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Spatial-Temporal Evolution of Sustainable Urbanization Development: A Perspective of the Coupling Coordination Development Based on Population, Industry, and Built-Up Land Spatial Agglomeration

Yanjing Zhang [1], Zhengguo Su [2,3], Guan Li [4,*], Yuefei Zhuo [4] and Zhongguo Xu [4,5]

1 Department of Civil and Architecture Engineering, Guangxi Cadres University of Economics and Management, Nanning 530007, China; zhangyanjing0308@163.com
2 Land Banking Center of Guangxi Zhuang Autonomous Region, Nanning 530028, China; suzhengguo126@126.com
3 Department of Land and Resources of Guangxi Zhuang Autonomous Region, Nanning 530028, China
4 Research Department of Land Science and Real Estate, Zhejiang University, Hangzhou 310029, China; yfzhuo@zju.edu.cn (Y.Z.); mailxzg@163.com (Z.X.)
5 Land Academy for National Development, Zhejiang University, Hangzhou 310029, China
* Correspondence: liguan1688@126.com; Tel.: +86-571-8697-1752

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Abstract: A series of negative effects of urban development have emerged owing to the imbalance of population, industry, and built-up land spatial agglomeration. This study proposes an integrated coupling coordination index system in sustainable urbanization evaluation based on population, industry, and built-up land, to evaluate the spatial-temporal evolution of coupling and coordination degree in Guangxi from 2005 to 2015. In addition, we adopted the exploratory spatial data analysis method to reveal the spatial pattern of coupling and coordination degree and its impact on sustainable urbanization. Finally, local indicator of spatial association (LISA) analysis was employed to identify the spatial heterogeneity of the coupling and coordination index values. The results, on the one hand, show that the coupling coordination degree of all counties increased yearly, but extremely slowly. The 88 counties in Guangxi are still in a low level of urbanization. On the other hand, a spatial agglomeration effect of urbanization levels is observed in this study. We found that the urbanization development is not independent. In other words, the urbanization level of each county will more or less be affected by its surrounding counties. In conclusion, in China, sustainable urbanization is closely related to the rational allocation of population, industry, and land resources. To promote the sustainable development of urbanization, it is necessary to strength the role of land use control and to rationally allocate these three elements in general.

Keywords: sustainable urbanization; spatial-temporal evolution; coupling coordination development

1. Introduction

Urbanization has become a common concern worldwide, in which economic, social, and ecological issues are embedded [1]. Whether the process of urbanization is healthy will affect the progress of human civilization [2]. As the negative impact on the environment become more prominent in the process of urbanization, people pay more attention to the process of urbanization and the intergenerational equity [3]. Furthermore, since the publication of "*Our Common Future*", sustainable development has become an important benchmark for urbanization. There has been not any explicitly definition for sustainable urbanization, because the process of urbanization always interweaves with many issues, including economic, social, and ecological development. Therefore, in view of the natural interpretation of "sustainable development", each country and region give their own definitions from cultural, environmental, development perspectives [2]. Considering the different stages of urbanization, there should be multiple views for different regions. For example, developed areas would concentrate on the intergenerational fairness of urbanization, ecological stress issues, and so on [2,4–6]. However, for the developing countries and regions, it is urgent for them to balance the relationship between development and protection, including curbing excessive land development and its impact on the environment, and proceeding higher quality development [1,7–10].

Because of the special national conditions of China, the development of cities in China is quite different from western countries. Chinese urbanization issues have received particular attention, not only domestically but also abroad [11–14]. In recent decades, China has experienced unprecedented rapid urbanization [7,15], which is manifested mainly as many people concentrated into urban areas. With the rapid advancement of industrialization, many industrial enterprises and laborers have assembled in urban areas [8,16]. An astonishing number of agricultural lands have also been transformed into built-up lands during this process, which can be characterized as" Land Urbanization" [17]. From a historical perspective of the development, China's urbanization process is an agglomeration process of population, industry, and built-up land in urban areas [11,18–21]. The high concentration process, in a short time, has brought tremendous impetus to the economic development of China [22]. However, it also poses considerable challenges to the management of resources and environment in China. On the one hand, a series of challenges for the environment emerges, including the loss of agricultural land, the excessive carrying capacity of the environment and the negative impacts on the natural environment. On the other hand, it also causes various social problems, such as urban sprawl, imbalanced regional development, social inequality, and uneven allocation of public resources [1,7,23–33]. Some studies have provided empirical evidence of the influence of urbanization. Some scholars show that urbanization has a significant effect on pollution-related agricultural input intensity [34]. The process of urbanization results in the reduction of carbon sequestration and the increase in carbon sources [35–38]. The change in scale and structure of built-up land caused by urbanization affects the increasing regional carbon emissions [39,40]. Urbanization is often closely associated with industrialization, and it causes intensive air quality problems and urban heat island(UHI) problems [41,42]. Furthermore, 60% of Chinese large cities are experiencing water shortages due to the rapid urban growth [43]. In summary, social and environmental issues that arise during the process of rapid urbanization affect a country's sustainable development [24,26,29,33,43]. For this purpose, the 13th Five-Year Plan proposed a new urbanization development strategy, the "National New-type urbanization Plan (2014–2020). This strategy was released jointly by the Central Committee of the Communist Party of China (CPC) and the State Council in 2014". In 2015, New-Type Urbanization Plan was proposed in the 13th Five-Year Plan. Many scholars believe the sustainable urbanization is an effective method to promote sustainable development in China's urban areas [44,45].

An increasing number of literature on sustainable urbanization exists in China. In general, these studies can be divided into the following categories: the first category pertains to the coordination relationship between urbanization and population, and the second category pertains to the coordination relationship between urbanization of land and industrial development. Many relevant studies have suggested that urbanization of land in China is the result of population growth and economic development [1,46,47]. Thus, the coordination study among land, population, and economic development during the urbanization process is the focus of this field [48]. Specifically, on the one hand, scholars attempt to measure characteristics of urbanization of land on different spatial scales [49–52]. Some studies show that in China, the urbanization of land and population have grown at the same pace [53,54]. However, some other studies point out that the urbanization of land is much faster [17,55]. Compared with other countries, China's urbanization process exhibits some incoordination characteristics [43,56,57], which lead to several extreme phenomena, such as "ghost cities" [58]. Scholars believe sustainable urbanization requires coordination between urban development and population growth. However, sustainable urbanization also needs to coordinate the relationship between land and economic development. In recent years, the imbalanced economic development problem caused by the overheated land development has become increasingly prominent [59]. The development zones positively affect industry development, including knowledge spillovers, retail activities and real estate development [60,61]. Development zones were regarded as a core development tool of local governments in China to attract foreign direct investments (FDI) successfully [62]. The explosive boom of development zones over the last 20 years was called the "development zone fever" [28,62]. From 1992 to 2003, the development zones in China increased from 1992 to 6866, and the total planned areas also increased to 38.6 thousand square kilometers. The two planning areas were even higher than the total urban built-up area [62,63]. In addition, the non-coordinated spatial distribution of population, industry, and built-up land has caused unhealthy urbanization issues in recent years [64]. Some scholars have attempted to determine its negative effects [65]. In the process of agglomeration of the population and cities, a large amount of natural resources was consumed, leading to a global environmental degradation [2].

The main point of the new-type urbanization development is to integrate the spatial distributions of the population, industry, and built-up land [66,67]. However, previous studies have focused mainly on the coordination between population and land, or population and industry. Some comprehensive studies on these three elements, which are a key to the National New-type Urbanization Plan, are limited. To bridge this gap, the research attempts to evaluate the situation of sustainable urbanization development by developing a coupling and coordination evaluation index for population, industry, and built-up land. In addition, urbanization is a non-stationary process over space [68]; some spatial aggregation patterns exist for these features. Studies have shown that industry development can improve the level of urbanization through positive spatial spillover effects [69], and urban agglomeration will be the main pattern for the new-type urbanization development in China [55]. Therefore, the spatial pattern of coupling coordination among these three elements would probably create some spatial dependence and spatial heterogeneity characteristics [70]. Some traditional methods ignore the spatial relationship for these three elements; thus, the results could hardly reveal the actual relationship among these three elements. Therefore, the exploratory spatial data analysis (ESDA) method is applied to explore the spatial pattern of the coupling coordination index. Different from developed countries and regions, developing countries and regions experiencing rapid urbanization are facing the dilemma between urban development and rational resource allocation [23,24]. The incoordination among population growth, industrial development and land resource consumption will lead to irrational urban expansions and serious ecological crisis [71–73]. Therefore, in this study, we try to evaluate the coupling and coordination relationship among population, industry, and built-up land, and then to figure out the spatial agglomeration on the development of sustainable urbanization. This study will inspire some developing countries and regions to rationally allocate resources for urban development, including population, industry, and built-up land.

2. Materials and Methods

2.1. Study Area

Guangxi, which is on the south-eastern border of China, has a unique geographical advantage and resource endowment (Figure 1). It is the only coastal minority autonomous region and is the only province in China linked to the Association of Southeast Asian Nations (ASEAN) countries by sea and land. It is an important hub that connects the domestic and Southeast Asian markets. In 2002, the host country of China-ASEAN Expo (CAEXPO) was settled permanently in Nanning, the capital of Guangxi. In 2015, the "the Belt and Road Initiative" development strategy was proposed, and Guangxi was involved as "an important gateway for the 21st Century Maritime Silk Road and the Silk Road Economic Belt" [74].

Figure 1. Location and spatial organization of Guangxi, China.

However, Guangxi has always been a relatively backward economic development region. Although in recent years, under the strategic boost of China-ASEAN Free Trade Area and Guangxi North Gulf Economic Zone, Guangxi has made remarkable achievements in economic construction. The GDP of Guangxi reached 1.68 trillion Yuan, indicating an increase of 8.1% year-on-year, higher than the national average. Driven by the rapid economic development, the scale of the city has also achieved rapid growth. From 2010 to 2015, the urbanization rate of Guangxi increased by an average of 1.4% points, and the urbanization process of Guangxi accelerated significantly, thereby exhibiting a rapid development momentum. However, the average urbanization level of Guangxi has a disparity from that of the nation. At present, the average urbanization rate in China is 56.1%, whereas that in Guangxi is 47.1%. The current level of urbanization in Guangxi is in the middle and lower levels of the country. Moreover, the economic development levels and speeds in Guangxi's counties also differ considerably. For example, the urbanization and modernization levels of urban areas such as Nanning, Liuzhou and Guilin are relatively high, but Guangxi still has 5.38 million people who live below the official poverty line [75]. The development of rapid urbanization is accompanied by inadequate and imbalanced regional development; therefore, it offers a typical case to analyze the spatial-temporal evolution of sustainable urbanization issue in China.

2.2. Analytical Framework

To evaluate the situation of sustainable urbanization development, a coupling and coordination evaluation index system was built. In addition, we analyzed the spatial-temporal pattern for sustainable urban development in Guangxi from 2005 to 2015. The whole analytical framework is shown in Figure 2.

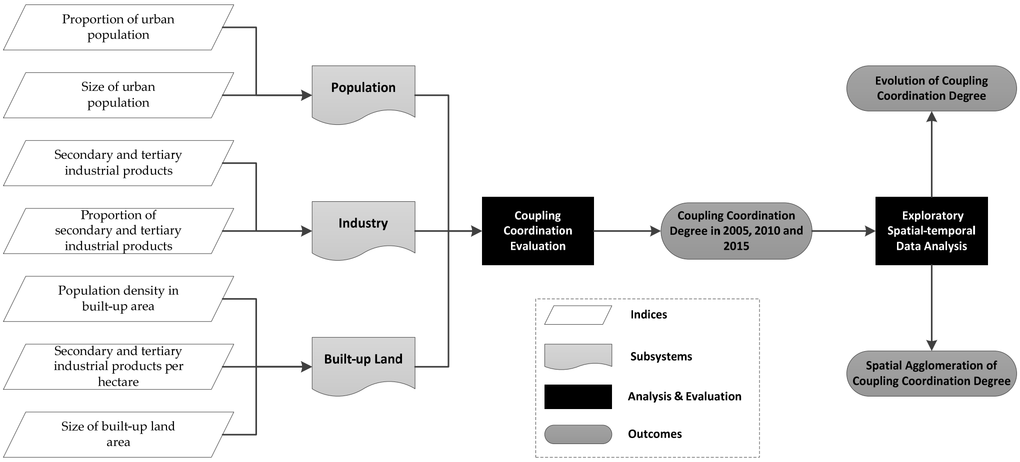


Figure 2. Analytical framework.

2.3. *The Evaluation Index System*

Studies have shown the many comprehensive indicators that describe the state of urbanization from the perspective of population, industry, and land [76,77]. The comprehensive evaluation index system for population, industry, and built-up land is developed by using the multi-index comprehensive evaluation method (Table 1). Existing literature suggests sustainable urbanization should consider three dimensions, namely, population urbanization, industry urbanization and land urbanization. The coupling coordination of the three dimensions is an important guarantee for sustainable urbanization [66]. The concentration of population in urban areas is an important feature of urbanization [8]; it is reflected mainly in the increase in the size of urban population, including the increase in the proportion of urban population in the regional population and the shift of agricultural population to non-agricultural population [16]. The population urbanization is represented mainly with the proportion of urban population, urban population size and labor force in secondary and tertiary industries. In the process of urbanization, the development of the industry promotes urban development and enhances urban competitiveness [78]. The index of Industrialization considers mainly the industrial scale and industrial structure [79,80]. The output value of secondary and tertiary industries and GDP density of secondary and tertiary industries characterize the industry scale. The industrial structure is characterized by GDP proportion of secondary and tertiary industries. Land is the spatial carrier of the continuous agglomeration of factors such as population and industry in the process of urbanization. Land urbanization should be coordinated with population and industrial development [56,57]. The indexes that measure the level of land urbanization mainly include population density in built-up area, per capita built-up area, and the scale of built-up land area.

Table 1. Coordination evaluation index system of population, industry, and land.

System	Subsystem	Index	Data Source
Coupling Coordination Evaluation Index System	Population Urbanization	P_1 Proportion of urban population (%)	China Statistical Yearbook Guangxi Statistical Yearbook
		P_2 Size of urban population (10^4)	China Statistical Yearbook
	Industrialization	I_1 Secondary and tertiary industrial products (10^4 Yuan)	Guangxi Statistical Yearbook
		I_2 Proportion of secondary and tertiary industrial products (%)	Guangxi Statistical Yearbook The Website of the National Bureau of Statistics of China
	Land Urbanization	L_1 Population density in built-up area (person/km^2)	Guangxi Statistical Yearbook Land-Use Change Survey
		L_2 Secondary and tertiary industrial products per hectare (10^4 yuan/km^2)	Guangxi Statistical Yearbook Land-Use Change Survey
		L_3 Size of built-up land area (km^2)	Land-Use Change Survey

2.4. Data

The built-up land use data are obtained from a survey of land-use change in Guangxi Province provided by the Guangxi Provincial Department of Land Resources. Each survey table contains accurate records of land area in types and years. We also collected related data of population and industry for all counties from the Guangxi Statistical Yearbook, China Statistical Yearbook, and the website of the National Bureau of Statistics of China. In this study, all the data was collected in 3 years (2005, 2010 and 2015).

2.5. Entropy Evaluation Method

To eliminate the subjective favor of valuator, the entropy method is used to determinate the weights. Different from natural science, the definition of the informational entropy, which is equivalent to the thermodynamic entropy in mathematics, refers to the measure of system uncertainty [77]. Thus, conversely, the system is imbalanced, the difference is great, and the change is immediate while the information entropy value is low. Finally, the weight of the index can be calculated according to the entropy value. The procedures of this method are as follows [66]:

(1) Construction of original index matrix

The original index matrix $X = \{x_{ij}\}_{m\times n}$ is constructed with n comprehensive evaluation indices in m research regions, where x_{ij} is the index j in region i.

(2) Data standardized

To eliminate the dimensional, magnitude difference of index, the data should be non-dimensionalized. The indices are divided into positive and negative classes:

$$x_{ij} = \begin{cases} (x_{ij} - minx_{ij}) / (maxx_{ij} - minx_{ij}), & if\ x_{ij}\ \ positive\ index \\ (maxx_{ij} - x_{ij}) / (maxx_{ij} - minx_{ij}), & if\ x_{ij}\ \ negative\ index \end{cases} \quad (1)$$

(3) The proportion of index j in year i is calculated as follows:

$$p_{ij} = x_{ij} / \sum_{i=1}^{m} x_{ij} \quad (2)$$

(4) The information entropy of index is

$$e_j = -K / \sum_{i=1}^{n} p_{ij} \ln p_{ij}, \ \ k = \frac{1}{\ln m}, \ 0 \le H_{ij} \le 1 \quad (3)$$

(5) The redundancy of information entropy is

$$d_j = 1 - e_j \quad (4)$$

(6) The weight of the index is

$$w_j = d_j / \sum_{j=1}^{m} d_j \quad (5)$$

(7) The value of the single index evaluation is calculated as follows:

$$X_{ij} = w_j \times x_{ij} \quad (6)$$

(8) The value of comprehensive evaluation in year i is calculated as follows:

$$X_i = \sum_{j}^{n} X_{ij} \tag{7}$$

where x_{ij} represents the value of index j in year i. $minx_{ij}$ and $maxx_{ij}$ indicate the minimum and the maximum of index j, respectively. m is the number of years and n is the number of index.

2.6. Coupling Coordination Degree Model

Coupling is derived from physics; it indicates that multiple systems or elements influence each other through their interaction with one another. The coupling degree reflects mainly the transition process between system disorder and its order state and reflects the interaction between system internal parameters [66]. The system coupling belongs to a dynamic relatively equilibrium state that may cause the evolution of the original system and change into a coupling system and eventually become a new system, namely, the composite system. The result of the analysis shows the development of a sustainable urbanization system is the result of coordination among population subsystems, industrial subsystems, and built-up land subsystems. Therefore, the coupling degree can not only reflect the interaction between them, but also evaluate the overall quality of sustainable urbanization. To meet the requirements of the development of new-type urbanization, the three subsystems of population, industry, and built-up land should be adjusted dramatically to achieve a relatively coordinated state. The system coupling degree function can be expressed as follows:

$$C_n = \left\{ \left(\prod_{i=1}^{n} X_i \right) \Big/ \prod_{\substack{i=1,2,\cdots,n-1 \\ j=i+1,i+2,\cdots,n}} \left(X_i + X_j \right) \right\}^{1/n} \tag{8}$$

The degree of coupling between population, industry, and built-up land is defined as follows:

$$C = \left\{ (X_1 \times X_2 \times X_3) / \left[(X_1 + X_2 + X_3)^3 \right] \right\}^{1/3} \tag{9}$$

where C is the coupling degree; and X_1, X_2 and X_3 represent the contribution of the population subsystem, industry subsystem and built-up land subsystem, respectively.

The coupling degree cannot easily reflect the overall effectiveness and synergy between subsystems. The coordination degree measures mainly the balance and harmony between systems and system components in the process of development and focuses on the benign interaction between systems. Therefore, the coupling coordination model is established to evaluate the degree of coordination and synergy effects of coupling between multiple subsystems to avoid effectively the disadvantages of high coupling degree caused by low level population, low level industry or the quality of built-up land input. The coupling coordination model is defined as follows:

$$D = (C \times T)^{1/2}$$

$$T = aX_1 + bX_2 + cX_3 \tag{10}$$

where D is the coordination degree; C is the coupling degree; T is the integrated and coordinated index of population, industry, and built-up land, which reflects the complete synergistic effect; a, b, and c are the undetermined coefficients. In the process of coupling and coordinating development, we find that population, industry, and built-up land have equal importance to sustainable urbanization. Thus, this study adopts the coefficient values of $a = b = c = 1/3$.

The coupling and coordinating degrees are a quantified reflection of coupling coordination of certain systems, which are widely used. We divide coupling degree C into the following four stages, based on previous studies: antagonism stage $D \in (0, 0.4]$, general coupling stage $D \in (0.4, 0.5]$, high coupling stage $D \in (0.5, 0.8]$ and system optimisation stage $D \in (0.8, 1]$. Similar to the degree of coupling, the degree of coordination was divided into four stages: low coordinating stage $D \in (0, 0.4]$, medium coordinating stage $D \in (0.4, 0.5]$, high coordinating stage $D \in (0.5, 0.8]$ and extreme coordinating stage $D \in (0.8, 1]$.

2.7. Exploratory Spatial Data Analysis

Exploratory Spatial Data Analysis (ESDA) is a method that detects whether nearby areas have similar or dissimilar attributes overall [81]. This method is applied widely in exploring spatial agglomeration and space anomalies globally and locally and in revealing the spatial interaction mechanism that operate between various spatial units [82].

2.7.1. Global Spatial Autocorrelation

The global spatial autocorrelation uses the global Moran's I index to test whether spatial dependence is positive in the distribution of spatial elements. Moran's I is defined as follows:

$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} |x_i - \overline{x}| |x_j - \overline{x}|}{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} \sum_{i=1}^{n} |x_j - \overline{x}|^2} \tag{11}$$

where x_i and x_j are the observed values in areas i and j, respectively; $\overline{x}$ is the mean of the observed values in the areas; W_{ij} refers to the binary spatial weight matrix, and n is the total number of observed spatial units. When the value of Moran's I is near 1 or -1 and under the condition of significance level $\partial = 0.05$, similar observations tend toward spatial agglomeration. Otherwise, when the value of I is close to 0, the distribution of observations is random or spatial autocorrelation does not exist.

2.7.2. Local Spatial Autocorrelation

Local Indicator of Spatial Association (LISA) was proposed by Anselin (1995) to explain the local clusters [83]. The LISA model is expressed as follows:

$$I_i = \frac{n(x_i - \overline{x}) \sum_i W_{ij} (x_j - \overline{x})}{\sum_i (x_i - \overline{x})^2} = Z_i \sum_j W_{ij} Z_j \tag{12}$$

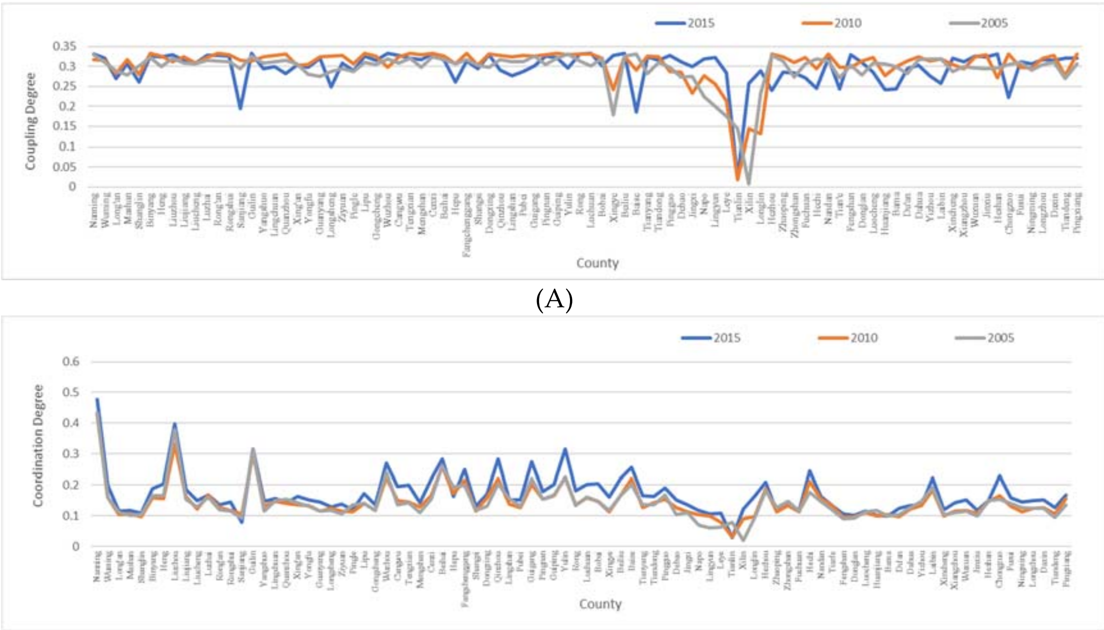
where Z_i and Z_j are the normalised forms of x_i and x_j. A positive I_i indicates significant local clusters, where the similarity value in the local space tends to agglomerate (High-High or Low-Low clusters). A negative I_i indicates significant local spatial outliers, where the similar value of local space presents the discrete distribution (High-Low or Low-High clusters).

3. Spatial-Temporal Evolution of the Degree of Coupling and Coordination

3.1. Temporal Changes in the Degree of Coupling and Coordination

The coupling coordination model is an important measure to evaluate the overall operating conditions of the system. As an underdeveloped area of China, the quantitative evaluation of the coupling and coordination of sustainable urbanization system has great reference significance to Guangxi's future population control of urban development, industrial layout adjustment and land supply.

The results show that by calculating the coupling index of 88 counties in Guangxi Province, the coupling index was relatively stable from 2005 to 2015. The mean of coupling degree in 2005, 2010 and 2015 are 0.2939, 0.3045 and 0.2973, respectively. However, it is obviously that the max or min value of coupling degree were increased. In addition, the coupling degrees of almost all of counties increased yearly as shown in Figure 3A. It means that the coupling degree of all counties increased yearly, but extremely slowly. Meanwhile, Table 2 shows that the index of coupling degree of the composite system of population, industry, and built-up land is generally low. Moreover, in Guangxi, all counties are still at the antagonism stage.



(A)

(B)

Figure 3. The Degrees of Coupling and Coordination of Population, Industry, and Built-Up Land. (**A**) The Degrees of Coupling of Population, Industry, and Built-Up Land; (**B**) The Degrees of Coordination of Population, Industry, and Built-Up Land.

Table 2. Coupling coordination of population, industry, and built-up land.

	Coupling Degree			Coordination Degree		
	2005	**2010**	**2015**	**2005**	**2010**	**2015**
Max	0.3315	0.3325	0.3331	0.4348	0.4304	0.4776
Min	0.0078	0.0186	0.0207	0.0193	0.0305	0.0278
Mean	0.2939	0.3045	0.2973	0.1433	0.1446	0.1694
Std.	0.0452	0.0466	0.0435	0.0595	0.0552	0.0666
Median	0.3060	0.3212	0.3112	0.1333	0.1322	0.1516

The coordination degrees in 2005, 2010 and 2015 are 0.1433, 0.1446 and 0.1694, respectively, after measuring the coordination index. Similar to the coupling degree, the coordination degree of Guangxi also increased slowly from 2005 to 2015. In addition, that, the coordination degree index of the composite system of population, industry, and built-up land is extremely low. In addition to Nanning, other counties are still at the low coordination stage. Figure 3B shows the coordination degree of these countries in 2015 is more evident than that in 2005 and 2010. Thus, from 2010 to 2015, an evident improvement in the coordination degree of the overall system as well as the population, industry, and built-up land was observed.

The coupling degree index in Figure 3A shows the coupling degree of population, industry, and built-up land system is close in most parts in Guangxi. This result suggests the intensive interaction among people, land and property is weak, and that the 88 counties in Guangxi are still in at a low level of urbanization. Moreover, each subsystem still needs to increase investment to promote the overall urbanization system to a higher coupling system direction. In addition, the distribution of coordination index in Figure 3B shows the coordination values of all cities are significantly higher than those of other counties in the urban area. Therefore, Guangxi, as an underdeveloped area, has polarization characteristics because population urbanization, industry agglomeration, and land urbanization focus mainly on urban areas of local cities. However, from 2005–2015, the minimum of the coupling and coordination degrees increased to more than the maximum, and the median increased to more than the mean (Figure 3). Therefore, during the study period, the differences among counties in Guangxi gradually narrowed. In the process of promoting the high-quality urbanization in the entire region, the trend of imbalanced development has been curbed effectively.

3.2. Changes in the Spatial Pattern Change of the Degree of Coupling and Coordination

In general, the coupling index of all counties is all in the antagonistic stage. In addition to Nanning and Liuzhou, the coordination index of other counties is all in the low coordinating stage. To reveal the spatial visualization process to coupling and coordination indices of population, industry, and built-up land agglomeration in the region, this research applies the Natural Breaks method to divide the coupling and coordination values of each county in the study area from low to high into four levels, namely, Levels 1 to 4. Similarly, the coordination index is divided into four corresponding levels.

Figure 4A–C shows that although the coupling index is generally low, it is still at the antagonism stage. However, the number of Level 1 counties gradually decreases from 2005 to 2015; from 5 in 2005 to 1 in 2015, thereby indicating the overall coupling degree of sustainable urbanization system increases continuously. Figure 4 shows the distribution of the coupling index in each county experienced the process of spatial reorganization, from relatively random dispersion distribution in 2005 to a certain spatial distribution pattern in 2015. The regions with effective coupling degree of sustainable urban system are distributed from the random distribution of major urban nodes in each city in 2005 to the core axis of the important node cities in 2015.

- From 2005 to 2010, the most evident characteristic is that the number of Level 4 counties increased dramatically from 40 to 58 The spatial distribution of those counties is concentrated mainly in the central and eastern regions. Although the coupling levels of the counties in the north-western region also improved, the degree of promotion is evidently behind the central and eastern regions. Generally, it forms the spatial pattern of "strong middle east and weak northwest".
- From 2010 to 2015, the spatial pattern of the coupling index also changed significantly. The number of Level 4 counties decreased from 58 to 48. The areas with high coupling level (Level 4) are distributed mainly in the following three regions: the southwest, the south central and the east central. At the same time, although the number of low-value regions (the areas concentrated in Level 1 and Level 2) decreased, these areas are still spatially distributed mainly in the northwest region.

The results show that the trend of coupling degree changes was alterable. The coupling degree varied with the allocation of population, industry, and land resource. In addition, the coupling index of 2015 suggests the areas with better coupling degree are as follows: the south-central area with Nanning-Beihai-Fangchenggang as its core, the southwest area with Tianyang-Pingxiang as its core axis and the east-central area with Liuzhou and Wuzhou as its core axis. These three coupling index clusters coincide exactly with the Beibu Gulf Economic Zone, the Revitalization Planning Zone of the left and right Old Revolutionary Area and the Xijiang Economic Belt. The results show that as an underdeveloped area, the implementation of the national strategy had a significant influence on the development level of regional urbanization and the evolution of the spatial pattern in Guangxi.

The spatial distribution of coordination index has similar characteristics to the coupling index. From 2005 to 2015, the coordination index of each county improved which the number of Level 4 counties increased from 4 in 2005 to 8 in 2015. The counties at Level 4 developed from random distribution in 2005 to concentrated in the south-eastern area in 2015. The main reason is that the newly added Level 4 counties are concentrated in the south-eastern region. From 2005 to 2015, the number of counties at Level 1 decreased significantly from 37 in 2005 to 20 in 2015. In addition, those counties were distributed mainly in the central and northern regions. Although the number of counties at Level 4 in the north-western region also decreased, they were still concentrated mainly in the north-western region (Figure 4) in 2015.

- From 2005 to 2010, the distribution of each coordination index level is basically stable. Similar to the coupling degree, the spatial distribution of coordination degree shows the spatial pattern of "strong central east and weak northwest".
- From 2010 to 2015, relative to 2005 to 2010, the spatial distribution of coordination index indicated an obvious change. Firstly, the number of counties at Level 1 decreased significantly from 36 in 2010 to 20 in 2015, and the areas were distributed mainly in the southwest and north regions. Secondly, the number of counties at Level 3 also increased significantly from 9 in 2010 to 18 in 2015. The newly added counties at Level 3 were distributed mainly in the southeast and central regions.

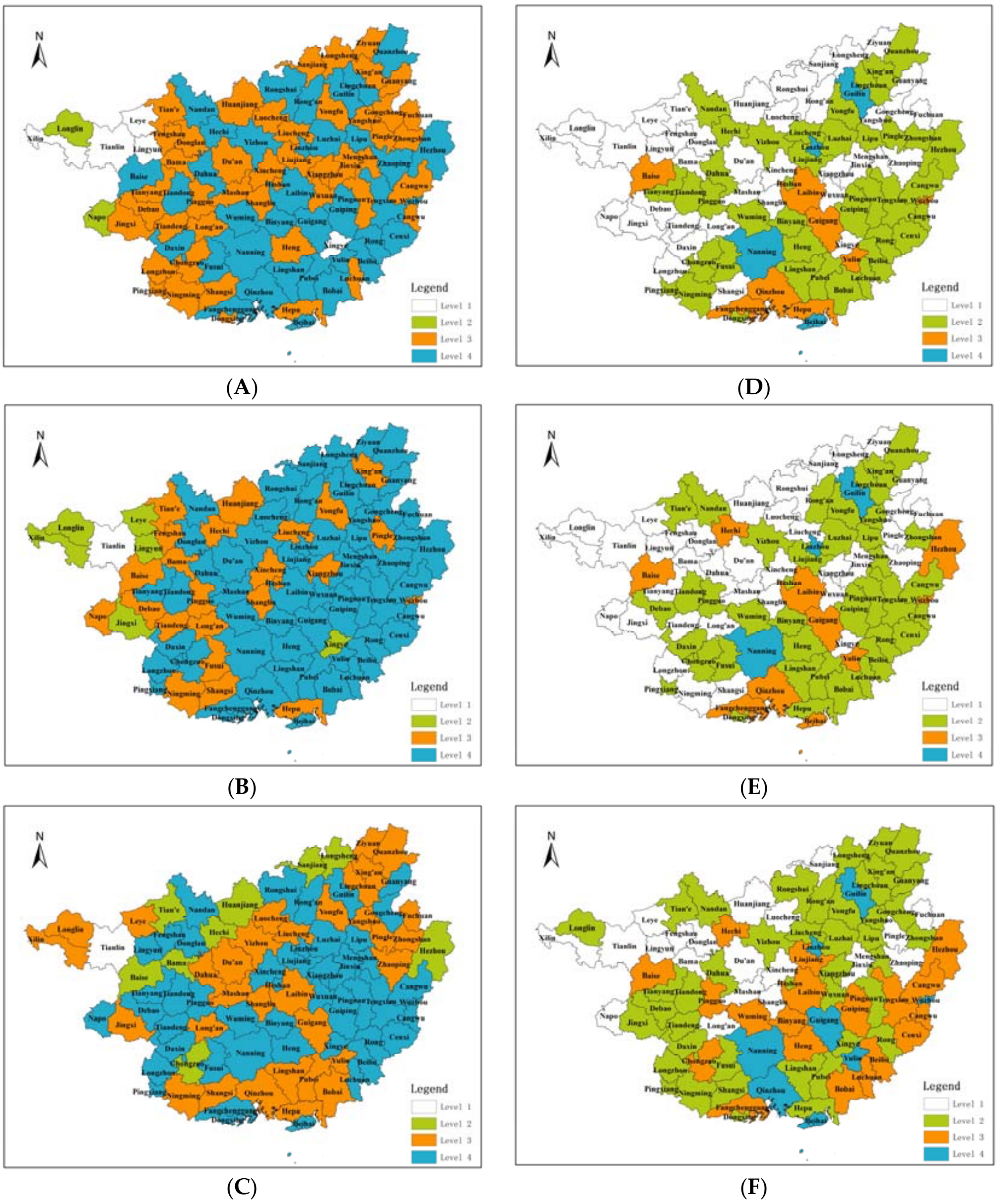


Figure 4. Change in the spatial pattern of the degree of coupling and coordination. (**A**) Coupling Degree in 2005; (**B**) Coupling Degree in 2010; (**C**) Coupling Degree in 2015; (**D**) Coordination Degree in 2005; (**E**) Coordination Degree in 2010; (**F**) Coordination Degree in 2015.

In addition, analyzing the spatial evolution results of coupling and coordination degrees can prove that the phenomenon of urbanization is not isolated. The sustainable urbanization level of the surrounding counties will also affect the urbanization development of each county. After comparing the spatial variation of the coupling index from 2005 to 2015, Xinye county, in the southeast of Guangxi, and its surrounding counties were observed to have a coupling degree of Level 4. Affected by its surrounding counties, the coupling degree of Xinye county also increased from Level 1 in 2005 to Level 4 in 2015 (the coupling degree value increased from 0.17 in 2005 to 0.3271 in 2015). Similarly, by comparing and analyzing the spatial distribution evolution results of coordination index of each county, the coordination degree of Yulin, in the middle, and Wuzhou, in the southeast, increased from Level 3 in 2005 to Level 4 in 2015 (the coordination degree value of Yulin increased from 0.2255 in 2005 to 0.3165 in 2015; the coordination degree value of Wuzhou increased from 0.2405 in 2005 to 0.2701 in 2015). The level of the surrounding areas of these two counties also increased by one degree during the study period.

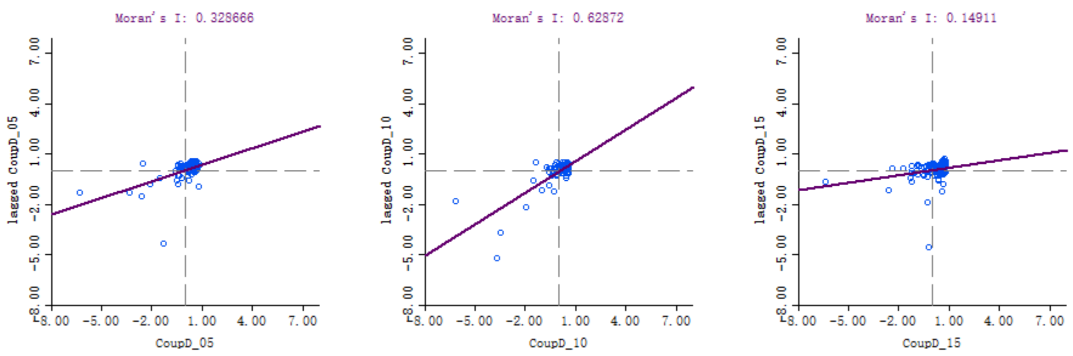
4. Spatial Disparities of Degrees of Coupling and Coordination and Its Impact on Sustainable Urbanization Development

4.1. Spatial Agglomeration and Evolution of Degrees of Coupling and Coordination on the Basis of ESDA

Studies have shown regional economic development is an open system [84]. In an open sustainable urbanization system, the degrees of coupling and coordination of a region are affected not only by its own factors, but also by the external conditions of its surrounding area [82,85]. The ESDA method focuses on assessing the spatial correlation or degree of dependence between objects and phenomena and can determine the spatial relationship between the region and its adjacent area by the spatial weight matrix.

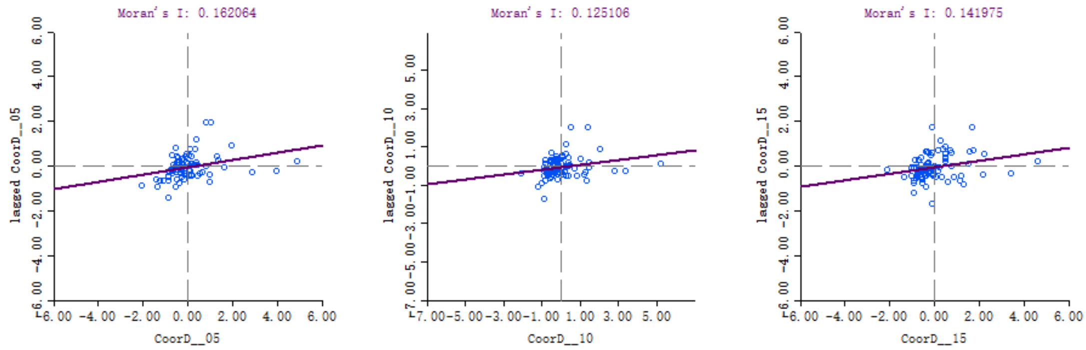
The results show the Global Moran's I values of the degree of coupling were 0.3287, 0.6287 and 0.1491 in 2005, 2010 and 2015, respectively, and the Global Moran's I values of the degree of coordination were 0.1621, 0.1251 and 0.142 in 2005, 2010 and 2015, respectively. The global Moran's I of the coupling and coordination degrees of sustainable urbanization in 88 counties in the study area were greater than 0. The Z statistic of the standardized test is positive and passed the 5% significance level test. Therefore, we can reject the null hypothesis that no autocorrelation of sustainable urbanization exists across counties (Figure 5).

All Global Morgan's I values are positive, thereby indicating the coupling and coordination of sustainable urbanization across counties have a positive spatial autocorrelation and spatial agglomeration exists in areas where the level of urbanization is similar in the county. The spatial agglomeration of the degrees of coupling and coordination changes over time. The degree of spatial agglomeration of coupling increased steadily from 2005 to 2010, and then weakened rapidly in the period 2010 to 2015. However, the degree of spatial agglomeration of coordination presents a tendency to weaken first and then increase.



(**A**) (**B**) (**C**)

Figure 5. *Cont.*



(**D**) (**E**) (**F**)

Figure 5. Moran Scatter Plot of coupling and coordination. (**A**) Coupling Degree in 2005; (**B**) Coupling Degree in 2010; (**C**) Coupling Degree in 2015; (**D**) Coordination Degree in 2005; (**E**) Coordination Degree in 2010; (**F**) Coordination Degree in 2015.

4.2. Evolution of Hot-Spot Areas and the Impact on Sustainable Urbanisation

The internal conditions should be studied to further consider the contribution of each county to the global spatial autocorrelation and to extend the global Moan's I to mask the local instability. Therefore, to better explain the spatial heterogeneity characteristics of the coupling and coordination degree of sustainable urbanization in each county, research on hot-spot areas and cold-spot areas should also be studied. The LISA values of 2005, 2010 and 2015 are calculated, and the significant regions are presented via the LISA cluster map (Figure 6).

The results show the coupling index of each county in Guangxi has evident characteristics of spatial agglomeration. The Type LL counties are cold-spot areas, and these areas are the agglomeration area of counties with lower coupling index. During the study period, when at the 0.05 significance level, Type LL counties remained essentially stable in quantity; these counties include mainly Longlin, Tianlin, Leye and Lingyun. Contrary to Type LL counties, Type HH counties are hot-spot areas, which are the agglomeration area of counties with higher coupling index. Compared with the other types, an evident increase in the number of Type HH counties is observed. From the perspective of spatial distribution, no change in the spatial distribution pattern of Type LL counties, mainly in the western region, is observed. The spatial distribution of Type HH counties has a clear process of centralization to the east, and its number and scale expand gradually. The coupling index of these counties is similar to that of their surrounding counties. In 2005, Type HH counties were located mainly in the east, including Cangwu, Wuzhou (city proper), Tengxian and Cenxi. Until 2015, six new Type HH counties have been added in this area, including Rongxian, Beiliu, Xinye, Guiping, Pingnan and Jinxiu. In addition, Type LH and Type HL counties represent clustering of dissimilar values, which is expressed as a negative local spatial autocorrelation [86]. In 2005, Yongfu and Xinye were Type LH counties. In 2010, Xing'an and Wuzhou (city proper) were added to this type. However, in 2015, no Type LH counties were included. Only Lingyun was categorized as a Type HL county. The results indicate a strong positive spatial correlation was observed in 2005–2015. Especially after 2010, the concentration of high coupling degree was distributed in the eastern region, forming a significant hot-spot area. Moreover, the concentration of low coupling degree was distributed in the western region, forming a relatively stable cold-spot area. The Type LH and HL counties signified strong negative spatial correlation and marked heterogeneity [82]. Few counties of both types were observed, and in 2015, only Lingyun was Type HL.

The spatial distribution of the degree of coordination shows a different spatial agglomeration pattern to that of the degree of coupling. During the study period, Types LL and HH counties occupied a dominant position in terms of number, thereby indicating the coordination degree has the characteristics of spatial agglomeration. In 2005–2015, Type LL counties were located similar to that of the coupling degree, from which the spatial distribution pattern of Type LL counties remained unchanged. As a result, a significant cold-spot area exists in the west, including Longyun, Leye, Tian'e, Lingyun and Fengshan. The Type HH counties in 2005 and 2010 display random distribution, but in 2015, they were concentrated in the southeast, including Binyang, Guiping, Rongxian and Bobai. Generally, the number of Type HL and Type LH counties has increased gradually, thereby indicating the coordination degree reflects the strong spatial heterogeneity. In 2005, only two counties belonged to this type, which was surrounded by neighbors with dissimilar values. However, by 2015, the number increased to six, and included Baise, Hechi, Lipu, Xinye and Hepu, thereby indicating the evident regional imbalance of the coordination of spatial heterogeneity of population, industry, and built-up land in this region; the spatial evolution of the Type LH counties is similar. In 2005 and 2010, only Xiangzhou belonged to this type. However, by 2015, the number of Type LH counties increased to three, and was distributed mainly around Type HH counties, especially Heshan and Xingye. A much evident regional difference in the process of sustainable urbanization in county area was observed according to the spatial pattern evolution of Type HL and Type LH counties.

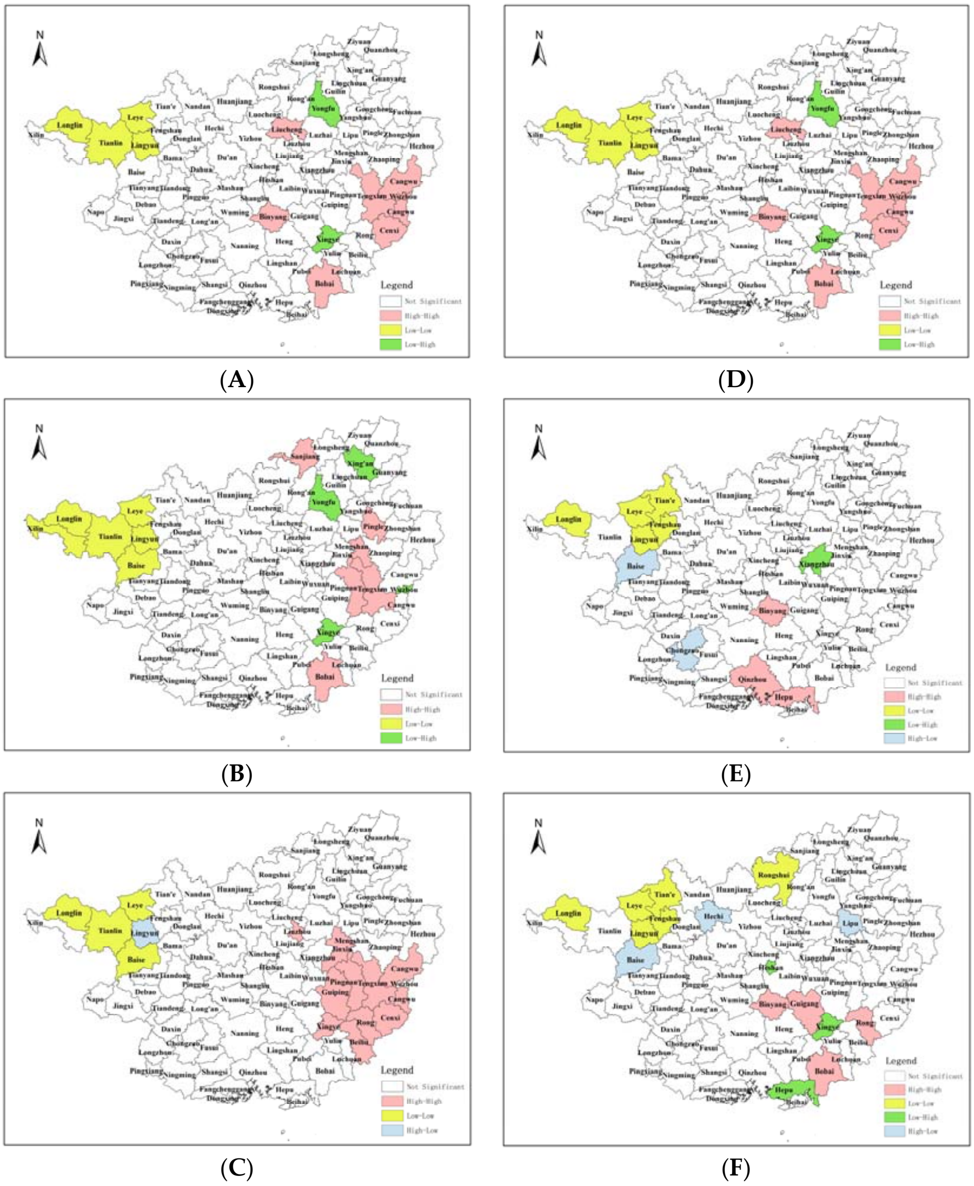


Figure 6. LISA cluster map of the degree of coupling and coordination. (**A**) Coupling Degree in 2005; (**B**) Coupling Degree in 2010; (**C**) Coupling Degree in 2015; (**D**) Coordination Degree in 2005; (**E**) Coordination Degree in 2010; (**F**) Coordination Degree in 2015.

Figure 6 shows that in the period of 2005 to 2015, the spatial disparities in the coupling degree of population, industry, and built-up land agglomeration showed the spatial distribution characteristic of being "High in the east and low in the west", thereby indicating the hot-spot areas were in the eastern areas of Guangxi, whereas the western areas were mainly cold-spot areas. In addition, in terms of their spatial evolution characteristics, the concentration effect of Type HH counties strengthened gradually with their increasing number. The spatial agglomeration has a significant spillover effect and plays a beneficial role in coordinating the urbanization development [82,87]. In 2015, influenced by the hot-spot area, Rongxian, Beiliu, Xinye, Guiping, Pingnan and Jinxiu were replaced as Type HH counties.

In addition, the spatial pattern evolution of coordination degree more significantly reflects the spatial heterogeneity of sustainable urban development. Thus, sustainable urbanization needs to coordinate fully the spatial aggregation of factors such as population, industry, and built-up land. However, because of the evident differences in the development stage and the characteristics of industry of each county, the coordination of spatial agglomeration shows certain randomness. However, in 2015, the spatial distribution of Type LH and Type HL counties is around mainly Type HH and Type LL counties, indicating the evolution of sustainable development is not a flat radiation process, but shows the characteristics of the difference with regional changes, similar to a rugged surface. Moreover, the process of sustainable urbanization has evident spatial differences. The spatial agglomeration of the key elements of sustainable urbanization such as population, industry, and built-up land should also be differentiated according to the spatial allocation approach for the characteristics of the regional spatial differentiation.

5. Conclusions and Suggestions

The exploratory research is an important measure to reveal the condition of urbanization development and discover the spatial dispersion of coupling coordination degree and the evolution characteristics of spatial model, as well as the influence on sustainable urbanization. This work guides the rational spatial allocation of resource. The degree of the coupling and the coordination of population, industry, and built-up land spatial agglomeration in the Guangxi province in the period 2005–2015 was calculated by using a comprehensive evaluation index system. In addition, the spatial pattern and temporal changes in the degree of coupling and coordination were analyzed through ESDA to determine the spatial agglomeration characteristics and spatial disparities evolution. The main conclusions can be drawn as follows:

- The coupling coordination index value shows the intense interaction between each subsystem of population and land, industry, and land and population and industry were weak because the 88 counties in Guangxi were still at a low level of urbanization. The value of coupling and coordination degrees has evident polarization characteristics; thus, the coordination values of urban areas would be evidently higher than that of other counties within the scope of urban areas. The minimum and medium of the coupling and coordination indices had surpassed the maximum and mean, respectively; thus, the imbalanced development situation in other districts and counties of Guangxi was likely to be moderate during 2005–2015.
- We find that from 2005–2015, the spatial distribution of the coupling and coordination degrees evolved from a random distribution to key cities as the core distribution. Moreover, the implementation of national strategies has a significant role in the development of regional urbanization and the evolution of spatial patterns. Moreover, by analyzing the spatial evolution results of the coupling and coordination degrees, we find the urbanization development is not isolated. The urbanization development of each county is also affected by the sustainable urbanization level of surrounding counties.
- The ESDA exploration analysis further validates the evident spatial correlation of sustainable urbanization developments among counties. The degree of coherence and coordination of sustainable urbanization in all counties shows a positive spatial autocorrelation, thereby indicating

a spatial agglomeration effect in the regions with the same level of urbanization. This study also finds evident spatial differentiation characteristics of the coupling and coordination indices based on LISA analysis. The spatial disparities in the coupling degree of population, industry, and built-up land agglomeration indicate the hot-spot areas were in the eastern areas of Guangxi, whereas the western areas were mainly cold-spot areas. Moreover, spatial agglomeration had a significant spatial spillover effect based on the concentration effect of Type HH counties.

- The spatial pattern evaluation of coordination index reflects more evidently the spatial heterogeneity of sustainable urban development. The spatial distribution of Type LH and Type HL counties occurs mainly around Type HH and Type LL counties, indicating the process of sustainable development evolution has the characteristics of difference with regional change. The development of sustainable urbanization has evident spatial differences. Therefore, in the process of promoting the development of sustainable urbanization, the spatial allocation of elements such as population, industry, and built-up land should adopt differentiated means according to the characteristics of regional spatial differentiation.

The results show that sustainable urbanization on the rational allocation of population, industry, and land resources. Therefore, it is not enough to merely focus on just one aspect of them. To promote sustainable urban development, it is important to balance the relationship of these three aspects. Normally, the allocation of population and industry are mainly affected by the market, but the land resources can be regulated through land use management [1,59,67]. Therefore, a strict land allocation management strategy is of great significance for sustainable urbanization [55]. Moreover, based on the exploratory spatial data analysis, the results present an obvious spatial spillover effect. In conclusion, to promote sustainable urban development, it is necessary to consider the allocation of these three aspects, as well as the status of surrounding areas.

This study selects relevant indicators from three dimensions of population, industry, and land to develop a coupling and coordination evaluation system for sustainable urbanization. This analytical framework could be applicable to other regions and counties in China. However, it need to be emphasized that there has been no universal evaluation framework of sustainable urbanization so far. However, the connotation of sustainable urbanization is very rich. A comprehensive evaluation framework needs to be built based on multiple perspectives. Moreover, compared with other developed regions in China, Guangxi has an extremely large difference in the characteristics of spatial aggregation of population, industry, and built-up land. Further exploring the influence of the spatial agglomeration of the three elements on the sustainable urbanization is possible by analyzing the spatial evolution of the coupling and coordination degree in other regions. However, we figured out the evolution of coupling and coordination degrees through ESDA. The mechanism of the process is hardly discussed in this research. Regarding that, it is necessary to introduce some advanced analytical techniques such as spatial regression model [72], geographically and temporally weighted regression (GTWR) model [88] and the geographical detector [89].

Author Contributions: Y.Z. and G.L. conceived and designed the study. Y.Z. and Z.S. performed the study; Y.Z., G.L. and Y.Z. analyzed the data; Z.S. contributed analysis tools; Y.Z. and G.L. wrote the paper. All authors read and approved the final manuscript.

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