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Temporal and Spatial Changes in Coupling and Coordinating Degree of New Urbanization and Ecological-Environmental Stress in China

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Abstract: Over the past years, new urbanization in China has accelerated steadily and led to a continuous increase in ecological-environmental (eco-environmental) stress. A deep understanding of the coupling relationship between new urbanization and ecological-environmental stress is essential to benefiting the urban management in making decisions. How to realize the coordinated development of urbanization and the eco-environment is not only the key issue in world economic and social development, but has also been a hot topic of research in recent years. However, the quantitative relationship and the interaction mechanism between the new urbanization and ecological-environmental stress are still unclear. To fill this gap, this study constructed comprehensive assessment indicators for evaluating new urbanization and eco-environmental stress systems to accomplish the following objectives. We aimed to identify the spatial and temporal pattern of coupling and coordinating degree between new urbanization and eco-environmental stress in China during the period of 2005–2016. The degrees of coupling and coordination of new urbanization and eco-environmental stress systems in China in 2005, 2010, and 2016 were calculated at the provincial level. The degrees of coupling and coordination have achieved stable and continuous improvement from 0.389 to 0.484. We further aimed to evaluate the regional coupling and estimate the stage of urbanization at which an optimal outcome could be achieved in order to ensure high-quality urbanization in China. According to the model of coupling and coordination degree, this paper divided the Chinese territory into four area types: well coordination, middle coordination, primary coordination, and reluctance coordination, and about 35% of the provinces belonged to the well and middle coordination types. Lastly, this paper analyzed the spatial pattern and cluster mode of the coupling coordination of new urbanization and eco-environmental stress systems by using ArcGIS and GeoDa. The analysis implied that coupling coordination existed with obvious regional disparity. Moreover, the degrees of coupling coordination of the developed east coastal and middle area were generally higher than those of the undeveloped west area. The findings indicate that for different regions, the reluctance coordination and primary coordination subclass regions should accelerate to realize green transformation, improve the industrial structure, and strengthen the environmental law-enforcing supervision. However, we could not conduct an internal structural analysis. Future research will focus on conducting an internal structural analysis and an element system metrics analysis.

Keywords: new urbanization; eco-environmental stress; degree of coupling and coordination; temporal and spatial changes

1. Introduction

China's urbanization has been a momentous event that has attracted wide international attention [1]. Since the reform and opening-up in China, its urbanization has made great achievements over the past 40 years, with the rate reaching up to 58.52% by the end of 2017. With the increasing growth of the urbanization rate, various problems, such as the continuous expansion of urban space, traffic congestion, and environmental degradation, are also gradually being highlighted [2–4]. Since the report of the 18th CPC national congress explicitly put forward the concept of new urbanization, this was the first official plan to regard new urbanization and ecological civilization as national policies [5,6]. Compared with previous urbanization development, which was more focused on scale expansion, population concentration, and spatial spread [7], new urbanization mainly focuses on the quality of urbanization development. On one hand, it is well-known that rough-type urbanization, besides having important socioeconomic impacts, also has many harmful ecological effects [8]. However, the new urbanization is based on sustainable development and urbanization quality, with the pursuit of the coordinated development of the economy, society, resources, and the environment [9]. On the other hand, the ecological environment is the foundation for the subsistence and development of human beings. Unfortunately, environmental pollution and ecological destruction caused by human economic activities has exerted great pressure on this foundation.

As a physical concept, coupling refers to the phenomenon where two (or more) systems affect each other through various interactions [10]. Similarly, the phenomenon where the two systems (new urbanization system and eco-environmental stress system) interact through their coupling factors is called the coupling system of new urbanization and ecological-environmental stress. In fact, there is an extremely complex interactive coupling relationship between new urbanization and eco-environment stress. Only through coordinated development can we promote the sound development of urbanization in an all-round way [11]. The new urbanization system influences the ecological-environmental stress system through the waste discharge generated in the process of urbanization activities. The ecological-environmental stress system provides space for the processing of new urbanization, as well as the final waste discharge. The new urbanization system has a stress effect on the environmental system, while the ecological-environmental stress system has a constraint effect on the new urbanization system. Therefore, the improvement of environmental quality can provide impetus and opportunity for new regional urbanization development.

On the basis of urbanization and ecological environment assessment, the research focuses mainly on the interaction mechanism between urbanization and the ecological environment, and new progress has been made in the coordinated development of urbanization and the ecological environment system. The interaction between new urbanization development and the ecological environment has gradually become a research hotspot in the related fields.

In terms of urbanization and ecological environmental system evaluation, domestic and foreign scholars have yielded substantial results about urbanization and ecological environment assessment. For example, David et al. defined urban areas in terms of population scale, land use scale, and population density [12]. Sanjib et al. took the population density, population change, and the density of commercial and residential areas within 5 km as the urbanization evaluation indexes [13]. Piotr et al. suggested that urbanization measurement should also consider the visible landscape changes, especially in the suburban area [14]. Maraja held the opinion that cultural ecosystem services play a crucial role in the process of urbanization [15]. Fang Chuanglin and Chen Mingxing et al. modified the comprehensive measurement index system of urbanization in China and obtained abundant research results [16,17]. Besides, much research has been conducted on the evaluation of ecological environmental pressure, and put forward many methods, such as the ecological footprint analysis method, green accounting method, emergent analysis method, comprehensive index method [18–20], etc.

Many scholars have also carried out relevant research on the interaction and coupling mechanism between urbanization and the ecological environment. For example, the International Human

Dimensions Programme on Global Environmental Change (IHDP) focused on the study of the interrelationship and interaction mechanism between urbanization and global change [21]. Deosthali simulated the impact of urbanization on local urban climate [22]. Deplazes et al. analyzed the multiple impacts of urbanization on urban wildlife [23]. Recently, the most prominent study has been a group of articles on cities published by Grimm et al. in January 2008 in the scientific journal *Science*. Among them, «Global change and the ecology of cities» explored the environmental changes and responses of urban social ecosystems at different scales, such as local, regional, and global, caused by human activities in the context of global environmental change [24]. Li discussed the coupling and coordination between the urbanization system and ecological environment system [25]. However, other scholars have studied the relationship between one aspect of the urbanization process and another aspect of the eco-environmental system. For example, Deosthali simulated the impact of urbanization on the local urban climate [22]. Vester and Von Hesler revealed the interaction mechanism between urban economic development and its environmental evolution [26]. Schoukens discussed the reconciliation ecology in practice during the process of urban development in the European Union [27]. At present, international research on the coupling relationship between urbanization and the ecological environment mainly focuses on the basic laws, mechanism, and rule of dynamic evolution [28,29]. Fang Chuanglin et al. systematically analyzed the basic theoretical framework of the interaction and coupling effect of urbanization and the ecological environment in megalopolis [30]. Cocklin et al. studied the relationship between urbanization and environmental vulnerability and human security in the south Pacific [31]. Chen et al. respectively constructed a comprehensive evaluation index system for urbanization from four aspects of population, economy, society, and land, and conducted a comprehensive measurement of urbanization since the reform and opening up based on the entropy value method. The study showed that the rapid evolution of urbanization had a wide and profound impact on resources, energy, and the environment [32]. Aiming at the relationship between new urbanization and the ecological environment carrying capacity, several scholars analyzed the interactions between urban agglomerations from different regions, such as Gansu, Chongqing, Xi'an, and the Yangtze River Delta [33–35].

Summarizing the above studies, we found that the quantitative relationship and the interaction mechanism between the new urbanization and ecological-environmental stress are still especially unclear. Additionally, the research related the new urbanization and eco-environmental stress is relatively weak. Especially at the moment, when China is transforming the development mode of urbanization, there are few research results on how to study the coupling relationship and formation mechanism between new urbanization and eco-environmental stress, and whether the change rules are consistent in different time-space ranges in China. Therefore, there is an urgent need to scientifically answer these questions.

This paper establishes a comprehensive index system for assessment of the level of new urbanization based on four aspects and eco-environmental stress based on three aspects. Furthermore, each indicator in the compound system is weighted with subjective and objective weight determination methods: the methods of AHP (Analytic Hierarchy Process) and the entropy method. Finally, a coupling coordination degree model focusing on the coupling processes and evolution trends of the compound system of new urbanization and eco-environmental stress is established, based on the physical model from 2005 to 2016. By quantitatively measuring the relationship between new urbanization and eco-environmental stress, this paper explores the coupling mechanism between the two systems and divides the Chinese territory into four area types. Finally, the paper also offers scientific decision-making for achieving the goal of eco-environment protection and promoting healthy new urbanization in China.

2. Materials and Methods

2.1. Assessment Objects and Data Sources

The study selected provinces as assessment objects and mainly focused on 31 provincial divisions in mainland China (except for the Hong Kong Special Administrative Region of China, the Macau Special Administrative Region of China, and Taiwan). Data for the indicators were derived from The China Statistical Yearbook of 2006–2017 (National bureau of statistics, 2006–2017) and China Statistical Yearbook on Environment of 2006–2017 (National bureau of statistics, & Ministry of Environmental Protection 2006–2017).

2.2. Constructing the Assessment Indicators of Two Systems

New urbanization has a multi-dimensional connotation. According to the proposal on the national plan for new urbanization: 2014~2020, China's urbanization must enter a new stage of transformation and development by focusing on improving quality. The quality of urbanization development includes the level of urban population employment, social security, education, medical care, infrastructure, the environment, and other aspects, so urbanization quality is the collective name for the pattern of urbanization under the requirement of resource utilization efficiency, space optimization degree, development elements matching, resources and environment carrying capacity, and urban and rural harmonious development. Combined with the previous research perspective and the interpretation of the concept of new urbanization [36–38], this study selected indicators from four directions, including the economic development level, social development level, service facilities level, and natural ecology level, to comprehensively measure the level of new urbanization in the research area.

The indicators of the eco-environmental stress system referred to the system established by Liu Yaobin et al. and Ma Libang et al. [39,40]. This paper also referred to the ecological and environmental pressure index constructed to evaluate the ecological and environmental pressure in the process of industrial economic development in China proposed by Xu Fuli et al. [41]. Zhao Xingguo et al. simplified the weight index to analyze the relationship between regional economic growth and resources and the environment in Yunnan province [42]. Meanwhile, considering the actual situation of the research area and the availability of data, the eco-environmental stress pressure index (resource-environmental Pressure Index) was constructed from the three aspects of the regional resources consumption index, regional environment pollution index, and regional environmental capacity index. The higher the eco-environmental stress index is, the greater the eco-environmental stress of the regional development is, and vice versa.

Following the principles of quantity, totality, purposiveness, systematicity, and scientificity [43], this paper constructed the evaluation index system. At the same time, when selecting the major indicators affecting new urbanization and eco-environmental stress, we drew upon existing achievements and the actual situation in developed regions. Then, the evaluation index systems for new urbanization and eco-environmental stress were established, which are shown in Table 1. At the same time, in order to avoid the influence of different dimensionalities of each indicator in the index system, the paper adopted the range-method to conduct standardized processing of data.

Table 1. Indicators for evaluating new urbanization and eco-environmental stress systems.

| System Layer | Factor Layer | Indicator Layer | Indicator Properties |
|---------------------------------------|--|--|----------------------|
| New urbanization system (NUR) | Economic development level (X ₁) | Per capita GDP (CNY) — <i>m</i> ₁ | + |
| | | Three production ratio (%) — <i>m</i> ₂ | + |
| | | Actual utilized foreign direct investment (10 ⁴ CNY) — <i>m</i> ₃ | + |
| | | Financial general public budget revenue (10 ⁴ CNY) — <i>m</i> ₄ | + |
| | | Total fixed assets investment (10 ⁴ CNY) — <i>m</i> ₅ | + |
| | Social development level (X ₂) | Business total of posts and telecommunications (10 ⁴ CNY) — <i>m</i> ₆ | + |
| | | Unemployment registration rate (%) — <i>m</i> ₇ | - |
| | | Population of Internet users (10 ⁴ person) — <i>m</i> ₈ | + |
| | | Number of students in ordinary colleges and universities (person) — <i>m</i> ₉ | + |
| | Service facilities level (X ₃) | Per capita road area (m ²) — <i>m</i> ₁₀ | + |
| | | Number of beds in medical and health institutions (units) — <i>m</i> ₁₁ | + |
| | | Number of operating public steam (electric) vehicles at the end of the year (units) — <i>m</i> ₁₂ | + |
| | | Density of highway network (km/km ²) — <i>m</i> ₁₃ | + |
| | Natural ecology level (X ₄) | Per capita green area (m ²) — <i>m</i> ₁₄ | + |
| | | Harmless treatment rate of domestic garbage (%) — <i>m</i> ₁₅ | + |
| Eco-environmental stress system (EES) | Consumption Index of Regional Resources (Y ₁) | Per capita coal consumption (ton) — <i>m</i> ₁₆ | - |
| | | Per capita crude oil consumption (ton) — <i>m</i> ₁₇ | - |
| | | Per capita natural gas consumption (m ³) — <i>m</i> ₁₈ | - |
| | Pollution Index of Regional Environment (Y ₂) | Per capita industrial wastewater discharge (ton) — <i>m</i> ₁₉ | - |
| | | Per capita sulfur dioxide emissions (ton) — <i>m</i> ₂₀ | - |
| | | Per capita smoke emissions (ton) — <i>m</i> ₂₁ | - |
| | Capacity Index of Regional Environmental (Y ₃) | Forest coverage (%) — <i>m</i> ₂₂ | + |
| | | Per capita water supply (ton) — <i>m</i> ₂₃ | + |
| | | Per capital energy production (10 ⁴ ton) — <i>m</i> ₂₄ | + |

Note: The data in Table 1 come from The China Statistical Yearbook of 2006–2017 (National bureau of statistics, 2006–2017) and China Statistical Yearbook on Environment of 2006–2017 (National bureau of statistics, & Ministry of Environmental Protection 2006–2017).

2.3. Coupling Analysis Method

2.3.1. Evaluating the Levels of the Systems

From Table 1, we can see that each system can be estimated by various indexes of indicator layer named *m*₁, *m*₂ . . . *m*_{*n*}. Then, *m*_{*ij*} is each index value of indicator *j* of order parameter *i*. The smaller the value of *m*_{*ij*}, the better the system efficiency; as such, *m*_{*ij*} is a negative indicator that contributes negative efficacy to the system, and vice versa. In this paper, the original data are processed as dimensionless by means of extreme value standardization, and the efficacy coefficient value of each original index is obtained. The efficacy coefficient (*d*_{*ij*}) is expressed as follows:

$$d_{ij} = (m_{ij} - m_{ij\min}) / (m_{ij\max} - m_{ij\min}), m_{ij} \text{ is a positive indicator} \tag{1}$$

$$d_{ij} = (m_{ij\max} - m_{ij}) / (m_{ij\max} - m_{ij\min}), m_{ij} \text{ is a negative indicator} \tag{2}$$

where *m*_{*ij*} is each index value of indicator *j* of order parameter *i* in Table 1, *m*_{*ij*max} is the maximum value of the indicator, *m*_{*ij*min} is the minimum value of the indicator, and *d*_{*ij*} is the efficacy coefficient of indicator *j* of order parameter *i*. *d*_{*ij*} ∈ [0, 1]. *d*_{*ij*} = 1 means the highest degree of satisfaction, whereas *d*_{*ij*} = 0 means the lowest degree of satisfaction.

Comprehensive efficacy of the system means the new urbanization or eco-environmental stress of the contribution of all indicators in the system. The comprehensive efficacies of new urbanization

and the eco-environmental stress system are calculated by using an integrated methodology. The comprehensive efficacy (U_i) is expressed as follows:

$$U_i = \sum W_{ij} \times d_{ij} (\sum W_{ij} = 1, j = 1, 2, \dots, n) \quad (3)$$

where U_i stands for the comprehensive efficacy of new urbanization or the eco-environmental stress system, w_{ij} is the weight of each order parameter, and j is the number of indicators of each system. By comparing and analyzing the advantages, disadvantages, and applicability of various commonly used index weighting methods, this paper adopted the AHP method to reflect the weight of factor layer [44]. The weight of the indicator layer is determined by the entropy method, which eliminates the subjective bias [45].

2.3.2. Model of Coupling and Coordinating Degree

Coupling degree can represent the degree of dependency or interaction between two systems. Based on the concept of coupling and the model of the coupling coefficient in physics, the coupling degree model for describing the mutual function of several systems can be expressed by the following formula:

$$C = \left\{ \frac{U_1 \times U_2 \times \dots \times U_n}{\prod (U_i + U_j)} \right\}^{\frac{1}{n}} \quad (4)$$

In the formula, C is the coupling degree. The model of the coupling degree involves two systems, and thus $n = 2$. The coupling function in this paper can be represented by the following relationship [10,46]:

$$C = \left[\frac{U_{NUR} \cdot U_{EES}}{(U_{NUR} + U_{EES})^2} \right]^{\frac{1}{2}} \quad (5)$$

Formula (5) indicates that $0 \leq C \leq 1$. When $C = 0$, the coupling degree between the two systems is the smallest and the two systems become uncorrelated; moreover, the system becomes disordered. When $C = 1$, the coupling degree is the biggest and the system becomes orderly. Therefore, the systems are more coordinated if the coupling degree is higher.

The coupling and coordination degree shows the feature where elements are in harmony and unity with one another throughout the evolution of the coupling system. New urbanization and the eco-environmental stress systems have a close relationship. The coupling coordination degree can be calculated as follows:

$$T = \alpha U_{NUR} + \beta U_{EES} \quad (6)$$

$$D = \sqrt{C \times T} \quad (7)$$

In the formula, T is the comprehensive coordinating index of the coupling system, D is the coupling coordination degree, and C is the coupling degree. The coupling coordination degree D ranges from 0 to 1 on account of the distribution of U_i . We set the values of α and β as 0.5 because new urbanization and the eco-environmental stress systems are equally important.

The higher the value of the coupling coordination degree, the greater the extent of coordinated development between systems. According to the results of this paper's coupling coordination degree measurement and the division of coordination types in physics, the paper divided the coupling coordination degree into 10 grades and three levels (as shown in Table 2) [47,48].

Table 2. The classification of the coupling coordination degree of new urbanization and eco-environment systems.

| Category | D-value | Subclass |
|--|-----------|--------------------------------------|
| Coordination category (Zone of tolerance) | 0.90–1.00 | High coordination subclass |
| | 0.80–0.89 | Well coordination subclass |
| | 0.70–0.79 | Middle coordination subclass |
| Transition category (Zone of reluctantly accept) | 0.60–0.69 | Primary coordination subclass |
| | 0.50–0.59 | Reluctance coordination subclass |
| | 0.40–0.49 | Near disorder recession subclass |
| Imbalanced recessionary category (Zone of unacceptable) | 0.30–0.39 | Light disorder recession subclass |
| | 0.20–0.29 | Moderate disorder recession subclass |
| | 0.10–0.19 | Serious disorder recession subclass |
| | 0.00–0.09 | Extreme disorder recession subclass |

Note: D-value stands for the coupling coordination degree.

2.4. Regional Development Index and Spatial Cluster Mode Recognition Method

2.4.1. Relative Development Rate (*Nich* Index)

The *Nich* index is the relative development rate index, which is used to measure the development rate of each region relative to the whole research area in a certain period of time. In this study, the *Nich* index is mainly used to discuss the development rate of the coupling coordination degree of each research unit relative to the whole country. The formula is as follows:

$$Nich = \frac{a_{2i} - a_{1i}}{a_2 - a_1} \quad (8)$$

where a_{2i} and a_{1i} respectively represent the development level of i region at the end and the beginning of a certain period. Furthermore, a_2 and a_1 respectively represent the average development level of the whole research area at the end and the beginning of a certain period.

2.4.2. Exploratory Spatial Data Analysis (ESDA)

To analyze the temporal and spatial changes in the coupling and coordinating degree of New Urbanization Level and Ecological-Environmental Stress, this paper adopted the method of Exploratory Spatial Data Analysis (ESDA) with ArcGIS 10.0 and GeoDa 0.9.3 software [49]. As a tool to describe the patterns of spatial association, ESDA is often measured by Moran's Index (Moran's I), which was put forward by Moran in 1950 [50]. Moran's I can test the spatial correlation of variables; while the setting of the spatial weight matrix is the premise of ESDA. For this reason, this paper fully took into account the actual situation, where the new urbanization level and ecological-environmental stress among geographically adjacent areas interact and influence each other, and constructs the spatial weight matrix of the reciprocal square of the shortest distance between administrative units at different levels. The computational formula of Moran's I is as follows:

$$Moran's\ I = \frac{\sum_{i=1}^n \sum_{j=1}^n W_{ij} (Y_i - \bar{Y}) (Y_j - \bar{Y})}{S^2 \sum_{i=1}^n \sum_{j=1}^n W_{ij}} \quad (9)$$

where Y_i is the practical value of the i th region, and W_{ij} is an element of a spatial weight matrix that indicates whether i and j are contiguous. Moran's I usually falls in the range of -1 to 1 , with negative values proving a chessboard-like arrangement of alternating dissimilar values and positive values; this clustering pattern of similar values proves a spatial autocorrelation [51].

2.5. Research Framework

To determine the quantitative relationship and the interaction mechanism between the new urbanization and ecological-environmental stress in China, we collected and analyzed data for 31 provincial areas from 2005 to 2016. At first, this paper establishes a new urbanization comprehensive system from four aspects (economic development level, social development level, service facilities level, and natural ecology level) and an eco-environmental stress comprehensive system from three aspects (consumption index of regional resources, pollution index of regional environment, and capacity index of regional environmental). After comprehensive efficacy evaluation, the paper identifies the spatial and temporal pattern of the coupling coordination degree between urbanization and eco-environmental stress from the national scale and provincial scale within the time frame of 2005–2016 by applying the coupling coordination degree mode. Then, we adopt the spatial layout recognition method to analyse the spatial agglomeration evolution character of the coupling coordination degree between new urbanization and eco-environmental stress in China. In this section, we mainly focus on the coupling process and the stages of coupling evolution, conditions, and the types in the coupling and coordinating degree of New Urbanization and Ecological-Environmental Stress. Through the above analysis, the paper finally draws the conclusion of the full text and tries to offer scientific suggestions for achieving the sustainable development of new urbanization and eco-environment protection. Figure 1 briefly describes the framework of this study.

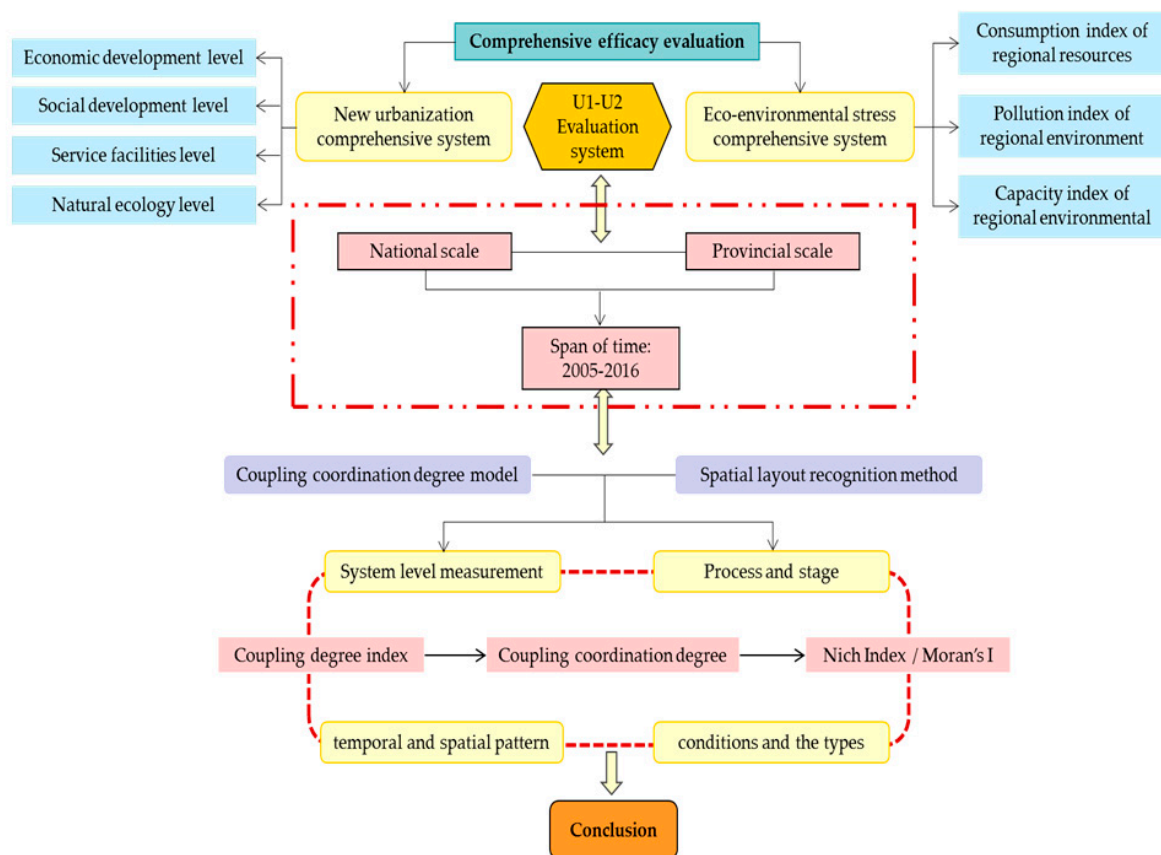


Figure 1. Overview of the research framework.

3. Results and Discussion

3.1. Temporal Dynamic Characteristic of Coupling Coordination Degree between New Urbanization and Eco-Environmental Stress in China: 2005–2016

Based on the above assessment indicator system and models, we can further evaluate the comprehensive levels of new urbanization and eco-environmental stress, and the coupling coordination degree of the two systems, using the data for 31 provincial areas from 2005 to 2016 (Table 3, Figure 2).

Table 3. Comprehensive levels and coupling coordination degree of new urbanization and eco-environmental stress in China from 2005 to 2016.

| Year | X1 | X2 | X3 | X4 | NUR | Y1 | Y2 | Y3 | EES | D-Value |
|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------|
| 2005 | 0.115 | 0.051 | 0.210 | 0.128 | 0.504 | 0.255 | 0.354 | 0.209 | 0.818 | 0.395 |
| 2006 | 0.124 | 0.060 | 0.218 | 0.119 | 0.521 | 0.258 | 0.266 | 0.198 | 0.722 | 0.389 |
| 2007 | 0.141 | 0.073 | 0.232 | 0.144 | 0.591 | 0.263 | 0.265 | 0.198 | 0.726 | 0.404 |
| 2008 | 0.160 | 0.086 | 0.248 | 0.149 | 0.643 | 0.265 | 0.262 | 0.198 | 0.726 | 0.413 |
| 2009 | 0.173 | 0.099 | 0.257 | 0.162 | 0.690 | 0.276 | 0.262 | 0.198 | 0.736 | 0.422 |
| 2010 | 0.193 | 0.111 | 0.269 | 0.171 | 0.743 | 0.286 | 0.263 | 0.182 | 0.731 | 0.429 |
| 2011 | 0.215 | 0.094 | 0.283 | 0.175 | 0.766 | 0.307 | 0.274 | 0.196 | 0.777 | 0.439 |
| 2012 | 0.230 | 0.101 | 0.298 | 0.182 | 0.811 | 0.329 | 0.281 | 0.178 | 0.787 | 0.447 |
| 2013 | 0.250 | 0.110 | 0.313 | 0.187 | 0.860 | 0.344 | 0.282 | 0.179 | 0.805 | 0.456 |
| 2014 | 0.265 | 0.117 | 0.325 | 0.191 | 0.898 | 0.355 | 0.281 | 0.164 | 0.800 | 0.460 |
| 2015 | 0.287 | 0.129 | 0.337 | 0.196 | 0.948 | 0.387 | 0.292 | 0.162 | 0.841 | 0.472 |
| 2016 | 0.300 | 0.150 | 0.320 | 0.200 | 0.970 | 0.422 | 0.291 | 0.167 | 0.881 | 0.484 |

Note: NUR stands for the evaluation results of the new urbanization. EES stands for the evaluation results of eco-environmental stress. D-value stands for the coupling coordination degree.

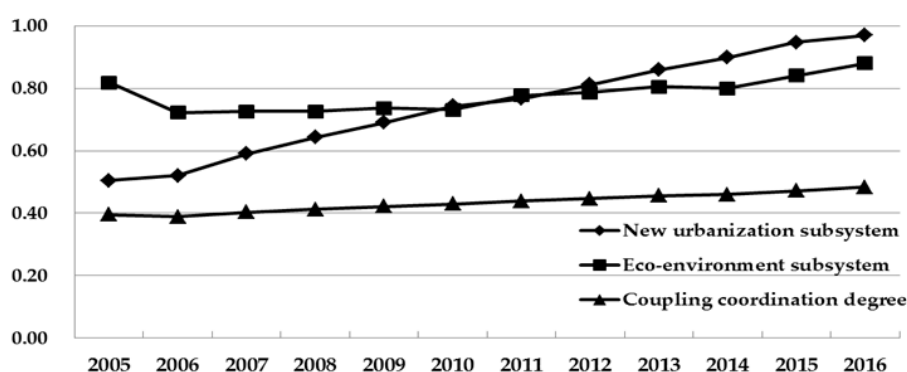


Figure 2. The trend graph of coupling coordination degree of new urbanization and eco-environmental stress systems in China from 2005 to 2016.

The coupling coordination degree of new urbanization and eco-environmental stress in the research areas was between 0.389 and 0.484, and the coupling coordination presents a rising trend year by year from 2005 to 2016 (Figure 2). It shows that the coupling coordination degree of interaction coupling between the two systems has increased steadily in the past decades.

Evolutionary causes of the coupling coordination degree were studied based on the changes in new urbanization and eco-environmental systems.

The level of new urbanization appears to be rising. The assessment result increased from 0.504 to 0.970 during the research period. In the analysis of the detailed indicator, the escalating trend of X_1 and X_2 was more obvious from 2005 to 2016. By contrast, X_3 and X_4 grew slowly. This indicates that the improvement of the economic and social condition is a major reason for the new urbanization. This logic also explains that relevant regional policies have led to the rapid development of new urbanization, such as the “Balance the Development of Urban and Rural Areas”, actively promoting

the civilization of agricultural labor force migration, comprehensively improving the urban functions, and reforming and improving the urban housing system.

The eco-environment level shows a tendency to “first fall then rise.” The evaluation result fell to 0.722 in 2006, and slightly rose to 0.881 in 2016. The regional consumption index Y_1 grew slowly year by year, regional environment pollution Y_2 fell initially and increased gradually, and the regional environmental capacity Y_3 declined slightly with the years. Overall, the level of regional environmental capacity improved greatly, but the increase in energy consumption and environmental pollution became obstacles that held back the healthy development of the regional eco-environment.

The evaluation of the coupling coordination of new urbanization and eco-environmental systems shows that the mutual harmony and consistency of every key element within the two systems increased. The coupling coordination degree between new urbanization and eco-environmental systems also strengthened from 2005 to 2016. The improvement of the level of new urbanization is embedded in the eco-environment. It continuously evolves, but is restricted by the eco-environmental system.

3.2. Spatial Pattern of the Coupling Coordination Degree between New Urbanization and Eco-Environmental Stress in China: 2005–2016

3.2.1. Trend and Evolution Character of Coupling Relationship between New Urbanization and Eco-Environmental Stress in Different Provinces

In the past years, the levels of new urbanization and eco-environment have changed greatly. New urbanization has different effects on the regional eco-environment because of the differences in development conditions (e.g., economic development level, social development level, service facilities level, and natural ecology level), and coupling coordination between the two systems show significant regional differences.

As shown in Figure 3a, the distribution of new urbanization in China was extremely uneven from 2005 to 2016. The distribution of each province value varied from 0.171 to 0.591. The level of new urbanization of Beijing is the highest among all the provinces, whereas that of Gansu is the smallest. The level of new urbanization of numerous provinces grew year by year, especially in 2016, when perfected infrastructure facilities, actual utilized foreign direct investment, intensive technologies, top-quality education resources, fixed asset investment, fiscal expenditure, and an abundant talent pool strongly advanced the new urbanization in Beijing, Jiangsu, Guangdong, and Shandong, promoting the economic development. By contrast, the scarce endowment of resources, poor transportation lines and other infrastructures, low highway density, undeveloped networks, business volume of postal and telecommunication, and unsound market economic construction further reduced new urbanization in Gansu, Qinghai, Xinjiang, and Tibet. With regard to the developing rate, the level of new urbanization in Shandong, Inner Mongolia, Chongqing, and Anhui increased at a high rate, but that of Tianjin, Beijing, Shanghai, and Qinghai increased slowly.

Figure 3b shows that the overall trend in eco-environmental stress of the provinces increased from 2005 to 2016. The eco-environmental level of the provinces declined to different extents, and that of Shandong, Jiangsu, Guangdong, and Shaanxi increased sharply. The eco-environmental levels in Yunnan, Qinghai, Jiangxi, Inner Mongolia, Xinjiang, and Chongqing were much lower than those in other provinces because some regions are rich in natural resources and have an underdeveloped industry and low fuel consumption. Some regions are crucial ecological barriers and ecologically fragile areas. They have a low population intensity and less consumption of resources. By contrast, Anhui, Henan, Hebei, and Shanxi had higher eco-environmental levels during the study period because these provinces had high concentrations of people, a large amount of industry pollutants, and high energy consumption.

As shown in Figure 3c, the degree of coupling coordination of new urbanization and eco-environmental systems increased in general. From 2005 to 2016, the coupling coordination of Shandong, Beijing, Jiangsu, and Guangdong rose to a larger extent than that of Gansu, Qinghai, Jilin, and Yunnan. Meanwhile, we introduced the concept of the “relative development rate” (*Nich* index),

which varied considerably for each province. The values of the *Nich* index of Shandong, Inner Mongolia, Jiangsu, Chongqing, Shanxi, Sichuan, Anhui, Henan, Tibet, Helongjiang, and Guizhou from 2001 to 2010 were more than 1. Thus, the increments of the degree of coupling coordination in these areas were greater than those of the national average level.

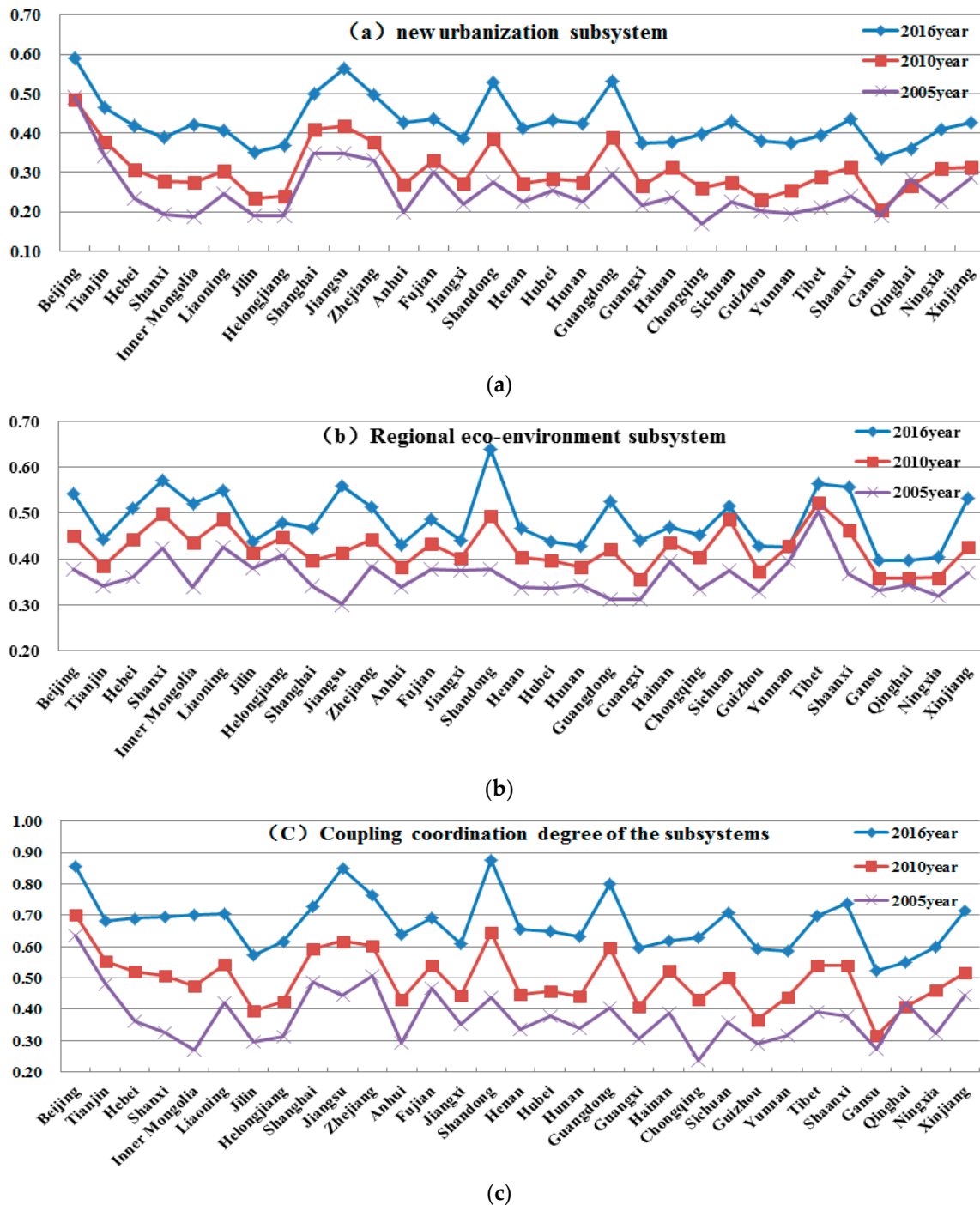


Figure 3. The trend graph of coupling coordination degree of new urbanization and eco-environmental stress systems evolution of each province from 2005 to 2016. (a) New urbanization subsystem. (b) Regional eco-environment subsystem. (c) Coupling coordination degree of the subsystems.

Coupling coordination in every province was at different levels. For example, all the research subjects for 2016 in this study were divided into several categories in accordance with the classification system of new urbanization and eco-environmental systems (Figure 4).

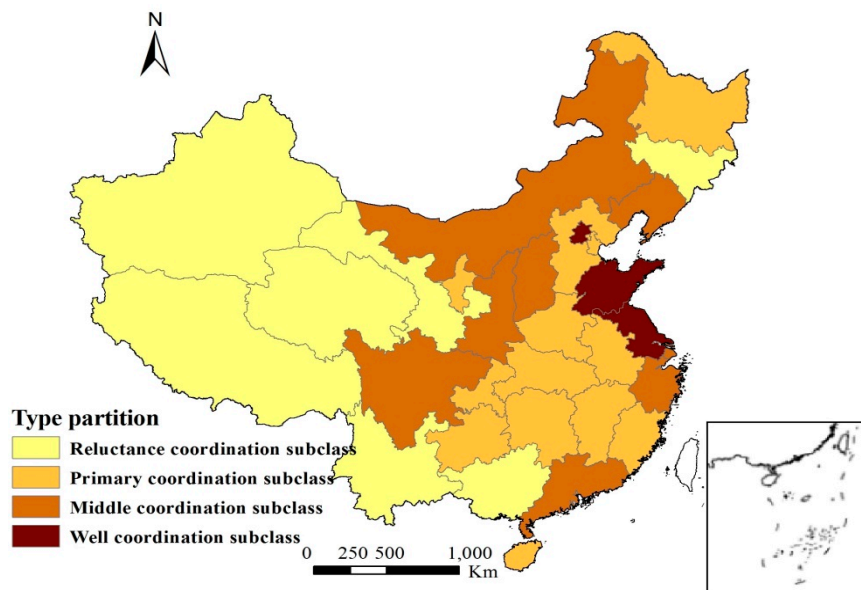


Figure 4. Maps of five types of coupling coordination degree of new urbanization and eco-environmental stress systems on the provincial level in 2016.

Provinces that belong to the high coordination subclass are Beijing, Jiangsu, and Shandong. These provinces are the most coordinated in terms of new urbanization and the eco-environmental system. Provinces that belong to the middle coordination subclass are Guangdong, Zhejiang, Shaanxi, Sichuan, Liaoning, Inner Mongolia, and Shanxi. Provinces in the primary coordination subclass are Hebei, Fujian, Hubei, Henan, Hunan, Tianjin, Chongqing, Heilongjiang, Anhui, Guizhou, Hainan, Ningxia, and Jiangxi; this subclass has the highest number of provinces, and the coordination of these provinces is weak. Provinces in the reluctance coordination subclass are Yunnan, Guangxi, Jilin, Qinghai, Gansu, Tibet, and Xinjiang, and their coordination ability is the lowest. The provinces in the coordination category, which account for 84 percent of all the provinces, are the focus of this study.

The overall situation of the country is good based on the pattern of coupling coordination of new urbanization and eco-environmental systems. Most provinces have reached a benign state. Coupling coordination displayed a gradient change trend in spatial terms. Figure 4 shows that the degree of coupling coordination in the eastern region is generally higher than that in the western region.

For different regions, the reluctance coordination and primary coordination subclass regions should accelerate to realize green transformation, improve the industrial structure, and strengthen the environmental law-enforcing supervision. Especially in big cities like Beijing, the government should encourage residents to travel “green”, promote intelligent transportation systems, and establish environmental monitoring and an early warning system; the middle coordination subclass regions should cultivate the industrial clusters with local characteristics and guide the economic progress to support the ecological environment improvement. Meanwhile, these areas should establish and improve environmental protection institution systems of supervision from discharging pollutants into the lakes; for the high level coordination and well coordination subclass regions, these areas are still in low-level phase, so accelerating the urbanization process and developing the circular economy are of the greatest importance. In addition, these regions should promptly create a mechanism for ecological compensation and system of property right.

3.2.2. Spatial Agglomeration Evolution Character of Coupling Coordination Degree between New Urbanization and Eco-Environmental Stress in China

To discuss the spatial cluster model of different regions, this study used the GeoDa software to calculate the Moran's I of each province and verify its significance. Additionally, the software was used to analyze the spatial concentration characteristic of the degree of coupling coordination of new urbanization and eco-environment systems. The results show that the comprehensive levels and coupling coordination degree of new urbanization and eco-environmental stress existed with obvious regional disparity (Table 4).

Table 4. The Moran's I value of the various indicators in 2005, 2010, and 2016.

| Year | Indicator | Moran's I | Z-Score | Significant Test |
|------|------------------------------|-----------|---------|------------------|
| 2005 | New urbanization | 0.381 | 4.312 | 1% |
| | Eco-environmental stress | 0.243 | 2.585 | 1% |
| | Coupling coordination degree | 0.306 | 3.370 | 1% |
| 2010 | New urbanization | 0.240 | 3.571 | 1% |
| | Eco-environmental stress | 0.144 | 2.275 | 5% |
| | Coupling coordination degree | 0.406 | 4.202 | 1% |
| 2016 | New urbanization | 0.304 | 3.184 | 1% |
| | Eco-environmental stress | −0.007 | −0.343 | Reject |
| | Coupling coordination degree | 0.270 | 2.743 | 1% |

Note: Z-score stands for the standard score. When Z-score is greater than 2.58, 1.96, and 1.65, the estimated coefficient is significant at the confidence level of 99%, 95%, and 90%, respectively.

Firstly, Moran's I for evaluating the new urbanization of each province in 2005, 2010, and 2016 was 0.381, 0.240, and 0.304, respectively. The Z-score (the standard score) in 2005, 2010, and 2016 was 4.312, 3.571, and 3.32, respectively. Apparently, the Z-score is significantly greater than 2.58 (the critical value at the 1% level). The result illustrated that new urbanization in China was in disharmony.

Secondly, Moran's I for evaluating the eco-environment of each province in 2005, 2010, and 2016 was 0.243, 0.144, and −0.007, respectively. The Z-score in 2005, 2010, and 2016 was 2.585, 2.275, and −0.343, respectively. Thus, the spatial distribution of the eco-environmental level changed from cluster mode to random mode.

Thirdly, Moran's I for the degree of coupling coordination in 2005, 2010, and 2016 was 0.306, 0.406, and 0.270, respectively. The Z-score in 2005, 2010, and 2016 was 3.370, 4.202, and 2.743, respectively. The unbalanced distribution of coupling coordination proved that the spatial distribution presented a cluster mode. The gap of the degree of coupling coordination widened with the increase in imbalance.

4. Conclusions

This paper noted the following based on the model of coupling coordination and by analyzing the spatial distribution of new urbanization and eco-environmental systems in China:

(1) New urbanization has been speeding up over the past decades, and the eco-environmental level has revealed a general fluctuation trend of "first fall then rise." The degrees of coupling and coordination have achieved stable and continuous improvement. The degrees of coupling and coordination have achieved stable and continuous improvement from 0.388 to 0.476.

(2) New urbanization and the eco-environmental systems in China are characterized by an obvious regional difference and clustered spatial coupling coordination. The gap in the degree of coupling coordination widened with increasing imbalance, and the degree of coupling coordination in the eastern region was generally higher than that in the western region. Furthermore, regional coupling coordination and regional economic development have a strong spatial relationship.

(3) Coupling degree is higher than coupling coordination degree in most parts of China, which indicates that the two systems failed to reach benign resonance in spatial terms with the effect

and restriction of national condition, stage of economic development, and historical development. The degrees of coupling and coordination of new urbanization and the eco-environment are different because of the policy orientation of different regions. Each region should take relevant policy measures to design and implement macro-control according to the respective economic development mode and the degree of eco-environmental coordination, as well as to ensure that new urbanization and eco-environmental systems move toward benign and sustainable coupling coordination. Reaching this state will significantly change the degree of coupling coordination of new urbanization and regional eco-environmental systems.

By applying the formula for the degree of coupling coordination to analyze the correlation of new urbanization and eco-environmental systems, the paper generally conducted a synchronism analysis of the distribution characteristics of volume data of two systems. However, we could not conduct an internal structural analysis. The next phase of this research will focus on conducting an internal structural analysis and an element system metrics analysis.

Author Contributions: L.Y. had the original idea for the study and wrote the first draft. Relative contribution of the authors is indicated by order of listing. Both authors framed the discussion in accordance with an initial idea of L.Y. X.L. was responsible for data collecting and data analysis. Q.L. and J.W. edited the manuscript and provided a critical final review. All authors read and approved the final manuscript.

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