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# Comprehensive Assessment of Production–Living–Ecological Space Based on the Coupling Coordination Degree Model

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**Abstract:** Production–living–ecological (PLE) space is the basic site of all human activities. The coordinated development of these three spaces is an important prerequisite for achieving sustainable development goals. However, a quantitative assessment of the overall coordination among these three spaces is limited in current research. This paper built an indicator system and a coupling coordination degree model to comprehensively assess the development status of PLE space in China. The statuses of 340 prefecture-level cities across the country from 2005 to 2015 were analyzed. The results showed that the national average first increased from 0.435 in 2005 to 0.452 in 2010 and then dropped to 0.445 in 2015. There was an obvious distribution line between slightly unbalanced cities and moderately balanced cities, close to the famous "Hu Huanyong Line." Most provincial capital cities were between the slightly unbalanced class and barely balanced class. Only Fuzhou in Fujian Province exceeded the barely balanced class in 2015. This paper provides several references for other developing cities to achieve sustainable and coordinated development.

**Keywords:** sustainable development; coupling coordination degree; production–living–ecology space; Hu Huanyong Line

## 1. Introduction

The rapid development of industrialization and urbanization has led to intense competition and conflict between humans and nature, causing a range of issues such as global climate change, the energy crisis, and food security [1], especially in developing counties. In 2012, the United Nations created a set of sustainable development goals (SDGs) to respond to the above problems [2]. In 2015, 17 sustainable development goals were officially adopted [3], and the "New Urban Agenda" was released in 2016 [4]. China actively promotes SDGs through a comprehensive portfolio of large projects [5]. The concept of production–living–ecological (PLE) space was first proposed in the report of the 18th National Congress of the Communist Party of China. It stressed that "the space for production should be intensive and highly efficient, the living space should be moderately liveable, and the ecological space should be unspoiled and beautiful." PLE space was proposed for promoting sustainable economic and social development, which has attracted increasing attention in China. PLE space in a city essentially covers the scope of the space of the activities that are related to people's material production and spiritual life [6]. Especially, human society engaging and economic activities imply that cities are artificial systems, not natural systems [7,8]. The relationships among the social, economic, and ecology spaces are not completely independent but are mutually restrictive and interconnected (Figure 1), which makes the system dynamic and complex [9–11].

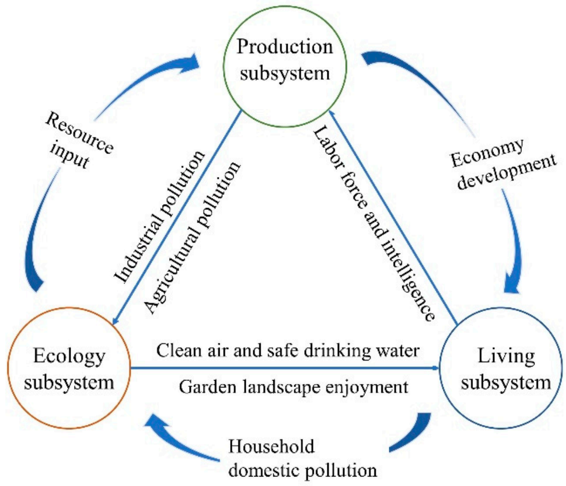



**Figure 1.** Coupling relationship among production space, living space, and ecological space. (Drawn by authors).

Intensive and efficient development of production space allows for increased development space and alternative development modes to improve quality of life and ecological service functions and is the basis of the liveability and ecology of living space. However, extensive economic development has resulted in serious environmental pollution problems, which threaten not only ecological quality and safety, but also people's living environment [12]. Ecological space provides production factors, such as water, land, and other resources, for production activities. At the same time, ecological space is also an indispensable aspect of the ability for people to enjoy natural experiences and a healthy life. Living space also provides labour and employment opportunities for economic activities in the production space. Different quality of life levels attract different levels of capital, and thus restrict the urban industrial structure [13].

The essence of the PLE problem is the contradiction between the limited versatility of natural resources and growing demand. In sustainable development research, exploring how to use limited resources to better develop the economy and to improve people's quality of life under the premise of not destroying the ecological environment has become a popular topic. Researchers in natural sciences have also proposed many frameworks for sustainable development indicators system. The pressure–state–response (PSR) model proposed by the Organization for Economic Cooperation and Development in 1993 is a classic framework [14]. The PSR framework was subsequently extended to a driving force–stress–state–impact–response (DPSIR) framework, which was adopted by the European Environment Agency in 1999. In 1997, the United Nations Environment Programme and the United States Non-Governmental Organization proposed a well-known three-system model of social, economic, and environmental systems [15]. The United Nations Commission on Sustainable Development established a universal sustainable Development indicator system framework, which is composed of four major systems: social, economic, environmental, and institutional [16]. The concept of the "water–energy–food nexus" was proposed at the Bonn Conference in 2011, which focused on how to balance the relationship between limited resources and growing demand [17]. In 2014, a series of methods were proposed by the Food and Agriculture Organization of the United Nations (FAO) [18] that were devoted to studying how to formulate strategies to develop new technologies and policies under this framework. Regarding how to better resolve this conflict or contradiction, some scholars believe that the versatility and limitation of land resources are the core of the contradiction [19]. In 2011, several international organizations, such as the United Nations Environment Programme, launched the "Future Earth" plan, with the Global Land Program (GLP) as its core content, and attempted to further explore the complex relationship between humans and nature by studying the science of land systems [20]. GLP focuses on land systems, which are conceptualized as the result of internal dynamic interactions of the social ecosystem and sees land as an important social and environmental bond to address the challenges and opportunities of food security, access to water, livelihoods, land degradation, and so on [21]. Eric et al. studied how to develop agricultural production and global economies without damaging forest systems, using limited land resources in developing countries [22]. To some extent, PLE space was also proposed based on the limitedness and versatility of land.

Research focus on PLE space in China has increased in recent years but not substantially. Regarding the classification system of PLE land use, Zhang et al. highlighted the ecological functions of land use types on the basis of a traditional land use classification and established classification standards for PLE spaces [23]. Different land use types are scored according to the primary and secondary functions of the land, and a production land, living land, and ecological land classification system was developed in the study [24]. Based on the identification of the main land use functions, a PLE land classification system was established for southwestern China [25]. Other studies have contributed to progress in other areas, such as the spatial zoning of the production–living–ecological functions [26], capacity evaluation [27], quantitative function identification and analysis [6], reconstruction and space optimization layout [28,29], and impacts of climate change on PLE space [30]. However, research on the quantitative evolution of the interaction among the three functions has not been systematically carried out. It is necessary to assess the status and performance of the three spaces as a whole.

The coupled coordination model can be used to measure the degree of coordination and cooperation between two or more subsystems in a complicated system. Coupling was originally a physical concept, indicating the existence of interactions between elements in a system [31]. The coordination concept is derived from systems theory and synergy theory. Coordination refers to the degree of harmony between systems or between system elements in the process of development, reflecting the trend in the system from disorder to order [32]. The key to systematic ordering is the "synergy" of intersystems within a system. The coupled coordination model quantifies this effect and accurately reflects the synergy of intersystem elements. This model has been widely used in research on urban ecology [33,34], low-carbon development [35,36], tourism [37,38], soil and plants [39], land urbanization [40], and other topics [41]. However, few studies have focused on the coupling coordination of PLE at present. The existing studies are mostly multi-time series at the regional scale [42,43].

This paper took 340 prefecture-level cities nationwide (excluding Hong Kong, Macao, and Taiwan) as the research objects to explore the situation of PLE space in China, and due to data availability, it only took the time period 2005–2015 into consideration. The purpose of this paper is: 1) to establish an index system that characterizes the spatial functions of PLE space at the prefectural level; 2) to construct a coupling coordination model to measure the temporal and spatial differentiation characteristics; and 3) to select typical cities to analyze their unbalanced status and to identify the main uncoordinated type in the three spaces.

## 2. Data and Methods

### 2.1. Data Collection and Preprocessing

The selection of indicators was based on previous studies. Considering the availability of data, energy intensity, agricultural production efficiency, industrial output value above scale, and land reclamation rate were chosen as the indicators of production space; NDVI (Normalized Difference Vegetation Index), PM2.5 (Fine Particulate Matter ≤ 2.5 μm), ecological land surface ratio, and $NO_2$ (Nitrogen Dioxide) were chosen as the indicators for the ecological space subsystem; and population density, service industry efficiency, night light index, and per capita food possession were chosen as the indicators for the life space subsystem. A detailed description of the indictors collected and calculated is in Table 1. Positive (+) or negative (−) mean that the indicators are helpful to improve the performance of subsystem or not.

The NDVI and night light index data were downloaded from the Resource and Environment Data Cloud Platform [44]. Since the night light data were only updated to 2013, the 2015 data were replaced with the data from 2013. PM2.5 data were downloaded from the Socioeconomic Data and Applications Center [45]. Other data were collected from the statistical yearbook.

**Table 1.** Indicators and description of production, living, and ecology subsystems.

| Subsystem | Indicator (Unit) | | Description | Positive (+) or Negative (−) |
|---|---|---|---|---|
| Production space subsystem | Energy intensity (ton coal equivalent/yuan) [46] | S1 | Energy consumed per unit of GDP | − |
| | Agriculture production efficiency (ten thousand yuan/km$^2$) [47] | S2 | GDP in primary sector per unit agricultural area | + |
| | Industrial output value above scale (RMB) [47] | S3 | Gross industrial output value above designated size | + |
| | Land reclamation rate (%) [47] | S4 | Cultivated area percentage in total land area | + |
| Ecological space subsystem | NDVI (dimensionless) [46] | S5 | Extent of vegetation coverage in the area | + |
| | PM2.5 (μg/m$^3$) [46] | S6 | PM2.5 content concentration in air | − |
| | Ecological land surface ratio (%) [46] | S7 | Proportion of ecological land area in total land area | + |
| | $NO_2$ (ton) [48] | S8 | Nitrogen dioxide emissions | − |
| Living space subsystem | Population density (cap/km$^2$) [47] | S9 | Population of land per unit area | − |
| | Service industry efficiency (ten thousand yuan/km$^2$) [47] | S10 | GDP of tertiary sectors (services) per unit construction land area | + |
| | Night light index (dimensionless) [49] | S11 | Spatial distribution of city lights at night | − |
| | Per capita food possession (ton per capital) [47] | S12 | Cereal amount per capita | + |

### 2.2. *Coupling and Coordination Model*

#### 2.2.1. Indicator Normalization

To ensure the scientific accuracy of the research evaluation results and eliminate the influence of different indicators on the same unit of measurement, it is necessary to standardize the original data indicators [1]. In this study, the original data matrix of the evaluation index of land and space utilization quality was standardized by the range method:

If the indicator had a positive impact on the comprehensive evaluation of the subsystem performance level, then the normalized value was calculated by the following Equation (1) or, conversely, by Equation (2):

$$X_{ij} = \frac{x_{ij} - min\{x_{ij}\}}{max\{x_{ij}\} - min\{x_{ij}\}} \quad (1)$$

$$X_{ij} = \frac{max\{x_{ij}\} - x_{ij}}{max\{x_{ij}\} - min\{x_{ij}\}} \quad (2)$$

where $X_{ij}$ represents the standardized value of indicator i for evaluation object j, $x_{ij}$ represents the original value, and $max\{x_{ij}\}$ and $min\{x_{ij}\}$ indicate the maximum and minimum values, respectively.

#### 2.2.2. Entropy Weight

To obtain the weight value more objectively, the entropy method was used to calculate the weight. "Entropy" stems from a physical concept of thermodynamics, which was later introduced into information theory. The entropy method can overcome the overlap of information between multiple indicator variables, thus objectively reflecting the internal changes between the indicators [50].

The entropy method has been widely used in the field of indicator evaluation research [51–53]. The information entropy of each evaluation index was calculated by the following equation:

$$F_i = \frac{X_i}{\sum_{j=1}^{n} X_{ij}} \quad (3)$$

$$\mathrm{k} = \frac{1}{\ln(n)} \quad (4)$$

$$H_i = -k \times \sum_{i=1}^{n} F_i ln F_i \ (\mathrm{i} = 1, 2 \ldots 12) \quad (5)$$

The weight value was calculated by the following equation:

$$W_i = \frac{1 - H_i}{\sum_{i=1}^{n} (1 - H_i)} \quad (6)$$

2.2.3. Coupling Coordination Degree Assessment

Liao et al. derived the calculation formula based on the dispersion coefficient [54]. It was applied to only two subsystems. Jiang et al. also discussed this formula, corrected errors in the previous coupling formula and extended them to multiple subsystems [55]. The coupling coordination degree can be obtained according to the following formula [56]: The value of coupling coordination degree is between 0 and 1. A higher value indicates a higher degree of coupling coordination [55].

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

$$\mathrm{T} = \alpha \times U_1 + \beta \times U_2 + \ldots + \gamma \times U_e \cdot (\alpha = \beta = \ldots = \gamma = 1/n) \quad (8)$$

$$C = \sqrt[n]{\left\{ \frac{U_1 * U_2 * \ldots * U_n}{\left( \frac{U_1 + U_2 + \ldots + U_n}{n} \right)^n} \right\}} \quad (9)$$

$$\mathrm{U} = \sum_{i=1}^{n} W_i * X_i \quad (10)$$

where D represents the coupling and coordination degree. $T$ reflects the overall effect and level of each subsystem. C is the coupling degree. U represents the performance of the subsystems. $W_i$ represents the weight value of indictor i. $X_i$ represents the standard value of indictor i in each subsystem.

There are three subsystems of production, life, and ecology in this study, so C and T are calculated by the following formulas, where $U_p$, $U_l$, and $U_e$ are the performance levels of the production space subsystem, living space subsystem, and ecological space subsystem, respectively. $\alpha$, $\beta$, and $\gamma$ represent the contributions of the production space subsystem, ecological space subsystem, and living space subsystem, respectively.

$$\mathrm{C} = \left( \frac{U_p * U_l * U_e}{\left( \frac{U_p + U_l + U_e}{3} \right)^3} \right)^{\frac{1}{3}} \quad (11)$$

$$\mathrm{T} = \alpha \times U_p + \beta \times U_l + \gamma \times U_e \cdot (\alpha = \beta = \gamma = 1/3) \quad (12)$$

## 3. Results and Analysis

### *3.1. Entropy Weight of Indicators*

Table 2 shows the weights of the above 12 indicators obtained by the entropy method. As shown, the industrial output value above scale had the greatest weight for the production space during 2005 and 2015. This means that economic factors had a great impact on the quality of PLE space utilization. However, it gradually declined, from 0.57 in 2005 to 0.52 in 2015, which shows that the contribution of the economy to the performance of PLE was decreasing. The weight of agricultural production efficiency and land reclamation rate constantly increased. For ecological space, the weight of ecological land surface ratio increased to above 0.6 and remained essentially stable from 2005 to 2015. For living space, of the indicators, the night light index had the greatest weight, but it dropped from 0.6 in 2005 to 0.5 in 2015. In contrast, the contribution of per capita food possession became increasingly important, increasing from 0.18 in 2005 to 0.3 in 2015.

**Table 2.** The weights of the above 12 indicators obtained by the entropy method.

| Indicator (Unit) | | Weight in 2005 | Weight in 2010 | Weight in 2015 |
|---|---|---|---|---|
| Energy intensity (ton ce/yuan) | $S_1$ | 0.01 | 0.01 | 0.01 |
| Agriculture production efficiency (ten thousand yuan/km$^2$) | $S_2$ | 0.25 | 0.29 | 0.28 |
| Industrial output value above scale (RMB) | $S_3$ | 0.57 | 0.51 | 0.52 |
| Land reclamation rate (%) | $S_4$ | 0.17 | 0.19 | 0.19 |
| NDVI (dimensionless) | $S_5$ | 0.13 | 0.10 | 0.12 |
| PM2.5 (μg/m$^3$) | $S_6$ | 0.22 | 0.22 | 0.21 |
| Ecological efficiency (%) | $S_7$ | 0.62 | 0.63 | 0.62 |
| $NO_2$ (ton) | $S_8$ | 0.03 | 0.05 | 0.06 |
| Population density (cap/km$^2$) | $S_9$ | 0.02 | 0.01 | 0.01 |
| Service industry efficiency (ten thousand yuan/km$^2$) | $S_{10}$ | 0.20 | 0.19 | 0.18 |
| Night light index (dimensionless) | $S_{11}$ | 0.60 | 0.51 | 0.50 |
| Per capita food possession (ton per capital) | $S_{12}$ | 0.18 | 0.30 | 0.32 |

### *3.2. Coupling and Coordination Degree of PLE*

In previous studies, there were many classifications for the results of coupling coordination degree. Yao et al. divided coupling coordination degree into three categories: coordination, transition, and imbalanced recession, which were subdivided into 10 subcategories [57]; Xu et al. divided coupling coordination degree into five classes, from unsatisfactory coupling coordination to satisfactory coupling coordination [56]. Fei et al. hold that the coupling coordination degree value (0~1) can be described by three stages: disorder stage, transition stage, and coordination stage [58].

To better distinguish the difference between degrees of coupling coordination, this paper classified the results into six categories, as shown in Table 3.

**Table 3.** Classification of the coupling and coordination degree of production–living–ecological (PLE) space.

| Classes | Interval Value | Classes | Interval Value |
|---|---|---|---|
| Seriously unbalanced (SeU) | $0 < D \leq 0.2$ | Barely balanced (BB) | $0.5 < D \leq 0.6$ |
| Moderately unbalanced (MU) | $0.2 < D \leq 0.4$ | Favourably balanced (FB) | $0.6 < D \leq 0.8$ |
| Slightly unbalanced (SU) | $0.4 < D \leq 0.5$ | Superiorly balanced (SB) | $0.8 < D \leq 1.0$ |

#### 3.2.1. National Situation

Figure 2 shows the statistical results of PLE space in 340 prefecture-level cities across the country in 2005, 2010, and 2015. The results show that no cities were seriously unbalanced or superiorly balanced from 2005 to 2015. There were 77, 53, and 75 cities in the moderately unbalanced class in 2005, 2010, and 2015, respectively. Additionally, most cities were slightly unbalanced, accounting for 70% (237/340), 67% (227/340), and 64% (217/340) of the total in 2005, 2010, and 2015, respectively. This means that the number of cities in the slightly unbalanced class gradually decreased during the past decades, while cities in the barely balanced class increased from 21 in 2005 to 56 in 2010 but decreased to 43 in 2015. The number of cities in the favourably balanced class remained essentially unchanged with five cities both in 2005 and 2015 and four cities in 2010.

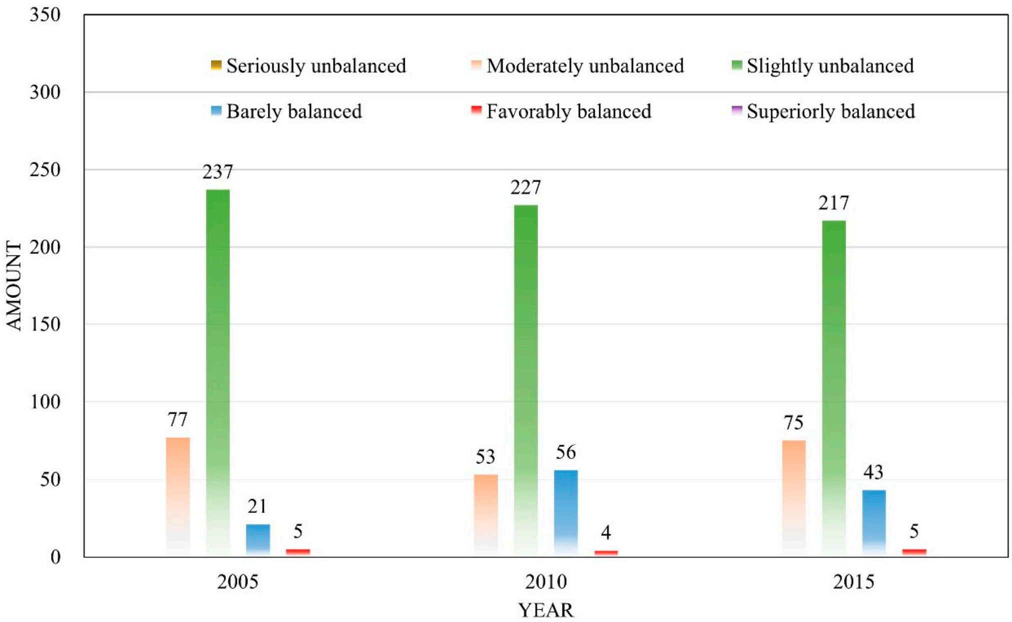



**Figure 2.** Statistical results for the 340 prefecture-level cities in the six classes.

Table 4 shows the maximum, minimum, average, and standard deviation of the coupling coordination degree in 2005, 2010, and 2015. On the one hand, the average increased from 0.435 to 0.452 and then dropped to 0.445. If the average value was used as an indicator of the national coupling coordination degree level, then the situation improved from 2005 to 2010 but worsened in 2015. To some extent, the standard deviation can reflect fluctuations in data series. The standard deviation increased from 0.052 in 2005 to 0.061 in 2015, reflecting the increasing degree of dispersion among individuals within the group.

**Table 4.** The maximum, minimum, average, and standard deviation of the coupling coordination degree.

| Year | Maximum (City Name) | Minimum (City Name) | Average | Standard Deviation |
|---|---|---|---|---|
| 2005 | 0.750 (Dongguan) | 0.300 (Haibei Tibetan Autonomous Prefecture) | 0.435 | 0.052 |
| 2010 | 0.646 (Foshan) | 0.296 (Haibei Tibetan Autonomous Prefecture) | 0.452 | 0.054 |
| 2015 | 0.687 (Foshan) | 0.296 (Haibei Tibetan Autonomous Prefecture) | 0.445 | 0.061 |

On the other hand, the results obviously showed that Haibei Tibetan Autonomous Prefecture was always the prefecture-level city with the lowest coupling coordination degree value from 2005 to 2015. In 2005, the maximum value was 0.75 for Dongguan in Guangdong Province, and the minimum value was 0.3 for Haibei Tibetan Autonomous Prefecture in Qinghai Province. In both 2010 and 2015, Foshan in Guangdong Province had maximum coupling coordination degree values of 0.646 and 0.687, respectively.

Figure 3 shows the spatial distribution of every class in 2005. It is obvious that cities that were in the slightly unbalanced class were mainly located east of the "Hu Huanyong Line," while most moderately unbalanced cities were in the opposite area. Barely balanced cities were generally located near the sea, except for E'zhou in Hubei Province and Jinan in Shandong Province. There were only five favourably balanced cities in 2005. In addition, 80% of them were located in Guangdong Province, Shenzhen, Foshan, Dongguan, and Zhongshan. The remaining area was Suzhou in Jiangsu Province.

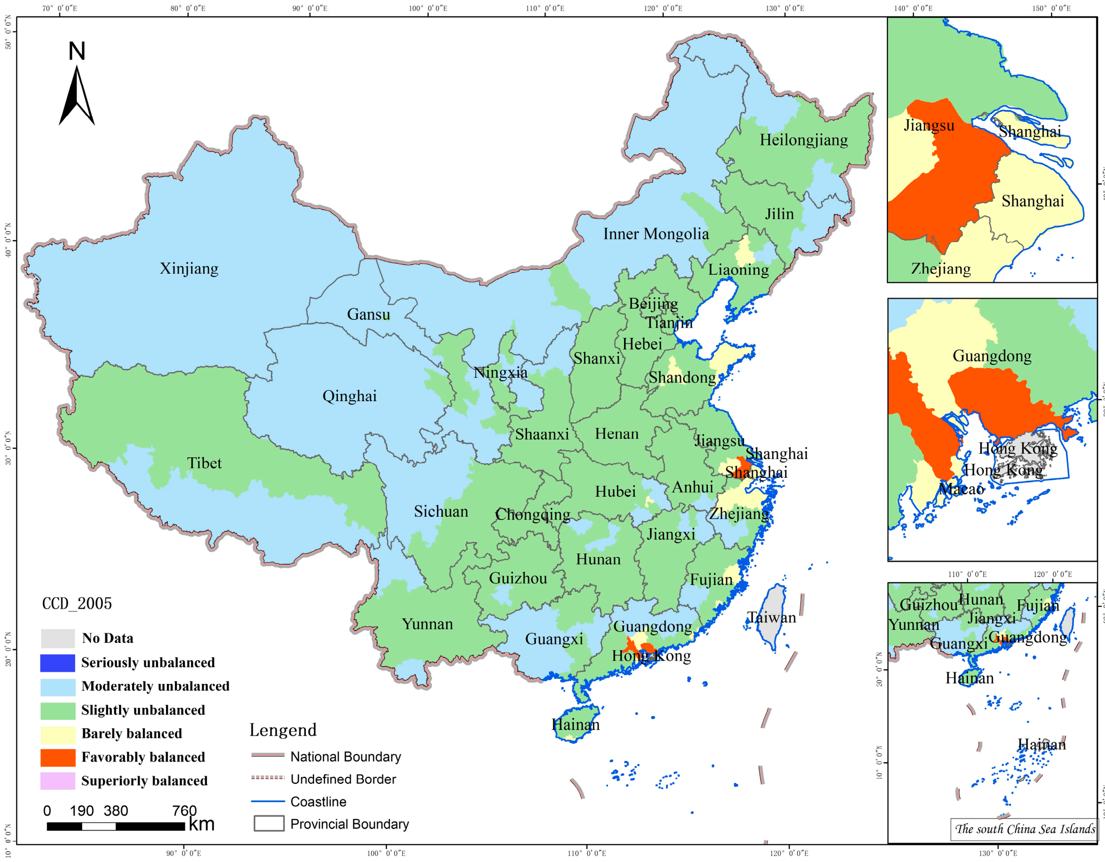
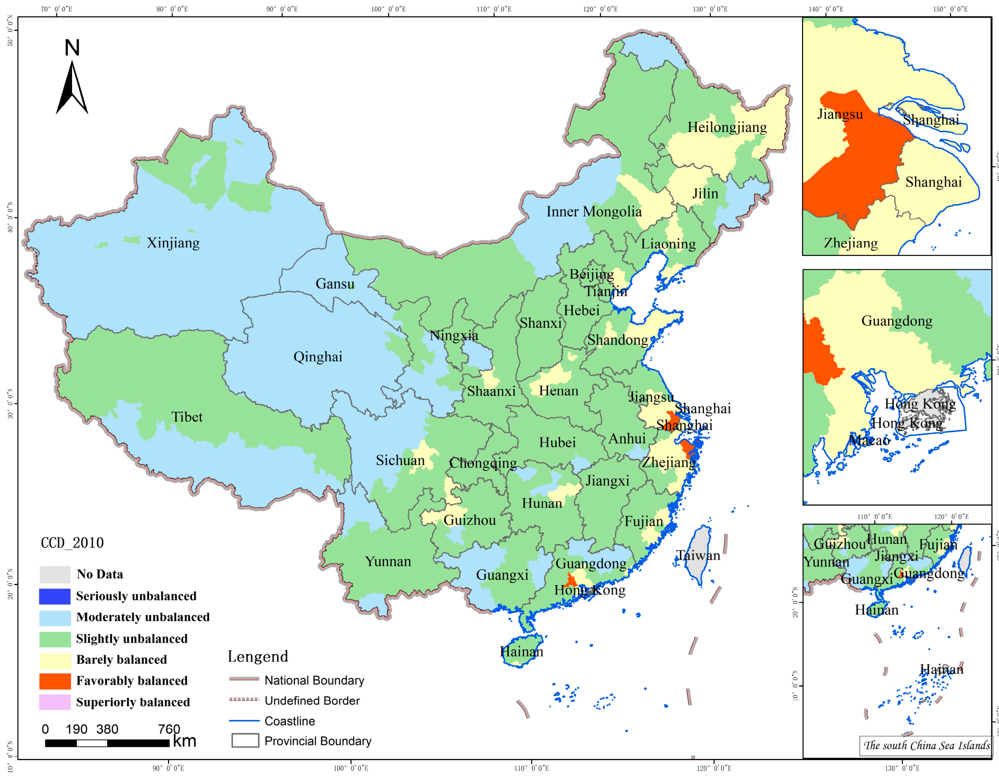


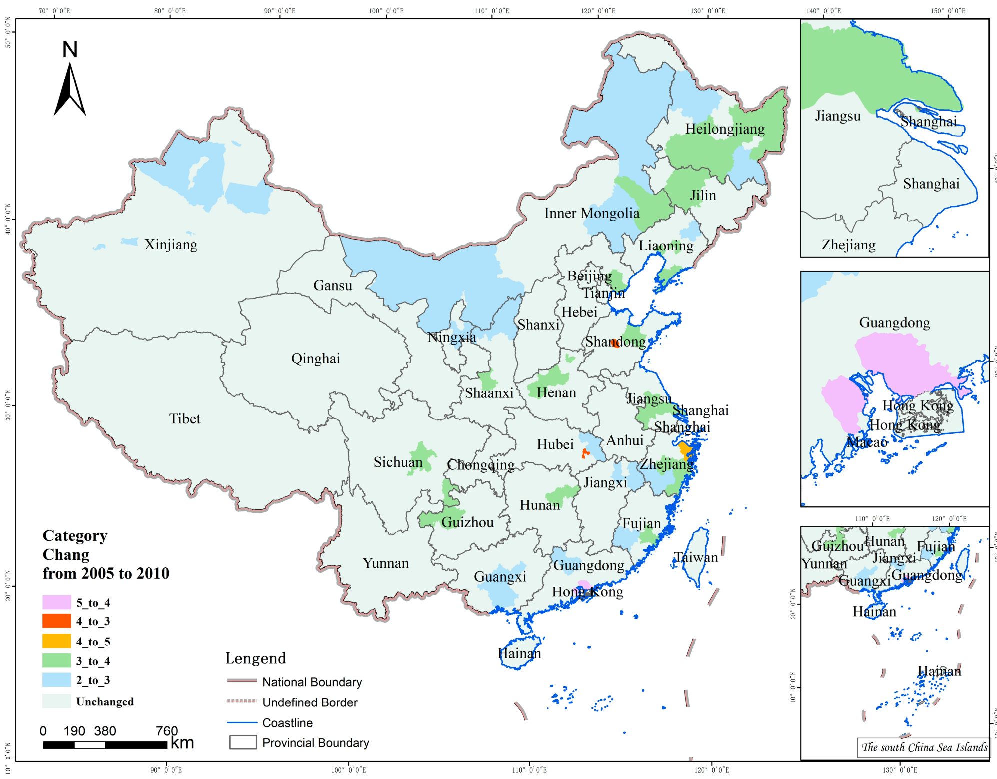

**Figure 3.** Spatial distribution of the cities in every class in 2005.

Figure 4 shows the spatial distribution of the different classes in 2010 and the cities that changed from 2005 to 2010. The cities that changed status mainly included two types, those that changed from moderately unbalanced to slightly unbalanced and those that changed from slightly unbalanced to barely balanced. From a spatial perspective, there was a positive expansion trend from southeast to northwest in 2010 compared with that in 2005.

Table 5 is the transition matrix of the cities that changed classes from 2005 to 2010. Row values represent the number of cities in different classes in 2005, and column values represent that in 2010. For example, the data in the second row and third column represent that from 2005 to 2010, 24 prefecture-level cities changed from moderately unbalanced to slightly unbalanced. The other data are similar. By 2010, approximately 31% of the prefecture-level moderately unbalanced cities improved to slightly unbalanced, which were mainly distributed in the northern region and the southeastern coastal region. Approximately 15% of the slightly unbalanced prefecture-level cities changed to barely balanced. Two cities changed from barely balanced to favourably balanced, namely, Ningbo and Zhoushan in Zhejiang Province. However, at the same time, two prefecture-level cities changed from barely balanced to slightly unbalanced: Laiwu in Shandong Province and E'zhou in Hubei Province. Three prefecture-level cities changed from favourably balanced to barely balanced, namely, Shenzhen, Dongguan, and Zhongshan, in Guangdong Province.




(**a**)




(**b**)

**Figure 4.** The spatial distribution of different classes in 2010 (**a**) and cities whose classes changed from 2005 to 2010 (**b**). Note: Two represents moderately unbalanced. Three represents slightly unbalanced. Four represents barely balanced. Five represents favourably balanced.

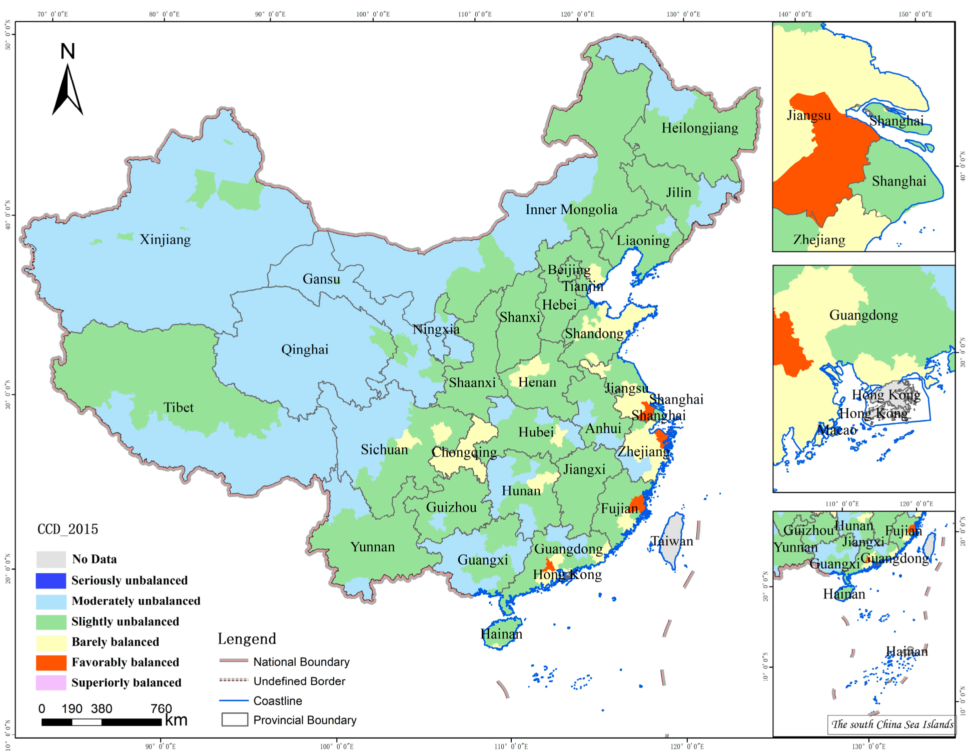
**Table 5.** Transition matrix of cities that changed classes from 2005 to 2010.

| Classes | SeU | MU | SU | BB | FB | SB | Total of 2005 |
|---|---|---|---|---|---|---|---|
| SeU | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MU | 0 | 53 | 24 | 0 | 0 | 0 | 77 |
| SU | 0 | 0 | 201 | 36 | 0 | 0 | 237 |
| BB | 0 | 0 | 2 | 17 | 2 | 0 | 21 |
| FB | 0 | 0 | 0 | 3 | 2 | 0 | 5 |
| SB | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total of 2010 | 0 | 53 | 227 | 56 | 4 | 0 | 340 |

Compared with 2010, the cities that changed to a lower class accounted for the majority of changed cities in 2015. As shown in Table 6, nearly 40% of the barely balanced cities changed to slightly unbalanced, mainly in the northeast and southwest, and 10.57% of the slightly unbalanced prefecture-level cities changed to moderately unbalanced, with a scattered distribution throughout the country. From 2010 to 2015, two moderately unbalanced prefecture-level cities changed to slightly unbalanced: Xianning in Hubei Province and Meizhou in Guangdong Province. Ten cities changed to barely balanced and were mainly distributed in the central part of the country (Figure 5).

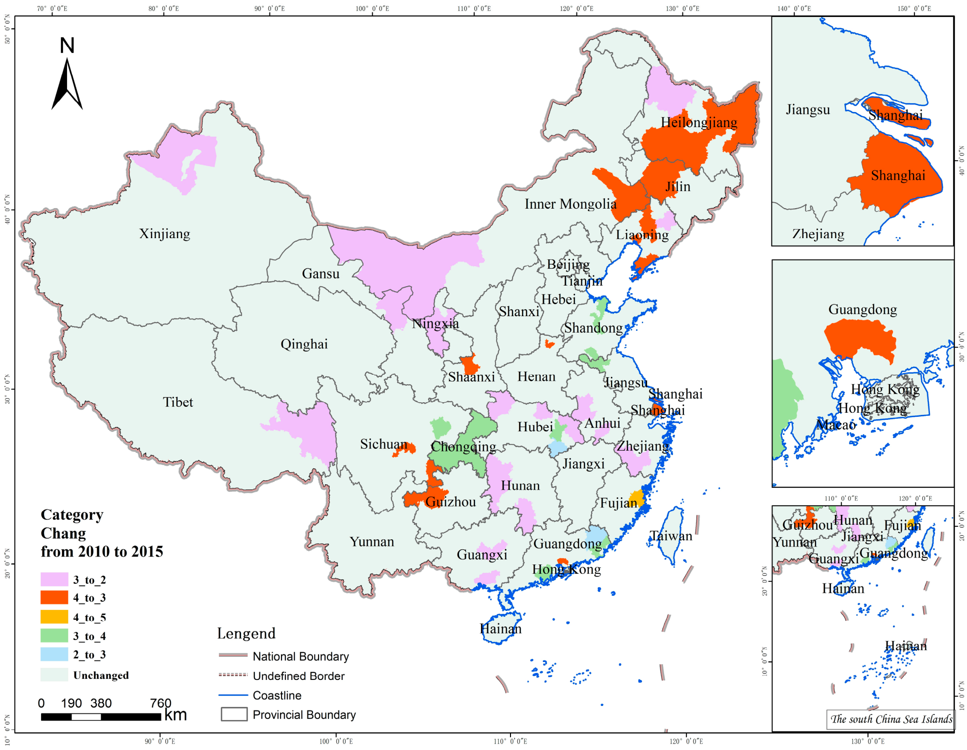
**Table 6.** Transition matrix of the cities that changed classes from 2010 to 2015.

| Classes | SeU | MU | SU | BB | FB | SB | Total of 2010 |
|---|---|---|---|---|---|---|---|
| SeU | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MU | 0 | 51 | 2 | 0 | 0 | 0 | 53 |
| SU | 0 | 24 | 193 | 10 | 0 | 0 | 227 |
| BB | 0 | 0 | 22 | 33 | 1 | 0 | 56 |
| FB | 0 | 0 | 0 | 0 | 4 | 0 | 4 |
| SB | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total of 2015 | 0 | 75 | 217 | 43 | 5 | 0 | 340 |




**(a)**

**Figure 5.** *Cont.*




(**b**)

**Figure 5.** The spatial distribution of different classes in 2015 (**a**) and cities whose classes changed from 2010 to 2015 (**b**). Note: Two represents moderately unbalanced. Three represents slightly unbalanced. Four represents barely balanced. Five represents favourably balanced.

### 3.2.2. Provincial Capital Cities

A provincial capital city is generally a central city in a province with political, economic, cultural, and other advantages. Development policies and capital resources will usually be skewed towards it. The coordinated development of production, living, and ecology in a provincial capital city can be a representation of the province. Therefore, this paper statistically analyzed four municipalities directly under the Central Government and 27 provincial capitals administrative regions (excluding Hong Kong, Macau, and Taiwan), as shown in Figure 6.

Figure 6 and Table 7 illustrate that most provincial capital cities had values between 0.4 and 0.6 in 2005, 2010, and 2015. That is, they were between the slightly unbalanced class and barely balanced class. Only Fuzhou in Fujian Province exceeded 0.6 in 2015. From 2005 to 2015, most of the provincial capital cities were above the national average. However, there were also several provincial capital cities that were always below the national average. These cities were Nanning, Lhasa, Lanzhou, and Urumqi. They are all in northwestern China, as shown in Figure 7. In addition, it should be noted that Nanchang also did not reach the national level of 2015. Half of the provincial capitals improved, especially Chengdu, Zhengzhou, Nanjing, Hangzhou, Chongqing, and Changsha, which are mainly in the southern and central parts of the country. However, Shanghai and Taiyuan worsened. The coupling coordination degree of Shanghai decreased from 0.526 in 2005 to 0.515 in 2010 and then to 0.492 in 2015. The coupling coordination degree value of Taiyuan dropped from 0.472 to 0.469 over the decade. The values of the remaining cities fluctuated. Some cities, such as Hohhot, Changchun, Shenyang, and Harbin, which are mainly distributed in the northeast, had values that first increased and then decreased, as shown in Figure 7. Other cities, such as Beijing, Guangzhou, Wuhan, and Hefei, had values that first decreased and then increased.

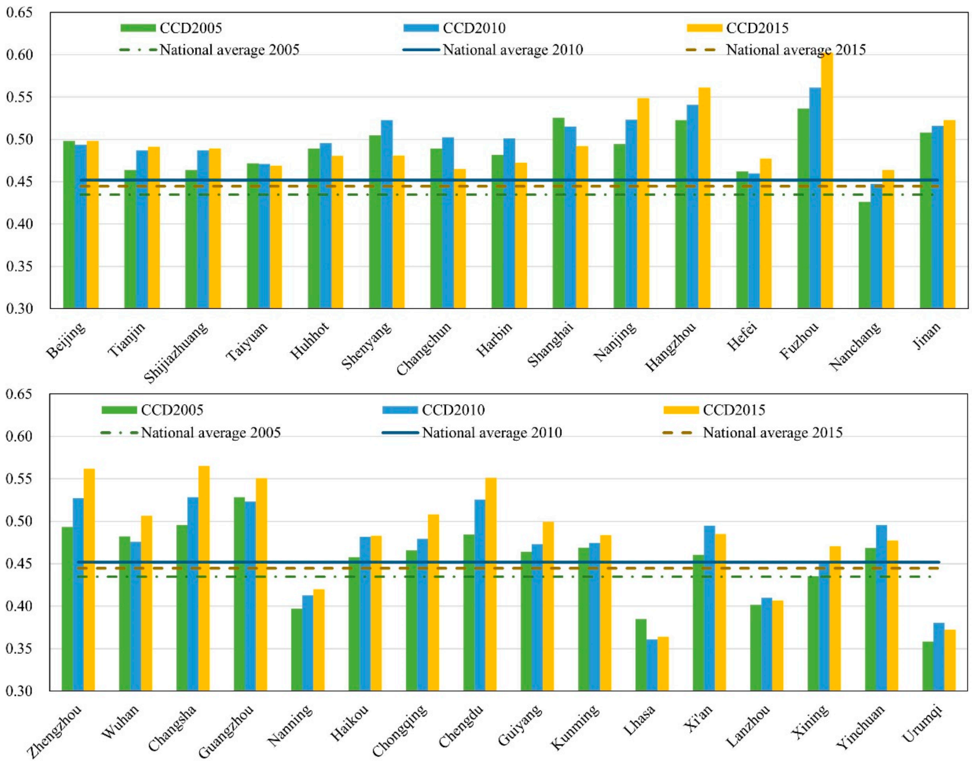



**Figure 6.** Coupling coordination degree of 31 cities from 2005 to 2015.

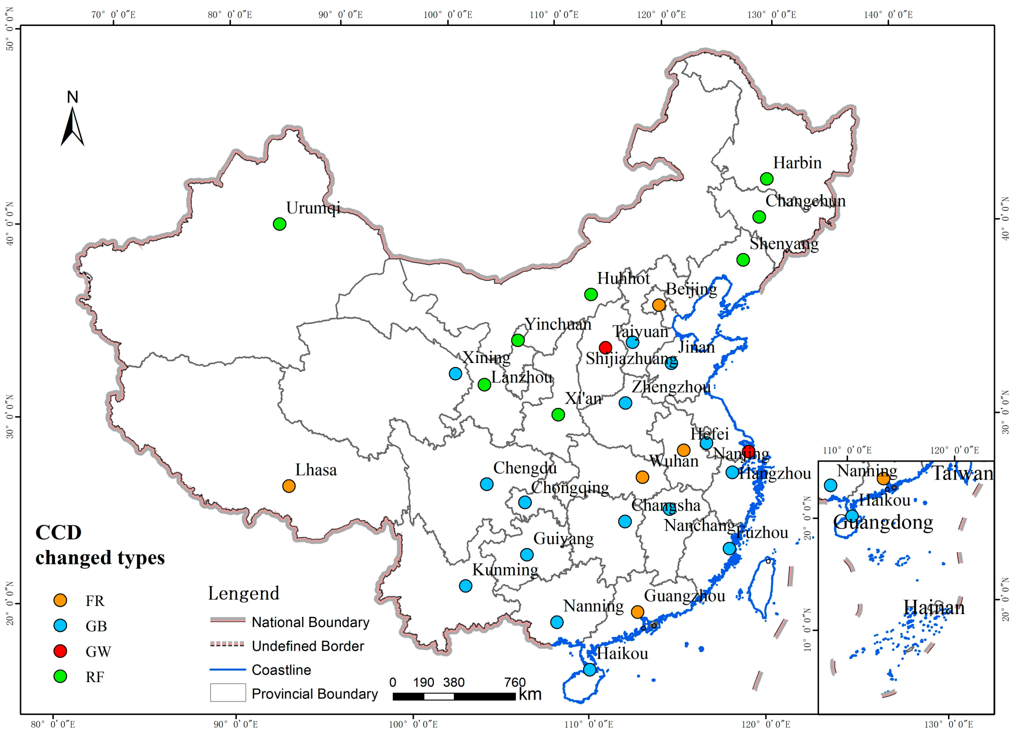



**Figure 7.** Spatsial distribution of different change types for provincial capital cities with coupling coordination degree changes. FR presents cities with coupling coordination degree decreased first and then increasing during 2005 and 2015. Note: RF is the reverse. GB represents the coupling coordination degree value increasing. GW represents the coupling coordination degree value decreasing.

**Table 7.** Coupling coordination degree (CCD) of 31 cities from 2005 to 2015.

| NAME | CCD 2005 | CCD 2010 | CCD 2015 | NAME | CCD 2005 | CCD 2010 | CCD 2015 |
|---|---|---|---|---|---|---|---|
| Beijing | 0.498 | 0.494 | 0.498 | Wuhan | 0.482 | 0.476 | 0.506 |
| Tianjin | 0.464 | 0.487 | 0.491 | Changsha | 0.496 | 0.528 | 0.565 |
| Shijiazhuang | 0.464 | 0.487 | 0.489 | Guangzhou | 0.529 | 0.523 | 0.551 |
| Taiyuan | 0.472 | 0.471 | 0.469 | Nanning | 0.397 | 0.413 | 0.420 |
| Huhhot | 0.489 | 0.496 | 0.481 | Haikou | 0.458 | 0.482 | 0.483 |
| Shenyang | 0.505 | 0.523 | 0.481 | Chongqing | 0.466 | 0.479 | 0.508 |
| Changchun | 0.489 | 0.502 | 0.465 | Chengdu | 0.484 | 0.526 | 0.551 |
| Harbin | 0.482 | 0.501 | 0.473 | Guiyang | 0.464 | 0.473 | 0.499 |
| Shanghai | 0.526 | 0.515 | 0.492 | Kunming | 0.469 | 0.475 | 0.484 |
| Nanjing | 0.495 | 0.523 | 0.549 | Lhasa | 0.385 | 0.361 | 0.364 |
| Hangzhou | 0.523 | 0.541 | 0.561 | Xi'an | 0.461 | 0.495 | 0.485 |
| Hefei | 0.462 | 0.460 | 0.477 | Lanzhou | 0.401 | 0.410 | 0.407 |
| Fuzhou | 0.536 | 0.561 | 0.603 | Xining | 0.436 | 0.453 | 0.471 |
| Nanchang | 0.426 | 0.447 | 0.464 | Yinchuan | 0.469 | 0.496 | 0.478 |
| Jinan | 0.508 | 0.516 | 0.523 | Urumqi | 0.359 | 0.381 | 0.373 |
| Zhengzhou | 0.493 | 0.527 | 0.562 | National averages | 0.435 | 0.452 | 0.445 |

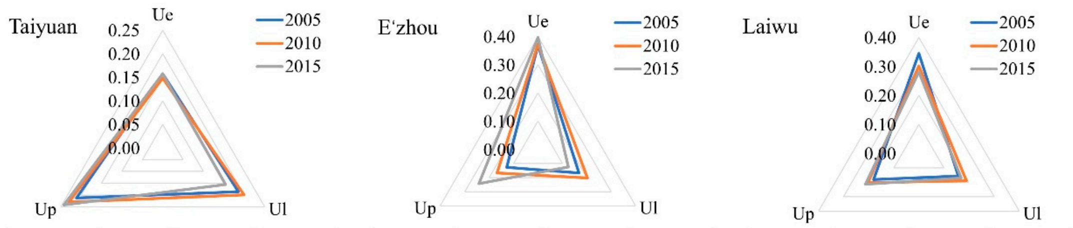
### 3.2.3. Representative Cities Decreasing in Coupling Coordination Degree Value

There are some cities getting worse from 2005 to 2015, which are proposed for "Representative Cities." In addition to the aforementioned Taiyuan and Shanghai, 25 prefecture-level cities had coupling coordination degree values that decreased from 2005 to 2015, as shown in Table 8. Most of the cities are located in the northwestern minority regions, such as Tibet, Xinjiang, Qinghai, and Gansu. The coupling coordination degree of these areas was also not originally high, and coupled with the decline in 2015, the situation in these cities became increasingly worse. Other cities with significant declines were Dongguan and Shenzhen in Guangdong Province, as well as Laiwu in Shandong Province and Ezhou in Hubei Province. In particular, the value for Dongguan decreased by 0.217 in 2010 compared with that in 2005 and decreased again by 0.041 in 2015 compared with that in 2010.

**Table 8.** Prefecture-level cities and autonomous prefectures in which the coupling coordination degree (CCD) value decreased.

| Province/Autonomous Region | Prefecture Level City/Autonomous Prefecture | CCD 2005 | CCD 2010 | CCD 2015 |
|---|---|---|---|---|
| Shanxi | Taiyuan | 0.472 | 0.471 | 0.469 |
| Inner Mongolia | Ulaanchab | 0.391 | 0.386 | 0.368 |
| Shanghai | Shanghai | 0.526 | 0.515 | 0.492 |
| Shandong | Laiwu | 0.524 | 0.483 | 0.479 |
| Hubei | E'zhou | 0.528 | 0.480 | 0.478 |
| Hubei | Enshi Tujia and Miao | 0.460 | 0.442 | 0.418 |
| Hunan | Shaoyang | 0.419 | 0.418 | 0.415 |
| Guangdong | Shenzhen | 0.603 | 0.548 | 0.544 |
| Guangdong | Dongguan | 0.750 | 0.533 | 0.491 |
| Guangxi | Hezhou | 0.380 | 0.379 | 0.352 |
| Sichuan | Aba Tibetan and Qiang | 0.351 | 0.336 | 0.327 |
| Yunnan | Lijiang | 0.398 | 0.393 | 0.384 |
| Yunnan | Wenshan Zhuang and Miao | 0.454 | 0.444 | 0.423 |
| Yunnan | Nujiang Dong | 0.392 | 0.386 | 0.382 |
| Yunnan | Diqing Tibetan | 0.376 | 0.371 | 0.347 |
| Tibet | Shigatse | 0.340 | 0.330 | 0.322 |
| Tibet | Chamdo | 0.419 | 0.411 | 0.355 |
| Tibet | Lhokha | 0.337 | 0.318 | 0.312 |
| Tibet | Nagchu | 0.457 | 0.419 | 0.404 |
| Tibet | Ngari | 0.476 | 0.450 | 0.446 |
| Tibet | Nyingchi | 0.356 | 0.344 | 0.320 |
| Gansu | Wuwei | 0.420 | 0.418 | 0.382 |
| Gansu | Jiuquan | 0.361 | 0.356 | 0.345 |
| Qinghai | Haibei Tibetan | 0.300 | 0.296 | 0.296 |
| Qinghai | Golog Tibetan | 0.393 | 0.381 | 0.344 |
| Xinjiang | Khotan | 0.357 | 0.354 | 0.350 |

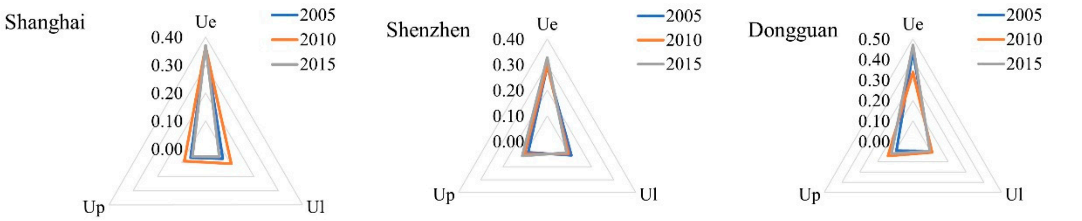
This paper uses radar charts to identify the limiting aspect accounting for the occurrence of increasingly worse situations, as shown in Figure 8. Nine cities were chosen as examples. They were Taiyuan, Laiwu, E'zhou, Shanghai, Shenzhen, Dongguan, Chamdo, Nagchu, and Haibei. The performance levels of the production space subsystem, living space subsystem, and ecological space subsystem are the three vertices of a triangle in the radar chart.




| Taiyuan | *Ue* | *Ul* | *Up* |
|---|---|---|---|
| 2005 | 0.157 | 0.186 | 0.212 |
| 2010 | 0.148 | 0.199 | 0.230 |
| 2015 | 0.157 | 0.155 | 0.242 |

| E'zhou | *Ue* | *Ul* | *Up* |
|---|---|---|---|
| 2005 | 0.369 | 0.167 | 0.128 |
| 2010 | 0.372 | 0.202 | 0.167 |
| 2015 | 0.396 | 0.125 | 0.242 |

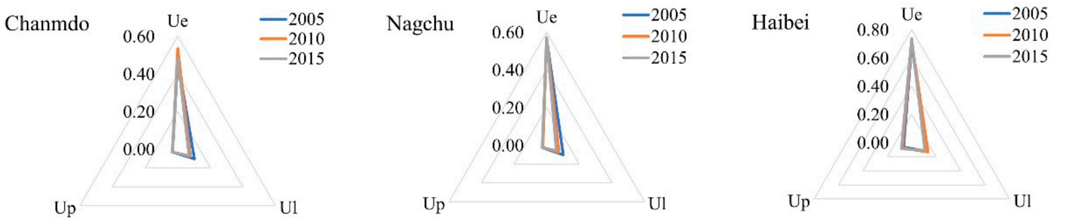
| Laiwu | *Ue* | *Ul* | *Up* |
|---|---|---|---|
| 2005 | 0.344 | 0.158 | 0.181 |
| 2010 | 0.302 | 0.190 | 0.203 |
| 2015 | 0.281 | 0.169 | 0.213 |




| Shanghai | *Ue* | *Ul* | *Up* |
|---|---|---|---|
| 2005 | 0.364 | 0.070 | 0.062 |
| 2010 | 0.365 | 0.106 | 0.088 |
| 2015 | 0.370 | 0.056 | 0.055 |

| Shenzhen | *Ue* | *Ul* | *Up* |
|---|---|---|---|
| 2005 | 0.294 | 0.109 | 0.086 |
| 2010 | 0.297 | 0.097 | 0.102 |
| 2015 | 0.327 | 0.088 | 0.113 |

| Dongguan | *Ue* | *Ul* | *Up* |
|---|---|---|---|
| 2005 | 0.438 | 0.097 | 0.093 |
| 2010 | 0.338 | 0.108 | 0.141 |
| 2015 | 0.470 | 0.096 | 0.121 |




| Chamdo | *Ue* | *Ul* | *Up* |
|---|---|---|---|
| 2005 | 0.473 | 0.103 | 0.032 |
| 2010 | 0.533 | 0.078 | 0.031 |
| 2015 | 0.484 | 0.070 | 0.033 |

| Nagchu | *Ue* | *Ul* | *Up* |
|---|---|---|---|
| 2005 | 0.564 | 0.101 | 0.026 |
| 2010 | 0.567 | 0.075 | 0.024 |
| 2015 | 0.572 | 0.060 | 0.027 |

| Haibei | *Ue* | *Ul* | *Up* |
|---|---|---|---|
| 2005 | 0.700 | 0.123 | 0.066 |
| 2010 | 0.715 | 0.132 | 0.076 |
| 2015 | 0.735 | 0.109 | 0.086 |

**Figure 8.** Performance level of the production space subsystem, living space subsystem, and ecology space subsystem of nine classical cities.

According to the radar charts and the reason for declining, it can be classified into three categories, as follows:

(1) Unbalanced cities like Taiyuan, Ezhou, and Laiwu.

The reasons for the declining coupling coordination degree were similar. In 2010, the decline was due to a decreasing $U_e$ and an increase in the other two, and in 2015, the decrease in $U_l$ accounted for the decline. Furthermore, the living space and production space performances of the three cities were better than that of the other six cities, while ecological space performance was not good enough. Especially, Taiyuan had the lowest ecological space performance among the nine cities, at only approximately 0.15. Compared with that of Haibei, the $U_e$ reached 0.735 at its highest.

(2) Unbalanced cities like Shanghai, Shenzhen, and Dongguan.

Shanghai and Shenzhen are highly developed cities and population centres, leading to various urban-related problems [59,60]. From 2005 to 2015, the degree of coupling and coordination in Shenzhen decreased because $U_l$ decreased while $U_p$ and $U_e$ increased. As a result, the gap between the three factors gradually increased. The situations in Shanghai and Dongguan were similar. The decrease in the degree of coupling and coordination in 2010 was mainly due to the decline in $U_e$ and the increase in $U_p$ and $U_l$. By 2015, the situation had reversed.

(3) Unbalanced cities like Chamdo, Nagqu, and Haibei.

These cities are all located in remote areas with slow economic development. They are also the key areas where poverty alleviation is urgently needed in China. Notably, the performance of $U_p$ and $U_l$ has always been insufficient, which will be the focus of future improvements.

## 4. Discussion

The coordinated development of the three spaces discussed in this paper is a response to the SDG goals of the United Nations and a specific goal of China's sustainable development. Therefore, it is necessary to consider the three as a whole, to comprehensively evaluate their performance. However, there are complex interactions among production space, living space, and ecology space. The research in this paper shows that the coupling coordination degree model is an effective method that can quantitatively evaluate the level of sustainable development among the three spaces and identify key indicators that affect system development. Combined with GIS tools, it was intuitively observed that spatial and temporal dynamic changes in coupling coordination degree occurred across the country. This paper is slightly more advanced than previous studies focusing on the relationship between the ecological aspect and production aspect. This study focuses at the prefecture-level city scale across the country, rather than a certain city or a region.

At the same time, the selection of indicators in the coupling coordination degree model is very important and has a direct impact on the results. Considering that PLE space involves many aspects, especially, living space involves transportation, education, medical condition, and so on, the indicators in this paper need to be further expanded. Due to the differences in the conditions of the resources, environment, and climate in various regions, the indicator system should also reflect this differentiation. For example, for the southeastern coastal areas where economic development has reached a certain level, more attention should be given to improving the living environment and restoring ecological functions. Cities in the northwestern region that have less economic development hope to promote economic development and quality of life without affecting ecological functions. Although this area is also concerned about improving the living space, there may be differences in the implementation of specific indicators. Therefore, in a subsequent evaluation, combining local characteristics and the construction goals of the government for building an indicator system could be included.

Although the degree of coupling coordination can be quantified, it is still slightly difficult to determine the reason behind the occurrence of unbalanced cities. To some extent, the radar chart qualitatively indicated which subsystem has a problem. However, there is still a lack of quantitative indicators to accurately confirm the conclusions. The main purpose of the evaluation of PLE space is to determine the current problems and note the direction for future development, so it is necessary for further research to conduct in-depth research from this perspective.

## 5. Conclusions

An indicator system and a coupling coordination degree model for the comprehensive assessment of the PLE space were established in this paper. The statuses of 340 prefecture-level cities across the country were analyzed from 2005 to 2015. It was found that there is an improving general trend across the nation, even if the average was fluctuating between 2005 and 2015. However, the difference among the cities gradually widened according to the increasing degree of dispersion. In other words, the coordinated development of PLE in different cities is very inconsistent. This is related to the historical situation and natural background of the city. That is, most slightly unbalanced and even better cities were located to the southeast of the Hu Huanyong Line, and other cities showed the opposite trend. This is very relevant to China's early development strategy.

For cities that are getting worse, the reasons need to be further clarified. In this way, it is helpful for policy makers to put forward improvement plans in a targeted manner. For example, for a resource-based city like Taiyuan, it is necessary to pay more attention to the protection of ecological space and quality improvement while redeveloping production. For poor areas such as Chanmdo, the focus is to avoid the destruction of the ecological environment as much as possible in the process of economic development and improvement of people's livelihood. The problems faced by different cities are different, so the coupling coordination model and radar chart provide a good idea and means for how to better achieve the sustainable development goals in the future.

However, this research still has some limitations. For example, the currently selected indicators rely more on statistical data than explicitly spatial ones, which is not enough for smaller-scale research. Future research may consider more detailed data indicators. In addition, from the time scale, it should be further refined, especially strengthening the consideration of historical data.

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