figure 3. Spatial distribution of the eco-environment carrying capacity with each dimension in the Wuhan Metropolitan Area. (a) Pressure (b) State (c) Response (d) The eco-environment carry capacity.

These data show different spatial distribution characteristics from the perspective of each dimension of the eco-environment carrying capacity in Figure 3. First, the index of pressure is a negative indicator, which means that the smaller the index value is, the greater the pressure of the regional eco-environment will be. Ezhou is dominated by traditional industries that consume large amounts of resources and release large pollutant emissions. The value of traditional industries accounted for more than 60% of the total industrial output value in 2016, which is the greatest environmental pressure in Ezhou (0.2827) in Figure 3a. Figure 3b reflects the current state of the regional ecosystem. Xianning, which has the important national ecological functional zones and is the main production district of farm products, has good water and biological and forest resources with the highest index of state (0.8224). In contrast, Wuhan has a large population and a large amount of construction land. Tail gas pollution and raised dust pollution in Wuhan are particularly significant, and the index of state in Figure 3b is at the lowest level (0.2142). Second, as shown in Figure 3c, the indexes of response in Ezhou (0.2960) and Xiaogan (0.3173) are very low in the Wuhan Metropolitan Area because the index of environmental protection expenditure has a great influence on the index of response.

4.2. Spatial Distribution Characteristics of New-Type Urbanization

To clearly describe the spatial distribution characteristics of new-type urbanization with each dimension in the Wuhan Metropolitan Area, this study adopted the Jenks natural breaks classification

method to analyze the urbanization level of nine cities. As shown in Figure 4f, the quality of new-type urbanization in nine cities shows clear spatial heterogeneity, which means that they are in uneven states of development. The average quality of new-type urbanization is 0.3071, and only Wuhan, Ezhou and Huangshi are more than the average. Moreover, new-type urbanization in Wuhan (0.8021) is significantly higher than that in other cities (≤ 0.3512).

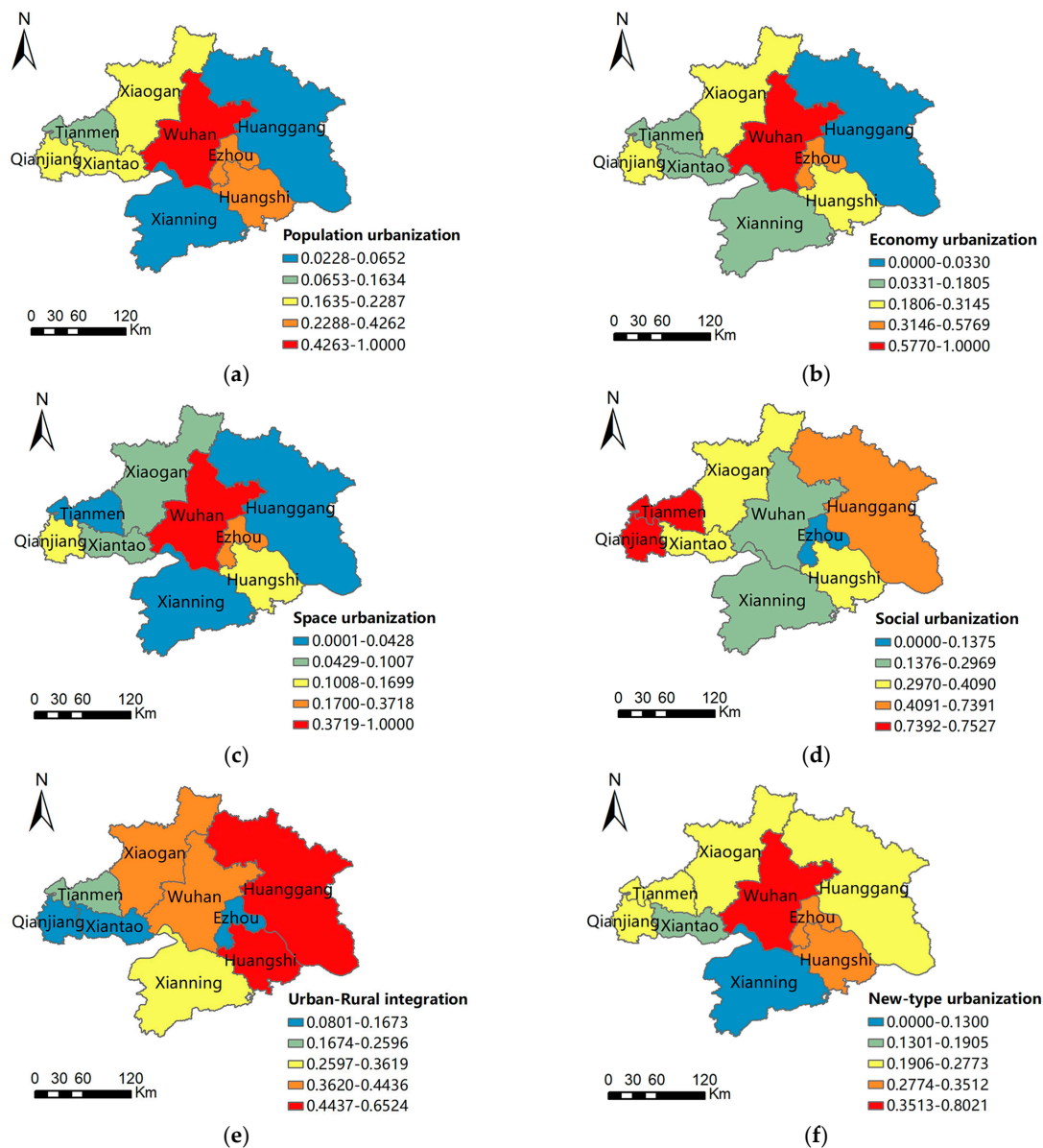


Figure 4. Spatial distribution of new-type urbanization with each dimension in the Wuhan Metropolitan Area. (a) Population urbanization (b) Economy urbanization (c) Space urbanization (d) Social urbanization (e) Urban-Rural integration (f) New-type urbanization.

Figure 4 shows that the cities have different spatial distribution characteristics in each dimension of new-type urbanization. First, as shown in Figure 4a, Wuhan, followed by Ezhou, is dominant in terms of population urbanization. The quality of population urbanization in Xianning (0.0652) and Huanggang (0.0228) is low. The proportion of the urban population to the total population in Wuhan is 35.01% higher than that in Huanggang, and the urban population density in Wuhan is 87.03% higher than that in Xianning. Second, as the engine of economic development in the Wuhan Metropolitan Area, Wuhan still has great advantages in economy urbanization. The proportion of the value of

the secondary and tertiary industry to GDP and the proportion of the added value of the high-tech industry in GDP in Wuhan rank first in the Wuhan Metropolitan Area. Ezhou has developed rapidly in recent years. The index of economy urbanization (0.5769) of Ezhou has exceeded that of Huangshi, which is a subcentral city of Hubei Province. The economy of Xiaogan, Qianjiang, and other cities is relatively weak, especially Huanggang. Third, Figure 4c shows that the Wuhan Metropolitan Area is in “a dominant” situation in terms of space urbanization. Wuhan, followed by Ezhou, has the highest proportion of built-up area in urban zones and land use efficiency. The value of the space urbanization index in other cities is less than 0.2000. Fourth, as shown in Figure 4d and Table 2, there is a significant gap in social urbanization in the Wuhan Metropolitan Area, reflecting the uneven distribution of medical, social security, education, and municipal construction in nine cities. Last, because the income and consumption expenditures of urban households and rural households in Qianjiang, Xiantao, and Ezhou are quite different, the degree of urban–rural integration in these regions is at a low level (Figure 4e). The gap in income and expenditure between urban areas and rural areas in Huanggang and Huangshi is small, so the degree of urban–rural integration is relatively high.

4.3. Spatial Distribution Characteristics of the Coupling and Coordination Development Degree

As shown in Table 2 and Figure 5, there are significant differences in the coordination degree between the eco-environment carrying capacity and new-type urbanization in the Wuhan Metropolitan Area. The coupling and coordination development degree, which ranges from 0.3433 to 0.7108, can be classified into five types. The coupling and coordinated development degree in the Wuhan Metropolitan Area is no more than 0.5, excepting Wuhan and Huangshi (Table 2). There are seven cities that are classified as having reluctant coordinated development (Figure 5).

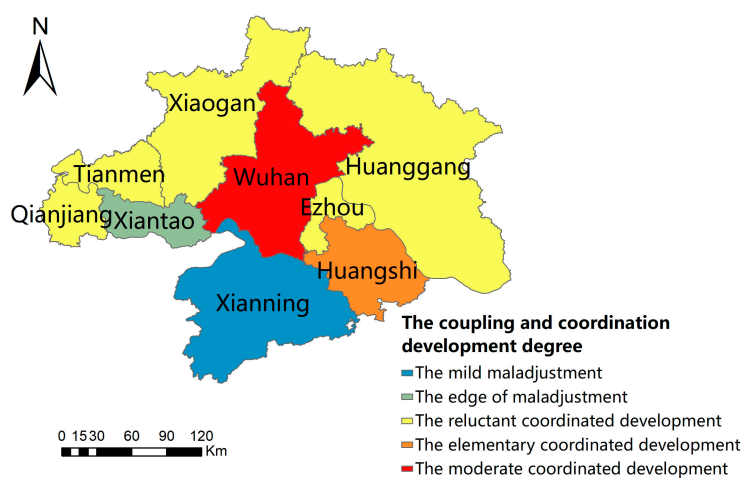


Figure 5. The spatial distribution of the coupling and coordination development degree in the Wuhan Metropolitan Area.

First, Figure 5 shows that Wuhan is classified as having moderate coordinated development. Although Wuhan is an economy-lagged city, the eco-environment carrying capacity in Wuhan is still classified as relatively good. This is because the value of the tertiary industry accounts for a high proportion of overall industry (52.84%) and the industrial structure is upgraded rapidly. In addition, awareness of environmental protection has been continuously improved. This region needs to upgrade traditional industries, such as steel, automobile, and building material. Based on the existing advantages, new industries, such as information technology, biological, and new material industries, should be systematically developed. Moreover, it is necessary to strengthen dust control and tail gas treatment and carry out ecological restoration of lake, soil and contaminated sites to form a benign interaction between the eco-environment and new-type urbanization.

Second, as shown in Table 2 and Figure 5, the index of the eco-environment carrying capacity of Huangshi (0.5352) is larger than the index of new-type urbanization (0.3081), which means that Huangshi is classified as economy-lagged and having elementary coordinated development. Due to the reduction of mineral resources in Huangshi, the number of metallurgy, energy, and building materials industries relying on mineral resources has gradually declined. It is essential to improve the quality and efficiency of economic development by seeking out and promoting substituted industrial development.

Third, Figure 5 shows that Ezhou, Huanggang, Xiaogan, Qianjiang, and Tianmen are classified as having reluctant coordinated development. This type is the most widely distributed in the Wuhan Metropolitan Area. Specifically, Ezhou is an environment-lagged city. The economic development of Ezhou is still dominated by heavy chemical industries with high consumption and high pollution, which has resulted in environmental pollution and ecological deterioration. The restriction of resources on urbanization development is increasing. Thus, seeking industrial optimization and upgrading is one of the major problems in Ezhou. As shown in Table 2, Huanggang, Xiaogan, Qianjiang, and Tianmen are classified as economy-lagged. The impact of social and economic activities on the eco-environment in these regions is still within the threshold of the carrying capacity of the eco-environment. The coupling degrees of Xiaogan (0.8944), Qianjiang (0.8999), and Tianmen (0.8998) are relatively high. However, the coupling and coordination development degrees of the three cities, which are 0.5325, 0.5681, and 0.5251, respectively, are not high. However, if the natural resources are overexploited in these regions, the carrying capacity of the eco-environment will decline, and the state of regional coordination will be broken. Therefore, coordinating the relationship between economic development and eco-environment construction is particularly important for these regions. As shown in Table 2, the quality of new-type urbanization of Huanggang (0.2247) is close to that of Xiaogan (0.2431), Qianjiang (0.2773), and Tianmen (0.2369), but the eco-environment carrying capacity of Huanggang (0.6135) is much higher than that of these three cities (from 0.3759 to 0.4399). Huanggang has rich ecological tourism resources and historical and cultural heritage, and it belongs to the Dabie Mountains Red Tourist Area [68]. Red tourism is a kind of tourism product with Chinese characteristics, which refers to various tourism resources related to the Chinese revolution and aims to promote patriotism and revolutionary spirit [69]. This indicates that Huanggang fails to make full use of rich natural resources, especially red tourism resources.

Fourth, Figure 5 shows that Xiantao is classified as on the edge of maladjustment. As shown in Table 2, the eco-environment carrying capacity of Xiantao is relatively high (0.5032), but the level of new-type urbanization is low (0.1905), which results in a lower degree of coupling and coordination development (0.4693). This suggests that many local resources have not been effectively utilized. The region should increase infrastructure investment and appropriately expand the scale of the city. At the same time, Xiantao should take advantage of local resource endowments to develop modern agriculture.

Finally, Figure 5 shows that Xianning is classified as having mild maladjustment. As shown in Table 2, the index of the eco-environment carrying capacity (0.6770) is much higher than the index of new-type urbanization (0.1300). The coupling degree (0.3064) and the coupling and coordination development degree (0.3433) in Xianning are the lowest in the Wuhan Metropolitan Area. In fact, with the unique superiority in agricultural and traveling resources, Xianning can develop ecological agriculture and ecological tourism to promote the development of urbanization. More significantly, since Xianning undertakes the dual functions of economic development and ecological conservation, it must protect natural conditions and the eco-environment as a precaution in case of the deterioration of the ecosystem.

5. Discussion

As mentioned in the introduction, this paper aimed to uncover the interactive coupling relationship between the eco-environment and new-type urbanization in the Wuhan Metropolitan Area from the perspective of the eco-environment carrying capacity. This research found that the spatial

distribution of the eco-environment carrying capacity in the Wuhan Metropolitan Area was different. Some researchers have suggested that the carrying capacity is varied and dynamic and depends on resource endowments and the interaction between humans and the environment [48,70]. In fact, many subsystems of the earth, such as climate change, groundwater exploitation, and biodiversity loss, have reached or are approaching their natural limits [34,71,72]. Lifestyles and socioeconomic activities need to be coordinated with the finite carrying capacity and environmental conditions in different regions [47]. In addition, this paper confirms what previous studies have indicated that the character and quality of new-type urbanization vary greatly from region to region, and differentiated urbanization development models need to be adopted [73]. The level of new-type urbanization in the urban metropolitan area often presents a “dominant” situation, such as that found in the Central Plains [74].

Using the coupling degree and the coupling and coordination development degree, this paper analyzed the relationship between the two systems. It has been proved that the coupling and coordinated development degree is more suitable to analyze the coordination degree of the two systems in different regions than the coupling degree [62]. The value of the coupling degree is highly concentrated from 0.8 to 1, and it is more stable for measuring the coordination degree of the two systems by using the coupling and coordinated development degree [56]. Similarly, this research showed that the coupling degree of the Wuhan Metropolitan Area is mostly distributed between 0.8 and 0.9. The distribution of the coupling and coordinated development degree is more uniform than the coupling degree. In addition, by comparing the coupling degree and the coupling and coordination development degree of the nine cities in the Wuhan Metropolitan Area, it can be found that there is no positive correlation between the two values. The coupling degree does not necessarily match the coupling and coordination development degree, and the high coupling level does not necessarily lead to a high coupling coordination level. Many scholars have studied the relationship between human activities and the environment in different ways. Wang et al. [33] adopted the double-exponential curve to analyze the relationship between urbanization and the eco-environment and the results indicated that the relationship can be described as an inverted U-shaped curve, which is called “The inverted-U shape environmental Kuznets curve (EKC)” [75]. However, some studies have argued that the EKC is insufficient to describe the complexity of the relationship between environment and economic development [76]. Stevenson [77] has shown that the threshold is a key element for coupled human and natural systems and it provides a basis for developing natural resources and preventing catastrophic changes. In addition, various approaches have been used to build the model of coupling social–ecological systems (SES) to explore the interaction relationship between human activities and nature, which can generate the synergistic effect among disciplines related to systemic change [78,79]. But there is still a serious challenge in modeling systemic changes in of the SES—the model may need to be reconstructed if the system undergoes changes [80–82]. A number of new methods and theories have been proposed in recent years which provide a broader analytical perspective with respect to the interactive relationship between human activities and nature. For example, Liu et al. [83] proposed the concept of telecoupling that refers to the interaction between human activities and nature over distances.

This paper showed that the coupling and coordination development degree of the Wuhan Metropolitan Area is not high. Only Wuhan and Ezhou are classified as having moderate or elementary coordinated development. In some areas, the problem that the development of urbanization does not match the eco-environment carrying capacity exists. On the one hand, the resources cannot be effectively exploited and utilized in some regions. Some researchers argue that resource distribution and the flow of production factors are more efficient in the metropolitan area due to the advantage of the economies of scale [84]. However, local governments at all levels will inevitably consider their own benefits, such as GDP, fiscal revenue, and tax losses, which will lead to the failure of voluntary cooperation and the inefficient utilization of resources [85]. Although the National Plan on New-type Urbanization (2014–2020) has already provided specific guidance for all levels of government, including

cooperation, the implementation of policy is a long-term process and has many obstacles. The Wuhan Metropolitan Area occupies a leading position and is now in a period of rapid growth where the gather function is stronger than the spreads function. This paper also showed that the overall urbanization development quality of the Wuhan Metropolitan Area is not high, and Wuhan plays a major role in population urbanization, economy urbanization, and space urbanization. In 2016, the National Development and Reform Commission (NDRC) supported Wuhan in beginning to building a national central city, which means that many labor, material, finance, and other elements with high quality will be transferred from other cities to Wuhan. The radiation effect of Wuhan on surrounding cities will also be weakened. Due to inadequate investment, superior characteristic industries of these regions, such as the hot spring tourism of Xianning and the red tourism of Huanggang, will not be fully developed. Therefore, it is important to implement differential industry strategies and appropriate urbanization development patterns for nine cities to coordinate resources among cities and avoid industrial convergence.

On the other hand, economic development exceeds the carrying capacity of the eco-environment in some regions. Since the idea of constructing a resource-saving and environmentally friendly society was put forward in 2007, the government of Hubei province has also made many attempts at industrial structure optimization, traffic network construction and regional coordination and communication mechanisms, such as the intercity railway of the Wuhan Metropolitan Area. The economies of surrounding cities rely on Wuhan and have had a certain degree of development, especially those of Ezhou and Huangshi. Due to geographic position, traffic conditions, industrial structure, and historical factors, Wuhan has a great impact on the social and economic development of Ezhou and Huangshi [86,87]. The results also support the view that the quality of urbanization in Ezhou and Huangshi is relatively high. However, environmental pollution in these regions is becoming increasingly serious, though the government pays less attention to environmental governance. For example, Ezhou is facing the greatest ecological pressure in the Wuhan Metropolitan Area, while its index of response is the lowest. Accordingly, how to solve the conflict between economic development and environmental protection is the key issue for these environment-lagged regions.

6. Conclusions

The Wuhan Metropolitan Area is now in a period of rapid growth. With the expansion of scale and space, many regions are also facing increasingly severe challenges related to resources and the environment. Therefore, this paper proposes corresponding policies from the aspects of coordinating the industrial division of labor, focusing on the eco-environment carrying threshold and strengthening policy guidance in an attempt to achieve the sustainable development of society, economy and eco-environment.

First, it is essential to clarify the development direction and function orientation of each city. The local industrial structure and the proper regional functional system must be established based on comparative advantage. The correlative and synergetic effect of industries should be fully developed to promote the coordinated development of Wuhan and surrounding cities. Second, due to the spatial heterogeneity of the eco-environment carrying capacity of the region, close attention should be paid to the threshold of the eco-environment carrying capacity and set up of the risk warning of the eco-environment for each city. A differentiated urbanization development strategy that is compatible with each city's eco-environment carrying capacity should be formulated. Last, policy guidance from the government at all levels is needed. To properly utilize natural resources, differentiated development patterns, including the regional industrial layout and spatial development pattern, should be scientifically planned. The government should strengthen the connection between urban master planning and general land use planning between cities and the Wuhan Metropolitan Area.

This paper analyzes the interactive coupling relationship between the eco-environment carrying capacity and new-type urbanization in the Wuhan Metropolitan Area by using data from 2016. It can provide some recommendations for guiding rational urbanization development. However, the static

coupling model cannot show the internal interaction of systems such as water, land, air and population, so the question of the internal structure of the systems remains to be discussed.

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