Research on the Spatiotemporal Coupling Characteristics between Urban Population and Land in China Based on the Improved Coupling Model of Polar Coordinates

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Abstract: Scientific quantitative measurement of the coupling relationship between urban population (UP) and urban land (UL) is conducive to promoting intensive land use, coordinated human–land development, and new urbanization development. This research proposed an improved coupling model of polar coordinates to study the spatiotemporal coupling characteristics between UP and UL at the prefecture-level city scale in China from 2010 to 2020. The study results include the following: (1) The growth rate of UL in China’s prefecture-level cities was higher than that of UP. The per capita urban land (PUL) was always within the ideal range, and the dynamic human–land coupling state remained reasonable. (2) The UP, UL, and dynamic human–land coupling rationality in China showed characteristics that were high in the east and low in the west. The PUL showed characteristics that were high in the northwest and low in the southeast. (3) This study divided China’s prefecture-level cities into four regions according to the coupling characteristics and formulated regionally differentiated optimization strategies. In summary, this study carried out a more scientific and reasonable quantitative measurement of the coupling relationship between UP and UL in China, resulting in a more reliable and targeted formulation of optimization strategies.

Keywords: coupling model of polar coordinates; coupling relationship; urban land; new urbanization; optimization strategy

1. Introduction

Since the reform and opening up, China’s urbanization process has advanced rapidly. With the growth of the urban population (UP) and the development of the social economy, the demand for urban land (UL) is also increasing [1–3]. On the one hand, UL is the carrier of social and economic development, which plays an essential supporting role in urban development. On the other hand, the disorderly expansion of UL has also brought about a series of problems, such as cultivated land occupation, ecological destruction, and extensive land use. These problems have restricted sustainable urban development [4,5]. China’s basic national land conditions are characterized by more people and less land, small per capita land and cultivated land occupation, and insufficient cultivated land reserve resources. Therefore, the Chinese government attaches utmost importance to land use, especially the
The protection of cultivated land [6]. The Chinese government has adopted policies and countermeasures, such as annual land use plan management, a human–land linking mechanism, land quota management, and urban development boundary management, to rationally allocate UL, control cultivated land occupation, and promote intensive UL use [7–9]. At the same time, the 20th National Congress of the Communist Party of China called for “advancing people-centered new urbanization”. Clarifying the spatiotemporal coupling characteristics between UP and UL is the basis for realizing sustainable land use. Differentiated UL allocation strategies should be further formulated according to the location and situation to support China’s new urbanization development scientifically [10]. Therefore, research on the coupling relationship between UP and UL is of essential theoretical and practical significance.

Experts and scholars have carried out extensive and profound research on issues related to population and construction land [11–13]. In terms of research scale, the majority of relevant nationwide research has been on the scale of provinces and urban agglomerations. By contrast, relevant nationwide research was rarely on the scale of prefecture-level cities. For example, Kong et al. used the decoupling model to study the relationship between urban and rural populations and construction land at the provincial level in China [14]. Zhang et al. discussed the periodicity, coordination degree, and evolution law of urban and rural population and land change at the national scale from 1996 to 2016 [15]. Zeng et al. cited the allometric model to analyze the relationship between the expansion of construction land and population in urban agglomerations in China [16]. In terms of research content, research on the single aspect of population or land mainly focused on the scale characteristics [17–19], change rules [20–22], driving factors [23–25], and optimization strategies [26–28]. For example, Mahmoud derived and quantified the driving factors of UL change in the study area to evaluate the relative importance of the factors in establishing new cities [29]. Gwan analyzed the scale of land expansion in Bamenda to examine the impact of urban expansion on farmers [30]. Meanwhile, research on the relationship between population and land mainly focused on the carrying capacity [31–33], spatiotemporal relationship [34–37], coupling relationship [38–40], and growth coordination [41–43]. Among them, most of the related research on the coupling relationship is concentrated in China. In terms of research methods, existing studies have mainly used the coupling coordination degree model [44–46], deviation coefficient method [47,48], IPAT model [49], and Tapio’s decoupling model of elasticity [50] to measure the coupling relationship between population and land. Among them, the most widely used is Tapio’s decoupling model of elasticity [51–53]. However, this model can divide the coupling relationship between population and land into eight types but cannot quantitatively measure the coupling rationality. Therefore, Li et al. proposed a coupling model of polar coordinates and used this model to analyze the coupling relationship between urban and rural construction land and population in Henan Province [54]. This model transforms the elasticity coefficient measure into the polar coordinate measure, which makes up for the deficiency of Tapio’s decoupling model of elasticity.

To sum up, this study has two main goals. On the one hand, this study uses the coupling model of polar coordinates to analyze the spatiotemporal coupling characteristics between UP and UL at the prefecture-level city scale in China more systematically. On the other hand, this study improves the coupling model of polar coordinates by supplementing the concept of coupling contribution to make the model more scientific and systematic. First, this study constructed a framework based on an improved coupling model of polar coordinates proposed in this study to measure the spatiotemporal coupling characteristics between UP and UL. Second, this study systematically studied the spatiotemporal coupling characteristics between UP and UL in China at the national and prefecture-level city scales from 2010 to 2020 from static and dynamic aspects. Specifically, this study first analyzed the overall scale evolution characteristics of UP and UL and the coupling characteristics between UP and UL at the national scale from 2010 to 2020. Then, this study compared and analyzed the spatial pattern distribution of scale characteristics of UP and UL and coupling
characteristics between UP and UL at the prefecture-level city scale from 2010 to 2015 and 2015 to 2020. Among them, the analysis of coupling characteristics mainly included two aspects: static coupling and dynamic coupling. Static coupling focused on analyzing per capita urban land (PUL). Dynamic coupling focused on analyzing coupling type, coupling rationality, coupling strength, comprehensive coupling contribution, coupling contribution of UP, and coupling contribution of UL. Finally, this study adopted spatial clustering analysis to summarize the regional coupling characteristics between UP and UL in China and discussed the regionally differentiated optimization strategies for promoting human–land coordination development to provide a reference for sustainable land resource utilization in China.

2. Materials and Methods

2.1. Research Methods

The concept of coupling, which is cross-subject, represents a joint relationship between two or more system elements that interact with and influence each other. In terms of measurement methods, coupling can be divided into two types: static coupling and dynamic coupling. Static coupling refers to the matching degree between the scales of system elements, commonly measured by differences or proportions between them, such as the coupling coordination degree model, IPAT model, etc. Dynamic coupling refers to the matching degree between the change rates of system elements, commonly measured by an elastic coefficient ratio, such as Tapio’s decoupling model of elasticity, coupling model of polar coordinates, etc. Previous coupling measurement methods focus on a single aspect of static or dynamic coupling measurement, but the coupling model of polar coordinates can combine the two aspects and measure the coupling characteristics more scientifically.

Thus, this study comprehensively analyzed the spatiotemporal coupling characteristics between UP and UL at the national and prefecture-level city scales from two aspects: scale characteristics and coupling characteristics (Figure 1). The measurement of scale characteristics directly adopts the scale of UP and UL. The coupling characteristics include static and dynamic human–land coupling characteristics. Among them, the measurement of static human–land coupling characteristics adopts PUL. The closer PUL is to the national standard, the more reasonable the static human–land coupling relationship is. On the contrary, the PUL is much larger or much smaller than the national standard, which indicates that the static human–land coupling rationality is relatively low. The measurement of dynamic human–land coupling characteristics adopts the improved coupling model of polar coordinates. This improved model, based on static human–land coupling measurement, utilizes the change rates of UP and UL to measure the urban human–land coupling characteristics. Based on this measurement framework, this study analyzed the spatiotemporal coupling characteristics between UP and UL at the prefecture-level city scale and further formulated targeted optimization strategies.

2.2. Improved Coupling Model of Polar Coordinates

The concept of decoupling began in the field of physics to refer to the disappearance of mutual relationships between two or more physical quantities with corresponding relationships. The OECD first proposed the decoupling theory to describe the relationship between the economy and the environment [55]. This theory is of great significance to the study of resource depletion [56], land use [57], urban expansion [58], and other related issues. Here, Tapio’s decoupling model of elasticity can help calculate the elasticity (E) according to the change rates of UP and UL. Then, the model divides the dynamic coupling relationship between UP and UL into eight types according to the positive and negative change rate and the size of E (Figure 2a). The calculation formula of elasticity (E) is as follows:

\[
E = \frac{R_L}{R_P} = \frac{(L_t - L_0)/L_0}{(P_t - P_0)/P_0}
\]
where $R_L$ and $R_P$ are the change rates of UL and UP during the study period, respectively; $L_0$ and $L_t$ are the scales of UL at the beginning and ending of the period, respectively; $P_0$ and $P_t$ are the scales of UP at the beginning and ending of the period, respectively.

**Figure 1.** Measurement framework of spatiotemporal coupling characteristics between UP and UL based on the improved coupling model of polar coordinates.

**Figure 2.** Tapio’s decoupling model of elasticity and the coupling model of polar coordinates: (a) Tapio’s decoupling model of elasticity. In this figure, $R_L$ and $R_P$ are the change rates of UL and UP, respectively; and $E$ is the population elasticity of construction land. (b) Coupling model of polar coordinates. In this figure, $\theta$ is the polar coordinate angle; $r$ is the polar coordinate radius; $PCL$ and $PCL_\infty$ are the per capita construction land scales and its ideal values, respectively; and $\delta$ is the tolerance coefficient of $PCL$.

Tapio’s decoupling model of elasticity has two shortcomings when analyzing the coupling relationship between UP and UL. First, the model attaches great importance to increment and ignores stock, while stock rationality is the basis for scientifically measuring incremental indicators. Second, the model can only obtain discrete coupling types but cannot continuously measure coupling rationality and strength. To solve these problems, this study used the coupling model of polar coordinates to analyze the dynamic coupling relationship between UP and UL (Figure 2b). This model transforms the elasticity coefficient measure into the polar coordinate measure. Specifically, the polar coordinate angle measures the coupling type and rationality between UP and UL, and the polar coordinate radius measures the coupling strength between UP and UL. Furthermore, the coupling
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model of polar coordinates considers not only the incremental measurement of UP and UL but also the stock measurement of PUL. The specific calculation formula is as follows:

\[ \theta = \arctan \left( \frac{R_L}{R_P} \right) = \arctan \left( \frac{(L_1 - L_0) / L_0}{(P_1 - P_0) / P_0} \right) \quad \theta \in [-180^\circ, 180^\circ] \]  

(2)

\[ r = CS = \sqrt{R_L^2 + R_P^2} = \sqrt{\left( \frac{L_1 - L_0}{L_0} \right)^2 + \left( \frac{P_1 - P_0}{P_0} \right)^2} \]  

(3)

\[ CR = \begin{cases} 
1 - |\text{Angle}(\theta - (-45^\circ))|/90^\circ & \text{PUL} > \text{PUL}_\text{rv} \times (1 + \delta) \\
1 - |\text{Angle}(\theta - 135^\circ)|/90^\circ & \text{PUL} < \text{PUL}_\text{rv} \times (1 - \delta) \\
1 - |\text{Angle}90(\theta)|/90^\circ & \text{other} : \text{PUL} \approx \text{PUL}_\text{rv}
\end{cases} \]  

(4)

\[ \text{Angle}(\alpha) = \begin{cases} 
\alpha - 360^\circ & \alpha > 180^\circ \\
\alpha + 360^\circ & \alpha < -180^\circ \\
\alpha & \text{other}
\end{cases} \]  

(5)

\[ \text{Angle}90(\alpha) = \begin{cases} 
\text{Angle}(\alpha - 45^\circ) & -45^\circ \leq \alpha < 135^\circ \\
\text{Angle}(\alpha - (-135^\circ)) & 135^\circ \leq \alpha < 180^\circ \text{ or } -180^\circ \leq \alpha < -45^\circ
\end{cases} \]  

(6)

where \( \theta \) is the polar coordinate angle; \( r \) is the polar coordinate radius; \( CR \) is the coupling rationality; \( CS \) is the coupling strength; \( \text{PUL} \) and \( \text{PUL}_\text{rv} \) are the per capita UL areas and its ideal value, respectively; \( \delta \) is the tolerance coefficient of PUL, which is set to 0.1 in this paper; \( \text{Angle}(\alpha) \) and \( \text{Angle}90(\alpha) \) are polar coordinate angle conversion functions. Among them, the value range of \( CR \) is \([0, 1]\). The larger the \( CR \) is, the more reasonable the dynamic coupling state between UL and UP will be. The smaller the \( CR \) is, the more unreasonable the dynamic coupling state between UL and UP will be.

Moreover, this study further improved the existing coupling model of polar coordinates. On the one hand, this study changed the coupling rationality measurement from the original angle ratio to the cosine function, thereby further transforming the coupling rationality calculation from linear to nonlinear. On the other hand, based on the coupling strength and coupling rationality, this study proposed the comprehensive coupling contribution, a new concept and measurement. The comprehensive coupling contribution can help measure the contribution of the dynamic coupling state of UP and UL in the rationality improvement of the static coupling measurement of PUL. Specifically, the comprehensive coupling contribution is equal to the product of the coupling rationality and the coupling strength. From a geometric perspective, the comprehensive coupling contribution is the projection length of the line connecting one sample point and the coordinate origin on the ray where the ideal coupling angle is located. Furthermore, the comprehensive coupling contribution can also be decomposed into the sum of UP and UL contributions. Similarly, the comprehensive coupling contribution is equal to the sum of the projected lengths of one sample point’s change rates of UP and UL on the ray where the ideal coupling angle is located. These improvements further enhance the scientific and systematic robustness of the coupling characteristic measurement of UP and UL. The specific calculation formula is as follows:

\[ CR = \begin{cases} 
\cos \left( \text{Angle}(\theta - (-45^\circ)) \right) & \text{PUL} > \text{PUL}_\text{rv} \times (1 + \delta) \\
\cos \left( \text{Angle}(\theta - 135^\circ) \right) & \text{PUL} < \text{PUL}_\text{rv} \times (1 - \delta) \\
\cos \left( \text{Angle}90(\theta) \right) & \text{other} : \text{PUL} \approx \text{PUL}_\text{rv}
\end{cases} \]  

(7)

\[ CC = CS \times CR = CC_X + CC_Y \]  

(8)

\[ CC_X = \begin{cases} 
R_P \times \cos 45^\circ & \text{PUL} > \text{PUL}_\text{rv} \times (1 + \delta) \\
R_P \times \cos(-135^\circ) & \text{PUL} < \text{PUL}_\text{rv} \times (1 - \delta) \\
R_P \times \cos(-45^\circ) & \text{other} : \text{PUL} \approx \text{PUL}_\text{rv}
\end{cases} \]  

(9)
was 1.15 times the change rate of UP (Figure 3a,b). In conclusion, the total amounts of UP and UL; (than the national PUL standard upper limit of 110 m²/person. However, considering the rationality of PUL (Figure 4c,d).

The average annual change rate of UP was 3.02%. In the same period, the total scale of UL increased from 7.69 km² in 2010 to 10.67 km² in 2020, and the change rate of UL decreased from 4.69% to 3.03%. The average annual change rate of UL was 3.46%, which is less than the national PUL standard upper limit of 110 m²/person. The coupling strength showed an overall decreasing trend (Figure 4b,c). Further, the polar coordinate radius decreased from 6.32 to 0.98, and the dynamic coupling state between UP and UL was highly reasonable and controllable range (Figure 4a).

2.3. Data Sources

This study investigated the spatiotemporal coupling characteristics between UP and UL in China from 2010 to 2020 at the national and prefecture-level city scales. The basic data included three parts. First, the UP data of China and various prefecture-level cities, referring to the permanent population, were derived from the “China Statistical Yearbook” and the statistical yearbooks of each province and city. Second, the UL data of China and various prefecture-level cities, including the areas of urban land and town land, were derived from the “Land survey results sharing application service platform” of the Ministry of Natural Resources. The missing data of 2017 and 2018 were supplemented by linear interpolation. Third, PULrv was selected using the upper limit of 110 m²/person in the “Code for classification of urban land use and planning standards of development land GB50137-2011 [59]”. The three types of data were all from authoritative data released by the government and were reliable.

3. Results

3.1. Overall Evolution Characteristics

3.1.1. Scale Characteristics

From 2010 to 2020, China’s urban resident population increased from 670 million in 2010 to 902 million in 2020, and the change rate of UP decreased from 3.82% to 2.03%. The average annual change rate of UP was 3.02%. In the same period, the total scale of UL increased from 7.69 km² in 2010 to 10.67 km² in 2020, and the change rate of UL decreased from 4.69% to 3.03%. The average annual change rate of UL was 3.46%, which was 1.15 times the change rate of UP (Figure 3a,b). In conclusion, the total amounts of UP and UL from 2010 to 2020 have been increasing yearly, but the change rates have gradually slowed. Specifically, the change rate of UL was higher than that of UP, and population urbanization lagged behind land urbanization.

![Figure 3. Evolution scale characteristics of UP and UL in China from 2010 to 2020: (a) changes in UP and UL; (b) change rate of UP and UL.](image)

3.1.2. Coupling Characteristics

PUL can help analyze the static coupling characteristics between UP and UL in China from 2010 to 2020. During this period, PUL in China showed an overall growth trend,
from 113.33 m²/person in 2010 to 118.21 m²/person in 2020, posting a total increase of 4.88 m²/person. The intensive-use level of UL decreased to a certain extent, which was higher than the national PUL standard upper limit of 110 m²/person. However, considering the slowing down of UP and UL growth during the period, PUL was also in a relatively reasonable and controllable range (Figure 4a).

The improved coupling model of polar coordinates can help analyze the dynamic coupling characteristics between UP and UL in China from 2010 to 2020. During this period, the polar coordinate angle between UP and UL change rates in China was between 41.25° and 56.23°, indicating that the coupling types were mainly expansive coupling and expansive negative decoupling (Figure 4b). From 2010 to 2020, the PUL in China was between 113.33 and 118.21 m²/person. According to the coupling model of polar coordinates, the PULrv was between 99.00 and 121.00 m²/person. Therefore, the ideal dynamic human–land coupling angle in China during the period was either 45° or −135°. Based on the above, the calculation results show that the coupling rationality during this period was reduced from 1.00 to 0.98, and the dynamic coupling state between UP and UL was highly reasonable. During the same period, the polar coordinate radius decreased from 6.32 to 3.65, and the coupling strength showed an overall decreasing trend (Figure 4b,c). Furthermore, the comprehensive coupling contribution was reduced from 6.32 to 3.58, which indicates that the dynamic coupling state between UP and UL positively contributes to the static coupling state of PUL. Among them, the coupling contribution of UP decreased from 3.11 to 1.43, and the coupling contribution of UL decreased from 3.32 to 2.07. The coupling contribution of UL was greater than the coupling contribution of UP to improve the static human–land coupling rationality, which accounted for a relatively high proportion.
of the comprehensive coupling contribution, indicating that UL contributes more to the rationality of PUL (Figure 4c,d).

3.2. Spatial Pattern Characteristics

3.2.1. Scale Characteristics

From the perspective of the spatial distribution of the UP scale in China (Figure 5a–c), the result generally showed the overall spatial characteristics of the higher UP scale in the southeast and the lower UP scale in the northwest. This outcome was basically consistent with the population distribution law revealed by the “Hu Huanyong Line.” The UP scale in Beijing-Tianjin-Hebei, Yangtze River Delta, Chengdu-Chongqing, and other regions was relatively large. From the perspective of the spatial changes in the UP scale in 2010–2020, the results presented the spatial characteristics of significant changes in the southwest region and small changes in the northeast region. Specifically, the scale of UP in the southwest regions of Chengdu, Chongqing, Guizhou, Yunnan, Shandong, Xinjiang, and other regions showed a significant expansion trend. By contrast, the scale of UP in some prefecture-level cities in the northeast region decreased or did not change significantly.

Figure 5. Spatial pattern of the UP and UL scales in the prefecture-level cities of China from 2010 to 2020: (a) regional UP in 2010; (b) regional UP in 2015; (c) regional UP in 2020; (d) regional UL in 2010; (e) regional UL in 2015; (f) regional UL in 2020.
From the perspective of the spatial distribution of the UL scale in China (Figure 5d–f), the results generally showed the overall spatial characteristic of the higher UL scale in the east and the lower UL scale in the west. Among them, the scale of UL in Beijing-Tianjin-Hebei, Yangtze River Delta, Chengdu-Chongqing, and Shandong was relatively large, and the scale of UL in Tibet, Qinghai, Gansu, and other regions was relatively small. From the perspective of the spatial change in the UL scale from 2010 to 2020, the results generally showed the spatial characteristic of significant changes in the southern region and small changes in the northern region. Among them, the scale of UL in the Shandong Peninsula, the middle reaches of the Yangtze River, the Chengdu-Chongqing region, and some areas of Tibet showed an apparent expansion trend, and the scale of UL in some prefecture-level cities in Northeast China did not change significantly.

3.2.2. Coupling Characteristics

PUL can help analyze the static coupling spatial characteristics between UP and UL in various prefecture-level cities in China (Figure 6a–c). The figures generally showed the spatial characteristics of the higher PUL in the northwest and the lower PUL in the southeast. Specifically, the PUL in Tibet, Qinghai, Xinjiang, Inner Mongolia, and other provinces was relatively high, and the UL use was relatively extensive. The prefecture-level cities with PUL less than 110 m$^2$/person were mainly distributed in North China, South China, and Southwest China. From the perspective of the spatial change in PUL in 2010–2020, the gap between the northwest and southeast regions of China had further widened. The PUL in Shandong Peninsula, Yangtze River Delta, and the middle reaches of the Yangtze River and Tibet had increased significantly, while the PUL in some prefecture-level cities in Guangxi, Shanxi, and other provinces had decreased. The northwest region has a vast territory with a sparse population but a higher PUL. On the contrary, the central, eastern, and southern regions have more people and less land but a lower PUL. This phenomenon indicates that population density and land resource endowment significantly impact the intensive use of regional UL.

The improved coupling model of polar coordinates can help analyze the dynamic coupling spatial characteristics between UP and UL in various prefecture-level cities in China (Figure 7a,b). In 2010–2015, the polar coordinate angle of prefecture-level cities in China was between 9.28° and 143.01°, with an average of 53.42°. This phenomenon indicates that the coupling type tends to be expansive negative decoupling. In 2015–2020, the polar coordinate angle of prefecture-level cities in China was between −178.27° and 179.39°, with an average of 18.29°. This phenomenon indicates that the coupling type tends toward weak decoupling. In 2010–2015 and 2015–2020, the coupling rationality of all prefecture-level cities in China was between −1.00 and 1.00. However, the average coupling rationality in the early stage was 0.13, while that in the later stage was 0.31. Therefore, the coupling rationality was improved during the period. In 2010–2015, the polar coordinate radius of prefecture-level cities in China ranged from 1.15 to 19.93, with an average of 5.95. In 2015–2020, the polar coordinate radius of prefecture-level cities in China ranged from 0.25 to 23.67, with an average of 5.41. Therefore, the coupling strength decreased during this period. In 2010–2015, the comprehensive coupling contribution of prefecture-level cities in China ranged from −8.24 to 15.01, with an average value of 0.96. In 2015–2020, the comprehensive coupling contribution of prefecture-level cities in China was between −7.98 and 15.57, with an average of 1.46. Therefore, the coupling rationality under coupling strength was generally improved during the period. Specifically, in 2010–2015, the coupling contribution of UP in various prefecture-level cities was between −5.82 and 13.67, with an average of 0.93. The coupling contribution of UL was between −11.11 and 11.54, with an average of 0.04. In 2015–2020, the coupling contribution of UP in each prefecture-level city was between −9.59 and 10.15, with an average of 0.96. The coupling contribution of UL was between −10.01 and 16.70, with an average of 0.36. Therefore, although the ability of UL to improve static human–land coupling rationality significantly increased during the period, the role of UP in the comprehensive coupling contribution was more significant.
3.2.2. Coupling Characteristics

PUL can help analyze the static coupling spatial characteristics between UP and UL in various prefecture-level cities in China (Figure 8a,d), from 2010 to 2015, there were four strong negative decoupling. From 2015 to 2020, there were eight coupling types: recessive coupling, and expansive coupling. Among them, 174 prefecture-level cities exhibited expansive negative decoupling. These prefecture-level cities were mainly distributed in the southwest and the northern and southeastern regions. Eighty prefecture-level cities, which were mainly distributed in the Beijing-Tianjin-Hebei regions, exhibited weak decoupling. Finally, 14 prefecture-level cities, which were mainly distributed in Heilongjiang, Gansu, and other provinces, exhibited strong negative decoupling. From 2010 to 2015, the coupling contribution of UP in various prefecture-level cities was between 7.98 and 15.57, with an average of 1.46. Therefore, the coupling rationality in the early stage was 0.13, while that in the later stage was 0.31. Therefore, the coupling rationality was improved during the period. In 2010–2015, the polar coordinate radius of prefecture-level cities in China ranged from 1.15 to 19.93, with an average of 9.59 and 10.15, with an average of 0.96. The coupling contribution of UL was between 7.98 and 15.57, with an average of 1.46. Therefore, the coupling rationality was 0.13, while that in the later stage was 0.31. Therefore, the coupling rationality was improved during the period. In 2010–2015, the comprehensive coupling contribution of PUL in 2010; (regional PUL in 2015; (regional PUL in 2020.

Figure 6. Spatial pattern of PUL in the prefecture-level cities of China from 2010 to 2020: (a) regional PUL in 2010; (b) regional PUL in 2015; (c) regional PUL in 2020.

Figure 7. Polar coordinate coupling scatter plot between UP and UL in the prefecture-level cities of China from 2010 to 2020: (a) coupling scatter plot from 2010 to 2015; (b) coupling scatter plot from 2015 to 2020.

From the spatial distribution of the dynamic coupling type between UP and UL in various prefecture-level cities in China (Figure 8a,d), from 2010 to 2015, there were four
coupling types: weak decoupling, strong negative decoupling, expansive negative decoupling, and expansive coupling. Among them, 174 prefecture-level cities exhibited expansive negative decoupling. These prefecture-level cities were mainly distributed in the northern and southeastern regions. Eighty prefecture-level cities, which were mainly distributed in Shanxi, Ningxia, Yunnan, and other provinces, exhibited expansive coupling. Seventy prefecture-level cities, which were mainly distributed in the southwest and the Beijing-Tianjin-Hebei regions, exhibited weak decoupling. Finally, 14 prefecture-level cities, which were mainly distributed in Heilongjiang, Gansu, and other provinces, exhibited strong negative decoupling. From 2015 to 2020, there were eight coupling types: recessive coupling, recessive decoupling, weak negative decoupling, weak decoupling, strong negative decoupling, strong decoupling, expansive negative decoupling, and expansive coupling. Among them, 107 prefecture-level cities, which were mainly distributed in Beijing, Gansu, Tibet, and other provinces, exhibited expansive negative decoupling. Eighty-seven prefecture-level cities, which were mainly distributed in Chongqing, Guizhou, and other provinces, exhibited weak decoupling. Sixty-five prefecture-level cities, which were mainly distributed in Inner Mongolia, Anhui, and other provinces, exhibited strong decoupling. A total of 19 recessive decoupling prefecture-level cities, eight weak negative decoupling prefecture-level cities, and four recessive coupling prefecture-level cities were mainly distributed in the northeast region. Thirty-three prefecture-level cities scattered throughout the country exhibited expansive coupling. Finally, 15 prefecture-level cities that were mainly distributed in Yunnan, Sichuan, and other provinces exhibited strong negative decoupling.

From the spatial distribution of dynamic coupling rationality between UP and UL in various prefecture-level cities in China (Figure 8b,e), the coupling rationality of various prefecture-level cities in China was mainly negative in 2010–2015. Specifically, high negative values were distributed in the northern region, while high positive values were distributed discretely in the central and southern regions. In 2015–2020, the number of prefecture-level cities with negative coupling rationality in China decreased, while that with positive coupling rationality increased. The overall spatial characteristics of coupling rationality in the eastern region were more significant than those in the western region. Comparing the spatial distribution of coupling rationality in the two periods, the coupling rationality in some areas, such as Xinjiang, Inner Mongolia, and Northeast China, showed a significant increasing trend, while a decreasing trend was observed in eastern Tibet.

From the spatial distribution of the dynamic coupling strength between UP and UL in various prefecture-level cities in China (Figure 8c,f), in 2010–2015, the high values of coupling intensity were mainly distributed in Guizhou-Chongqing, Anhui-Jiangxi, and Gansu. The low values were mainly distributed in Northeast China, North China, and Xinjiang. In 2015–2020, the high values of coupling strength were mainly distributed in Tibet-Qinghai-Xinjiang and Shandong Peninsula, and the low values were scattered in South China, Central China, and Northeast China. Comparing the spatial distribution of coupling strength in the two periods, the coupling strengths of the Shandong Peninsula, Northeast China and Western Tibet, Qinghai, Xinjiang, and other regions in China showed a significant increasing trend, while a decreasing trend was observed in Central China and South China.

From the perspective of the spatial distribution of comprehensive coupling contribution of UP and UL in various prefecture-level cities and towns in China (Figure 9a,d), from 2010 to 2015, the high negative values of the comprehensive coupling contribution were mainly distributed in Inner Mongolia, Gansu, Qinghai, and other regions. Some high negative values also had a scattered distribution in South China. The high positive values were mainly distributed in Guizhou, Fujian, Hubei, Anhui, and other regions. From 2015 to 2020, the high negative values of comprehensive coupling contribution were mainly distributed in Shandong, Qinghai, and Tibet. The high positive values were mainly distributed in Inner Mongolia, Henan, Hunan, and other regions. Comparing the spatial distribution of comprehensive coupling contribution in the two periods, the coupling rationality con-
sidering coupling strength during the period showed a significant increasing trend, and the improvement of comprehensive coupling contribution of the northern prefecture-level cities was more prominent.

![Coupling type, coupling rationality, and coupling strength between UP and UL in the prefecture-level cities of China from 2010 to 2020: (a) regional coupling type from 2010 to 2015: I is recessive coupling, II is recessive decoupling, III is weak negative decoupling, IV is weak decoupling, V is strong negative decoupling, VI is strong decoupling, VII is expansive negative decoupling, VIII is expansive coupling; (b) regional coupling rationality from 2010 to 2015; (c) regional coupling strength from 2010 to 2015; (d) regional coupling type from 2015 to 2020; (e) regional coupling rationality from 2015 to 2020; (f) regional coupling strength from 2015 to 2020.](image-url)
The coupling contribution of UP in some prefecture-level cities in Northeast China toward improving the static human–land coupling relationship generally in the two periods showed that the coupling contribution of UP in Northwest Jiang, and other regions. The comparison of the spatial distribution of UP coupling contribution were mainly distributed in Chongqing, Sichuan, Guizhou, Yunnan border areas, and other regions. From 2015 to 2020, the high negative values of UP coupling contribution were mainly distributed in Yunnan, Guizhou, Chongqing, Hunan, and other regions. From 2015 to 2020, the high negative values of UP coupling contribution were mainly distributed in Yunnan, Guizhou, Chongqing, Hunan, and other regions. From 2010 to 2015, the high positive values of UP coupling contribution were distributed in Tibet, Qinghai, Xinjiang, and other regions. In the future, we should further control the scale of new UL, strengthen the potential of stock land use, strengthen the potential of stock land use, and improve the comprehensive coupling contribution of UL. In general, the high negative values of the coupling contribution of UP were distributed in the southwest region, while the high positive values were distributed in the northwest region. From 2010 to 2015, the high negative values of UP coupling contribution were mainly distributed in Yunnan, Guizhou, Chongqing, Hunan, and other regions, and high positive values were mainly distributed in Tibet, Sichuan, and other regions.

**Figure 9.** Coupling contribution of UP and UL in the prefecture-level cities of China from 2010 to 2020: (a) regional comprehensive coupling contribution from 2010 to 2015; (b) regional comprehensive coupling contribution from 2010 to 2015; (c) regional coupling contribution of UL from 2010 to 2015; (d) regional comprehensive coupling contribution from 2015 to 2020; (e) regional coupling contribution of UP from 2015 to 2020; (f) regional coupling contribution of UL from 2015 to 2020.
other regions. From 2015 to 2020, the high negative values of UP coupling contribution were mainly distributed in Chongqing, Sichuan, Guizhou, Yunnan border areas, and Northeast China. The high positive values were mainly distributed in Tibet, Qinghai, Xinjiang, and other regions. The comparison of the spatial distribution of UP coupling contribution in the two periods showed that the coupling contribution of UP in Northwest China toward improving the static human–land coupling relationship generally increased. The coupling contribution of UP in some prefecture-level cities in Northeast China, Central China, and South China decreased.

From the spatial distribution of the coupling contribution of UL in various prefecture-level cities in China (Figure 9c,f), in general, the high negative values of the coupling contribution of UL were distributed in the western region, while the high positive values were distributed in the southern region. From 2010 to 2015, the high negative values of UL coupling contribution were mainly distributed in Qinghai, Xinjiang, Gansu, Inner Mongolia in the west, Jiangxi, and Anhui in the southeast, and high positive values were mainly distributed in Guizhou, Yunnan, Chongqing, Hunan, and Fujian. From 2015 to 2020, the high negative values of UL coupling contribution were mainly distributed in Tibet, Qinghai, and Xinjiang in the west and Shandong, Jiangsu, and other regions in the east. The high positive values were mainly distributed in Inner Mongolia, Henan, and Hunan. The comparison of the spatial distribution of UL coupling contribution in the two periods showed that the contribution of UL in North China and Northeast China toward improving static human–land coupling relationship generally increased. The coupling contribution of UL in Shandong and Southwest China declined.

4. Discussion

Although many scholars have conducted research specifically on the human–land coupling relationship in China, previous studies on the measurement of human–land coupling mostly focused on the single aspect of static coupling measurement [45,46,60] or dynamic coupling measurement [40,52,53]. Such studies neglected the comprehensive analysis of the two aspects. To make up for the shortcomings of previous research, Li et al. proposed the coupling model of polar coordinates by combining static and dynamic coupling measurements [54]. This model can measure the coupling rationality and coupling strength. Based on the coupling model of polar coordinates, this study innovatively supplemented the concept of coupling contribution. The improvement made this model more scientific and systematic. Furthermore, this study adopted the improved coupling model of polar coordinates to analyze coupling type, coupling rationality, coupling strength, comprehensive coupling contribution, and so on. Thereby, this research analyzed the spatiotemporal coupling characteristics between UP and UL in China more scientifically and reasonably. Finally, based on the coupling characteristics between UP and UL in China’s prefecture-level cities, this study can reasonably divide cities into differentiated regions and formulate targeted optimization strategies.

First, this study selected six cluster indicators: PUL, coupling rationality, coupling strength, comprehensive coupling contribution, coupling contribution of UP, and coupling contribution of UL. Second, this study used the grouping analysis tool in ArcGIS clustering distribution mapping to analyze the coupling characteristics between UP and UL in China from 2015 to 2020. Third, this study divided China’s prefecture-level cities into four regions (Figure 10), including northern excessive land use and recessive decoupling region, eastern excessive land use and expansive negative decoupling region, central and southern intensive land use and expansive coupling region, and western extensive land use and expansive coupling region. Finally, according to the coupling characteristics of each region, this study formulated targeted optimization strategies.
accelerate the speed of population urbanization, and continue to promote the economical and intensive use of UL.

(2) Eastern excessive land use and expansive negative decoupling region: this region included 33 prefecture-level cities, mainly involving Shanghai, Shandong, Jiangsu, Anhui, and four other provinces. The PUL in this region also exceeded the national standard, and the land use was relatively extensive. At the same time, dynamic human–land coupling rationality was negative, indicating that the urban human–land relationship continued to deteriorate. The main reason was the rapid growth of UL. In the future, we should strictly control the scale of new UL, strengthen the potential of stock land use, accelerate the speed of population urbanization, and continue to promote the economical and intensive use of UL.

(3) Central and southern intensive land use and expansive coupling region: this region included 216 prefecture-level cities, mainly distributed in Hebei, Beijing, Tianjin, Shanxi, Henan, Hubei, Hunan, Jiangxi, Zhejiang, Fujian, Guangdong, Guangxi, Guizhou, Chongqing, Yunnan, Shaanxi, Hainan, and 17 other provinces. The PUL in this region was the same as the national standard, and the land use was relatively intensive. At the same time, dynamic human–land coupling rationality was positive, indicating that the relationship between UP and UL gradually changed to rationality. The main reason was the reduction of UL. In the future, we should control the scale of new UL, implement the “human–land linking” system, and reverse the trend of excessive growth of UL.

(4) Western extensive land use and expansive coupling region: this region included 39 prefecture-level cities, mainly distributed in Xinjiang, Tibet, Qinghai, Gansu, Sichuan, and five other provinces. The PUL in this region was far more than the national standard, and the land use was extremely extensive. At the same time, dynamic human–land coupling rationality was negative, which indicated that the urban human–land relationship...
continued to deteriorate. The main reason for this was the rapid growth of UL. In the future, the scale of new UL should be strictly limited, the demand for land should be mainly solved by tapping the potential of stock land, and the system of “increment-stock linking” should be strictly implemented to reverse the trend of decreasing the level of intensive use of UL.

5. Conclusions

This study proposed an improved coupling model of polar coordinates to analyze the spatiotemporal coupling characteristics between UP and UL at the prefecture-level city scale in China from 2010 to 2020. Based on the analysis results, the study discussed regionally differentiated optimization strategies for urban human–land coordination development in China through spatial clustering analysis. Results showed the following: (1) From the perspective of overall evolution, the UP and UL scales of China’s prefecture-level cities increased yearly. The change rate of UL was higher than that of UP. PUL was always within the ideal value range, and the dynamic human–land coupling state remained reasonable. (2) From the perspective of spatial pattern, the UP and UL scales of China’s prefecture-level cities were spatially high in the east and low in the west, whereas PUL was spatially high in the northwest and low in the southeast. The dynamic human–land coupling rationality was spatially higher in the eastern region than in the western region. (3) According to the coupling characteristics between UP and UL, this study divided China’s prefecture-level cities into four regions: northern excessive land use and recessive decoupling region, eastern excessive land use and expansive negative decoupling region, central and southern intensive land use and expansive coupling region, and western extensive land use and expansive coupling region. This study further proposed differentiated optimization strategies for the urban human–land coordinated development of each region to advance the new urbanization construction.

This study systematically studied the coupling rationality between UP and UL at the prefecture-level city scale in China. On the one hand, this study constructed a measurement framework of spatiotemporal coupling characteristics between UP and UL based on the improved coupling model of polar coordinates. This framework is a more scientific and reasonable way to quantitatively measure the coupling relationship between UP and UL. In particular, this study proposed an improved coupling model of polar coordinates, which improves the calculation method of coupling rationality and introduces the concept of comprehensive coupling contribution, enhancing the scientific and systematic robustness of coupling analysis methods. On the other hand, according to the coupling characteristics between UP and UL in China, regionally differentiated optimization strategies were formulated. The strategies can provide a reference for the relevant research and practice of China’s urban human–land coordinated development. This study also has some shortcomings that need to be improved. On the one hand, due to the availability of data, the selected time range for this study is relatively short. In the future, related research can expand the time range of data under favorable data conditions. On the other hand, this study only analyzed the coupling characteristics from the perspective of UP and UL. In the future, related research can further explore the driving factors that affect coupling rationality and strength to clarify the driving mechanism of the change in the coupling relationship. Based on the mechanism, a more in-depth understanding of the coupling relationship between UP and UL can be achieved. Meanwhile, this study only analyzed the coupling characteristics between UP and UL without analyzing the coupling characteristics between urban social economy and UL. The improved coupling model of polar coordinates can also help systematically and quantitatively study the coupling rationality characteristics between the urban social economy and UL in China, which is equally important for the analysis of intensive UL use. The research results can provide decision support for determining the scale of UL reasonably through the human–land coupling mechanism, thereby promoting the intensive use and high-quality development of UL. Furthermore, the intensive use of UL will also protect cultivated land resources and ecological space, ultimately promoting the sustainable use of national land space.
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