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The Coupling and Coordination of Urban Modernization and Low-Carbon Development

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Abstract: In the context of global resource scarcity, the integrated and coordinated development of urban modernization and low-carbon development is becoming more and more crucial. In order to calculate the degree of coupling coordination between urban modernization and low-carbon growth in 31 Chinese provinces from 2010 to 2021, this paper thoroughly applies the entropy approach and coupling coordination model; the geographical correlation of the degree of coupling coordination of various regions was confirmed using the Moran's I test method; and by utilizing the gray correlation degree model, we examined the elements that affect the degree of coupling coordination between the two in the various provinces. We found that: (1) there are periodic fluctuations in the coupling coordination between the two during the research period, with a general rising tendency year after year; (2) the degree of coupling and coordination between the two shows the characteristics of HH clustering (eastern region) and LL clustering (western region); and (3) the degree of coupling and coordination between the two is influenced by different factors in different regions. Overall, low-carbon variables have a significant impact on the eastern area, but urban modernization factors have a significant impact on the central, western, and northeastern regions. This study can provide policy recommendations for provincial governments in various regions, help identify favorable factors for coordinated development, and improve the role of some influencing factors in a targeted manner, thereby improving the level of urban modernization and low-carbon coordinated development and promoting urban development and ecological harmony.

Keywords: urban modernization; low-carbon development; coupling coordination; Moran's I; gray correlation

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1. Introduction

The use and development of natural resources cannot be isolated from urban modernization, which is a key strategy for fostering economic growth. Numerous areas have experienced severe resource constraints and environmental deterioration as a result of the rapid rise of urbanization, leading to significant waste pollution and high carbon emissions [1]. In a contemporary culture, the metrics used to gauge a nation's socioeconomic development, level of production, and the happiness of its citizens should also consider elements like resources, the environment, green energy, and low carbon emissions [2], and employ the circular economy to achieve high-quality social development [3]. The "Opinions on Promoting Green Development in Urban and Rural Construction" were published by the General Office of the State Council in 2021. These opinions called for the integration of ecological and urban civilizations, the implementation of carbon peak and carbon neutrality tasks, and the promotion of better, quicker, and higher quality economic and social development. In 2023, the State Council also published the white paper "Green Development in China in the New Era". In order to overcome resource and environmental limits, China must now actively promote green, low-carbon, and high-quality development while also creating new cities that harmoniously coexist with nature. In order to move toward low-carbon development and support the green transformation of development methods, research on the coordinated development of urban modernization and low-carbon development is an essential issue that has to be solved.

Western European nations like the United Kingdom are where modernization and urbanization first emerged [4]. The Industrial Revolution was largely responsible for these developments. Due to war-related factors, China's modern urbanization has lagged behind for a very long time. It was not until 1953 that it started to advance by incorporating heavy industrial models from nations like the Soviet Union [5]. Although urban modernization has rapidly increased between 2010 and 2021, its overall quality is still not very good. Its development has been the subject of considerable inquiry by both domestic and international academics. H. Tang [6] discovered that the population has been the main focus of China's modernizing development strategy for about 50 years and examined the connections between people, resources, and the environment. He proposed the challenge facing China's modernization and sustainable development by contrasting the western modernization idea; urbanization and carbon emissions have an inverted U-shaped relationship, according to research by Zhang Ning on the effect of urbanization on carbon dioxide emissions [7]. C. Martin [8] created the idea of urban intelligent sustainable restoration and researched three crucial factors that influence urban growth. M. Dzikuc [9] investigated the problems linked to the development of urban transportation in Poland and the quality of life of urban residents. Conflicts from various perspectives can be resolved by multi-level governance systems. Y. Li [10] gave solutions to the issue of social sustainable development and offered proposals for the synchronized development of China's new urbanization, industrialization, information technology, and agricultural modernization based on the analysis of interactive models.

The 11th Five-Year Plan, which China suggested as a set of measures and policies to fulfill its targets for energy conservation and emission reduction, is where China first began to implement low-carbon development [11]. In order to encourage energy conservation and emission reduction through market mechanisms, China opened its first carbon emission trading market in Shenzhen in 2017 [12]. Its development has considerable reference significance, according to academic research. X. N. Song [13] presented the fundamental idea of a low-carbon economy, reviewed the impact of green low-carbon measures on economic growth, and examined the pattern of China's economic growth under the influence of low-carbon environmental practices. According to Dou's analysis of the reality of China's transition to a low-carbon society, the government needs to implement specific policies and countermeasures in order to address issues with institutional, technological, and financial impacts and other aspects [14]. J. L. Guan [15] pointed out the importance of China's low-carbon growth by drawing on the successful experience of Japan's low-carbon economy and putting out policy recommendations from the perspective of green development strategies. A low-carbon society is a key mechanism for urban development and environmental protection, along with water and energy conservation. Green transportation and low-carbon emission technologies are important aspects of promoting low-carbon development C. T. Lee [16] studied the impact of climate change mitigation in Asia on global carbon emissions.

Improving the social living environment, raising people's quality of living, and fostering happiness are the cornerstones of urban modernization and low-carbon development. Both domestic and foreign academics have held conversations about the two's recent development. J. Ma [17] examined how low-carbon cities and climate change relate to one another, identified important technologies for low-carbon urban design, and looked at the issue from three angles: theory, concept, and practice. B. Warren [18] redesigned Australia's low-carbon energy trajectory after analyzing its climate and energy policies from 1998 to 2013 and discovered that these policies failed during the fight between urban modernization and low-carbon development, resulting in incoherent and disconnected circumstances. In order to analyze the spatiotemporal characteristics of urbanization and ecological environment coupling and coordination development in multiple cities in Anhui

Province, L. Qian [19] built an evaluation index system for the coordinated development of cities and the ecological environment. For the coordinated growth of urbanization, X. Sun [20] built an assessment index system and employed spatial lag and fixed impact models to analyze the contributing elements. In the Beijing Tianjin Hebei region, it was discovered that the degree of coordinated urbanization and environmental development had geographic consequences.

A city's excellent urban modernization development system can support low-carbon development, and a similarly excellent low-carbon development system can support the growth of urban modernization systems. This is based on the scholars' research on the interactive mechanism of the coupling and coordination relationship between multiple factors [20]. We also discovered that it is advantageous for the coordinated development of various systems or elements to address the issue of uneven development between urban modernization systems and low-carbon systems. In conclusion, substantial research has been carried out on urban modernization and low-carbon development both domestically and overseas, but there are still some areas that require improvement. First, there is a dearth of quantitative research in the field of urban modernization and low-carbon development studies, which nearly exclusively take a qualitative approach. Secondly, there are few empirical studies on the measurement of the coupling and coordination relationship between urban modernization development and low-carbon development, and experts have focused on the logical relationship between economic growth and environmental protection. Thirdly, there is no quantitative examination of the overall coordination level of China on a provincial basis; instead, the research subjects chosen by scholars are primarily a number of surrounding cities in a certain region.

This article involves a scientific and quantitative analysis of the level of synergy between urban modernization and low-carbon development in 31 Chinese provinces starting from the actual development state in various locations. In order to scientifically assess the real state of development in 31 provinces during the past few years from the perspectives of urban modernization and low-carbon coupling coordinated development, a U-GL coupling coordinated development assessment index system was created. Second, we gathered and compile pertinent data from different provinces across the nation between 2010 and 2021 using the entropy approach to quantitatively calculate the comprehensive index and impartially assess the degree of connection and coordinated development between the two. Then, the spatial-temporal evolution characteristics of the coordinated growth of urban modernization and low-carbon coupling in various provinces were scientifically evaluated using the significance test of Moran's I in the spatial autocorrelation coefficient. The last step was to use the gray correlation model to examine the indicators for each province and examine the variables that influence the coupling coordination level of each province.

The current state of urban modernization and low-carbon coordinated development in various provinces is addressed in this study, and its spatial correlation is confirmed. It also measures how much influence certain elements have on the coordinated development of coupling and then suggest policy recommendations for various regions that are supportive of the coordinated development of urban modernization and low-carbon coordinated development in each province. The research contribution of this article primarily consists of providing replicable theoretical methods and empirical support for the low-carbon development of domestic and foreign cities, coordinating the economic modernization development of various cities with green, environmentally friendly, and low-carbon development, forming an integrated development pattern, contributing to China's goal of reaching its carbon peak and carbon neutrality, and providing policy recommendations for local governments.

2. Materials and Methods

2.1. Evaluation Indicator System

Coordination of urban comprehensive carrying capacity and economic growth is a key step toward urban sustainability [21]. We may encourage urbanization growth in a variety of ways by boosting people's income, increasing employment prospects, generating the scale effect of businesses and industries, and integrating resource optimization to form structural effects. The evolution of urban modernity is influenced by urban infrastructure [22]. The mechanism that affects urban modernization is primarily formed by lowering the cost of population migration, improving urban service capacity and quality, and improving the spatial form of urbanization; population flow will affect regional economic development and population structure [23], thereby affecting urban development and changing urban morphology. At the same time, human culture is a manifestation of national and regional cities' complete power [24]; urban modernization is also represented in technical innovation, which has a profound impact on the future development pattern of urbanization. As a result, this article builds the urban modernization subsystem, which consists of four components: economic development, infrastructure, people and humanities, and technological innovation.

Low-carbon development must be completely integrated across the entire urban development lifespan. Forming low-carbon plans based on one's own resource and ecological endowment, as well as implementing environmental governance through green design, are examples of this [25] by combining green construction and low-carbon production to create low-carbon circulation, life, and consumption development and then creating a closed-loop and low-carbon pattern with resource efficiency, lower emissions, environmental cleanliness, ecological security, and liquidity through pollution emission planning, and building modern urbanization on the foundation of effective greenhouse gas emission control, thus contributing to China's "3060" dual carbon strategy aim. As a result, this study employs J. F. Zong [26] and Y. Zhang [27] to build a low-carbon subsystem based on four factors: ecological endowment, environmental governance, low-carbon development, and pollutant emissions. A U-G system (urban modernization and low-carbon coupling system) with a total of 21 indicators is built by combining the UM and GL subsystems (see Table 1). Positive indicators (+) and negative indicators (-) are used to evaluate the coupling and coordination of urban modernization and low-carbon development in various provinces across multiple dimensions. Additionally, "+" denotes that larger data are better; "-" denotes that smaller data are preferable.

Table 1. A comprehensive evaluation indicator system for coordinating and connecting urban upgrading with low-carbon development.

Primary Indicator	Secondary Indicator	Third Level Indicators	Attribute
Urban modernization subsystem (UM)	U1 Economic development	M1 Per capita GDP (yuan)	+
		M2 Per capita disposable income of urban residents (yuan)	+
		M3 Proportion of secondary and tertiary sector of the economy in GDP (%)	+
		M4 Local general public budgeting revenue (100 million yuan)	+
	U2 Infrastructure	M5 Per capita urban road area (square meters)	+
		M6 Urban water usage penetration rate (%)	+
	U3 Population Humanities	M7 Proportion of urban population at the end of the year (%)	+
		M8 Population at the end of the year (10,000 people)	+
		M9 Per capita possession of public library collections (volumes)	+
	U4 Innovation	M10 Education expenditure as a percentage of total fiscal expenditure (%)	+
		M11 Science and technology expenditure (100 million yuan)	+
		M12 Internal expenditure of research and development (R&D) funds (10,000 yuan)	+

Table 1. *Cont.*

Primary Indicator	Secondary Indicator	Third Level Indicators	Attribute
Low-carbon subsystem (GL)	G1 Ecological endowment	L1 Green coverage rate in built-up areas (%)	+
		L2 Per capita park green area (square meters)	+
		L3 Area of urban green space (hectare)	+
	G2 Environmental governance	L4 Harmless treatment capacity of household waste (10,000 tons)	+
		L5 Daily sewage treatment capacity (10,000 cubic meters)	+
	G3 Low-carbon development	L6 Energy conservation and environmental protection expenditure (100 million yuan)	+
		L7 Electricity consumption (100 million kilowatt hours)	-
	G4 Pollution discharge	L8 Completion status of forestry investment (10,000 yuan)	+
		L9 Exhaust gas sulfur dioxide emissions (10,000 tons)	-

2.2. Study Models

2.2.1. Entropy Method

This article uses the entropy method to compare the weights between various indicators. The entropy approach is a widely used method for objectively evaluating indicators, with the magnitude of information entropy between indicators serving as the primary basis for weighting [28]. The statistical dispersion of indicators determines the weight of the indicators. The higher the statistical dispersion, the more information it provides and the more weight indicators are given [29]. This article calculates the weight of indicators using the entropy approach and gives weights based on the amount of information between evaluation indicators.

(1) Standardized processing:

The processing method for positive indicators is:

$$X_{ij} = \left[\frac{x_{ij} - \min(x_{1j}, x_{2j}, \cdots, x_{nj})}{\max(x_{1j}, x_{2j}, \cdots, x_{nj}) - \min(x_{1j}, x_{2j}, \cdots, x_{nj})} \right] \tag{1}$$

The processing method for negative indicators is:

$$X_{ij} = \left[\frac{\max(x_{1j}, x_{2j}, \cdots, x_{rj}) - x_{ij}}{\max(x_{1j}, x_{2j}, \cdots, x_{nj}) - \min(x_{1j}, x_{2j}, \cdots, x_{nj})} \right] \tag{2}$$

x_{ij} is the unprocessed data, X_{ij} is the processed data, and at the same time, 0.01 is added to each piece of data after processing to prevent the value from being 0 [28].

(2) Calculate the proportion of the jth indicator in province i:

$$\varphi_{ij} = X_{ij} / \sum_{i=1}^{n} X_{ij}, i = 1, 2, \cdots, 31; j = 1, 2, \cdots, 21 \tag{3}$$

(3) Calculate the entropy value of the indicator:

$$e_j = -1/\ln n \sum_{i=1}^{n} \varphi_{ij} \ln \varphi_{ij} \tag{4}$$

(4) Calculate the coefficient of difference:

$$g_j = 1 - e_j \tag{5}$$

(5) Calculate the proportion of a single indicator:

$$\omega_j = g_j / \sum_{j=1}^{m} g_j \tag{6}$$

(6) Evaluate the collaborative comprehensive score of different provinces [30]:

$$Sc_i = \sum_{j=1}^{m} \omega_j X_{ij} \tag{7}$$

2.2.2. Coupling Coordination Degree Model

Based on earlier research, this paper employs a physics-based coupling coordination model to quantitatively quantify the degree of coupling and collaboration between the two [31] in order to depict the coordination status between systems. The following is the construction model:

$$C = \left[(U \times G)/(U+G)^2 \right]^{\frac{1}{2}}, T = 0.5U \times 0.5G, D = \sqrt{C \times T} \tag{8}$$

C represents the primary coupling value, T represents the collaborative value between the UM subsystem and the GL subsystem; and D is the final coupling co-scheduling. This article is based on clustering thinking. In order to better balance the range and amount of data between each group as close as possible, the natural breakpoint method is used to divide the coupling coordination level into 6 levels. The natural discontinuity classification approach is utilized to determine the coordination level of the U-G coupling system (see Table 2) based on the range of D values in different intervals, and the coupling value is $0 < Q < 1$. However, because the highest coupling degree value in the actual circumstance is less than 0.620, the coupling value in the $[0.620, 1]$ interval will be ignored for the time being.

Table 2. Classification of Coupling Levels.

Coupling Value	Coordination Level	Coupling Value	Coordination Level
[0.000, 0.255)	Severe imbalance	[0.364, 0.406)	Mild synergy
[0.255, 0.320)	Moderate imbalance	[0.406, 0.516)	Moderate synergy
[0.320, 0.364)	Mild disorders	[0.516, 0.620)	Highly collaborative

2.2.3. Spatial Autocorrelation Model

The computed coupling degree value was verified using the global and local Moran's I in the spatial autocorrelation coefficient [32], and the solution formula is:

$$I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} (x_i - \overline{x})(x_j - \overline{x})}{S^2 \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}} \tag{9}$$

where w_{ij} is the adjacency matrix between provinces, with one for adjacent provinces and zero for non-adjacent provinces.

2.2.4. Gray Correlation Model

Utilize the gray correlation degree model to quantify the level of influence on the coupling coordination degree value [33].

(1) After converting all data to a range of $(0.002, 1)$, use the formula to obtain the correlation coefficients between each value:

$$\varsigma_i(t) = \frac{\min\limits_{i,t}\left|X_0'(,t) - X_i'(,t)\right| + \rho\max\limits_{i,t}\left|X_0'(t) - X_i'(t)\right|}{\left|X_0'(t) - X_i'(t)\right| + \rho\max\limits_{i,t}\left|X_0'(t) - X_i'(t)\right|} \tag{10}$$

$X_0'(t)$ represents the standardized data, $X_i'(t)$ represents the data of various impact indicators, and the ρ-value is generally taken as 0.5 [34].

(2) Calculate the gray correlation degree through the correlation coefficient, with the formula:

$$\varsigma_{i,r} = \frac{1}{T}\sum_{t=1}^{T}\varsigma_i(r,t),\ \varsigma_{i,t} = \frac{1}{R}\sum_{r=1}^{R}\varsigma_i(r,t),\ \varsigma_i = \frac{1}{R \cdot T}\sum_{r=1}^{R}\sum_{t=1}^{T}\varsigma_i(r,t) \tag{11}$$

2.3. Data Sources

The data range from 2010 to 2021 and are derived from numerous statistical yearbooks. The data for the GL subsystem indicator come from the "China Environmental Statistical Yearbook" and the "China Electric Power Statistical Yearbook", whereas the data for the UM subsystem indicator come from the "China Statistical Yearbook" and the "China Energy Statistical Yearbook". Linear interpolation was used to process the statistical yearbooks' missing data. Due to the lack of data from Hong Kong, Macau, and Taiwan, this study will not consider these three regions. Additionally, due to space limitations, the values for these three regions are temporarily marked as 0.

3. Results

3.1. Comprehensive Level of Urban Modernization and Low-Carbon Development

In 31 Chinese provinces from 2010 to 2021, the synergy level (UM) and low-carbon coordination level (GL) of urban modernization were measured using the entropy technique. The "Action Plan for Air Pollution Prevention and Control" [17] was published by the State Council in 2013 and set forth specific action guidelines for pollution prevention and control from a variety of angles. This document served as a roadmap for increasing comprehensive governance efforts and establishing regional cooperation mechanisms. In 2018, the US government insisted on starting a trade war with China, which had some effects on the global market economy. As a result, in order to facilitate the comparative analysis of diachronic evolution and synchronicity, this paper studies three stages, namely, 2010–2012, 2013–2017, and 2018–2021, to carry out a collaborative analysis on collaborative systems and subsystems in different stages of 31 provinces.

According to Figure 1, the coordination level of urban modernization in the first stage is higher in most eastern and northeastern provinces than in the second and third stages, while it is highest in the most central provinces, indicating a provincial-level difference. Vertically, the average level of urban modernization coordination in each province in the first stage is 0.322, with nine provinces exceeding the average level; the average coordination level in the second stage was 0.282, a 12.4% decrease from the previous stage; and the average coordination level in the final stage was 0.293, a 3.9% increase from the previous stage.

According to Figure 2, the level of coordination of urban modernization in various provinces reached a record low in 2013, with a national average coupling degree of 0.193. This has had a substantial detrimental influence on the degree of coordination of urban modernization in the 31 provinces in the second stage, resulting in a 10% fall in the average comprehensive level. The national average coupling results from 2010 to 2021 are consistent with the recent development trend of urban modernization in China, as well as the study conclusions of other researchers. There are spatial differences in the coordination level of urban modernization among different regions and provinces, with cities in eastern regions such as Jiangsu, Shanghai, Beijing, and Zhejiang ranking among the top in the country in terms of modernization coordination level; western regions such as Tibet, Gansu, and Qinghai rank at the bottom.

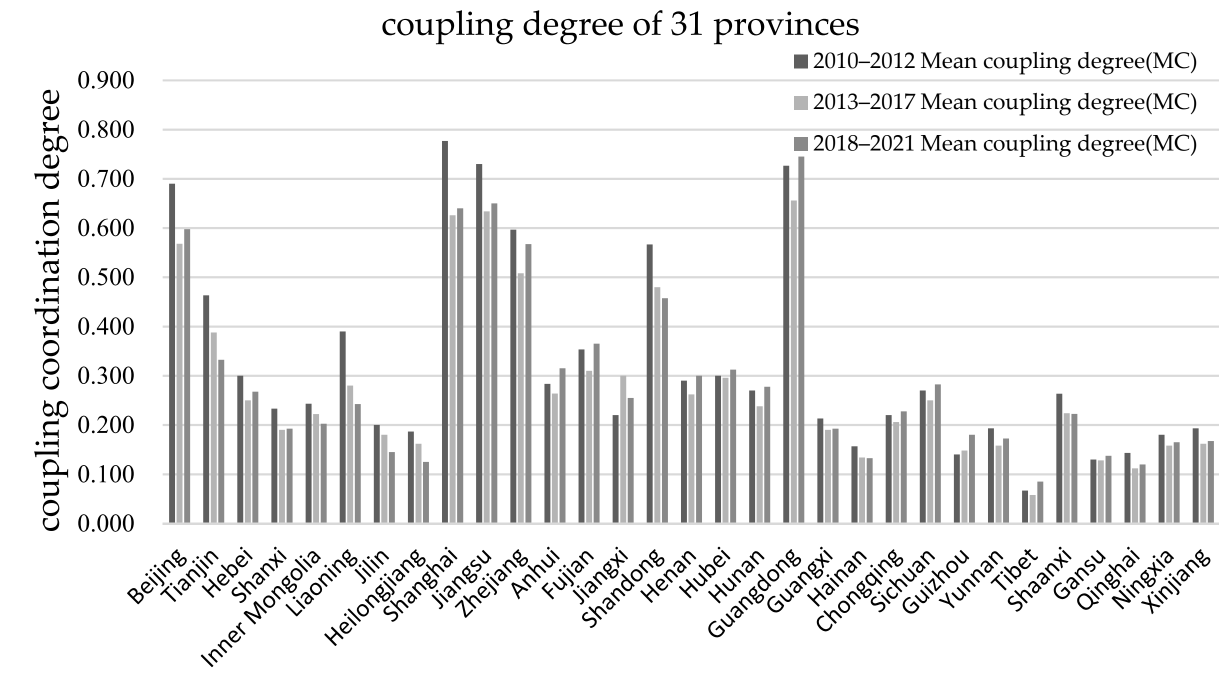

Figure 1. Mean coupling degree of urban modernization in three stages.

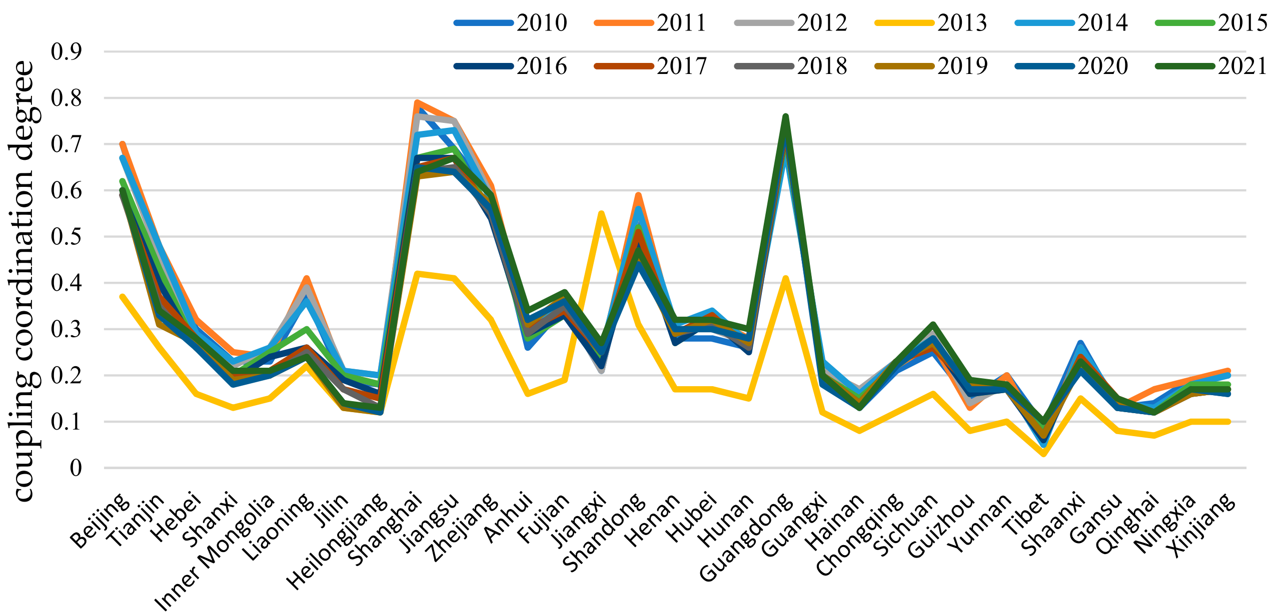

Figure 2. Average coupling level of urban modernization from 2010 to 2021.

According to Figure 3, there were geographical disparities in low-carbon coordination levels during the research period. The coordination level of low-carbon development in most provinces' third stage fell compared to the first and second stages, whereas it increased in the three phases of provinces in the Beijing Tianjin Hebei region. Low carbon emissions averaged 0.294 in 31 provinces between 2010 and 2012, with 11 provinces topping the norm. In 31 provinces, the average level of low-carbon development was 0.277 from 2013 to 2017. A total of 14 provinces had levels higher than the average, and in 31 provinces, the average level was 0.276 from 2018 to 2021. Overall, 12 provinces had levels higher than the average.

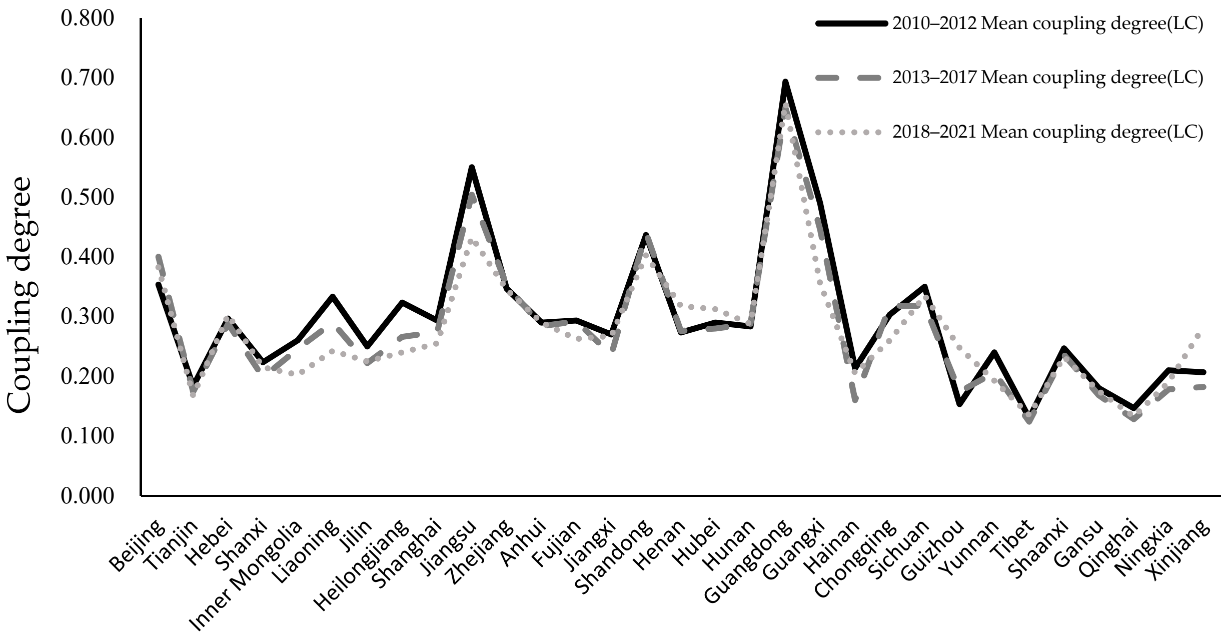

Figure 3. Average coupling degree of low-carbon industries in three stages.

As illustrated in Figure 4, the overall level of low-carbon development in various provinces fell dramatically between 2014 and 2018, and there were considerable variances in low-carbon development among China's 31 provinces. The spatial distribution pattern, on the other hand, is essentially congruent with urban modernization.

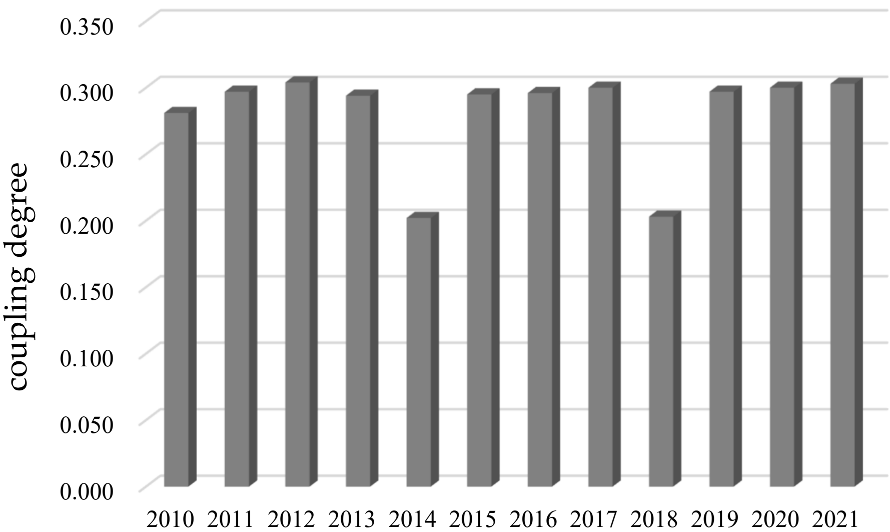

Figure 4. Mean coordinated level of low-carbon coupling from 2010 to 2021.

3.2. Coupling Coordination Degree

The coordination assessment values of the urban modernization and low-carbon dual subsystems were obtained based on the preceding research. The coupling coordination scheduling of 31 Chinese provinces from 2010 to 2021 was then computed using the model (see Table 3), and the coupling coordination procedure of the two was performed in time series.

Table 3. Coordination of national urban modernization, low-carbon coupling from 2010 to 2021.

Province	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Beijing	0.490	0.497	0.502	0.430	0.461	0.505	0.510	0.516	0.451	0.504	0.504	0.492
Tianjin	0.377	0.389	0.379	0.333	0.339	0.373	0.361	0.378	0.333	0.357	0.334	0.347
Hebei	0.384	0.394	0.381	0.325	0.343	0.380	0.383	0.387	0.329	0.383	0.399	0.387
Shanxi	0.335	0.346	0.332	0.287	0.300	0.320	0.320	0.320	0.280	0.323	0.329	0.335
Inner Mongolia	0.343	0.357	0.364	0.314	0.324	0.360	0.363	0.335	0.289	0.324	0.324	0.331
Liaoning	0.405	0.432	0.436	0.372	0.375	0.390	0.367	0.371	0.321	0.353	0.357	0.357
Jilin	0.330	0.334	0.338	0.297	0.303	0.331	0.327	0.314	0.292	0.297	0.303	0.306
Heilongjiang	0.346	0.352	0.353	0.311	0.312	0.341	0.322	0.314	0.269	0.291	0.311	0.300
Shanghai	0.492	0.485	0.489	0.418	0.430	0.465	0.465	0.481	0.418	0.454	0.458	0.464
Jiangsu	0.547	0.569	0.572	0.485	0.506	0.555	0.548	0.546	0.462	0.524	0.529	0.535
Zhejiang	0.462	0.484	0.483	0.415	0.432	0.478	0.479	0.478	0.426	0.489	0.477	0.483
Anhui	0.364	0.387	0.384	0.334	0.347	0.381	0.384	0.390	0.343	0.397	0.394	0.415
Fujian	0.381	0.409	0.412	0.351	0.366	0.400	0.400	0.406	0.364	0.408	0.395	0.404
Jiangxi	0.342	0.353	0.351	0.431	0.311	0.343	0.346	0.364	0.321	0.367	0.370	0.380
Shandong	0.475	0.505	0.514	0.439	0.453	0.497	0.497	0.492	0.426	0.466	0.472	0.482
Henan	0.364	0.377	0.384	0.327	0.344	0.374	0.380	0.393	0.347	0.405	0.403	0.409
Hubei	0.374	0.390	0.387	0.333	0.356	0.394	0.397	0.400	0.353	0.412	0.400	0.409
Hunan	0.364	0.371	0.380	0.326	0.341	0.374	0.376	0.380	0.338	0.367	0.393	0.400
Guangdong	0.585	0.600	0.602	0.519	0.528	0.594	0.596	0.600	0.531	0.606	0.606	0.612
Guangxi	0.411	0.398	0.396	0.346	0.374	0.396	0.389	0.389	0.348	0.341	0.371	0.381
Hainan	0.287	0.311	0.307	0.245	0.258	0.283	0.274	0.282	0.255	0.333	0.269	0.277
Chongqing	0.345	0.361	0.371	0.303	0.414	0.349	0.353	0.350	0.323	0.356	0.352	0.359
Sichuan	0.390	0.389	0.396	0.341	0.352	0.390	0.392	0.388	0.349	0.392	0.404	0.417
Guizhou	0.274	0.264	0.274	0.245	0.258	0.291	0.303	0.304	0.287	0.332	0.333	0.340
Yunnan	0.331	0.331	0.322	0.272	0.282	0.311	0.311	0.314	0.273	0.307	0.307	0.315
Tibet	0.228	0.214	0.201	0.173	0.188	0.241	0.197	0.218	0.209	0.222	0.239	0.251
Shaanxi	0.357	0.357	0.357	0.308	0.319	0.357	0.350	0.350	0.314	0.339	0.338	0.353
Gansu	0.280	0.277	0.273	0.248	0.255	0.278	0.277	0.287	0.255	0.286	0.280	0.291
Qinghai	0.269	0.283	0.255	0.226	0.233	0.255	0.245	0.255	0.240	0.259	0.250	0.255
Ningxia	0.320	0.316	0.299	0.266	0.271	0.304	0.300	0.295	0.278	0.306	0.300	0.304
Xinjiang	0.316	0.324	0.307	0.266	0.278	0.304	0.299	0.304	0.387	0.304	0.295	0.307
Nationwide	0.373	0.382	0.381	0.332	0.344	0.375	0.371	0.374	0.336	0.371	0.371	0.377

According to Table 3, the coordination degree of urban modernization and low-carbon coupling in 31 Chinese provinces from 2010 to 2021 ranged from 0.240 to 0.620. The provinces with the highest coordination degree achieve a high level of coordination, while the provinces with the lowest coordination degree achieve a serious level of imbalance, according to the coordination degree intervals in Table 2. As a result, China has a relatively low level of coordinated development between urban modernization and low-carbon emissions. Most provinces have disregarded each other in terms of urban modernization, the reduction of carbon, and low carbon emissions and have not attained a healthy state of coordinated development, with a substantial gap between different provinces.

Based on the data presented above, the average coupling degree of the national MC, LC, and M-L systems during a 12-year period can be calculated (see Figure 5). From a national viewpoint, the general degree of cooperation between urban modernization and green low-carbon energy has shifted marginally during the research period, although the shifts in 2013 and 2018 were bigger than those in previous years. Specifically, the degree of coupling coordination gradually improved from 2010 to 2012 but declined from 0.381 in 2012 to 0.332 in 2013, a decrease of more than 12.8%. The coupling coordination degree stayed consistent at 0.374 from 2014 to 2017 and then declined from 0.374 in 2017 to 0.336 in 2018, a decrease of more than 10.1%. Between 2019 and 2021, the coupling coordination degree gradually climbed to 0.377, the greatest value in recent years. According to this, China's general coupling coordination degree between urban modernization and low-carbon growth is slowing, but there has been a fall in representative years. As a result, it is critical to precisely identify the influencing variables that influence the degree of coupling coordination between the two, as well as to make targeted policy recommendations to support the coordinated development of urban modernization and low-carbon coupling in various provinces.

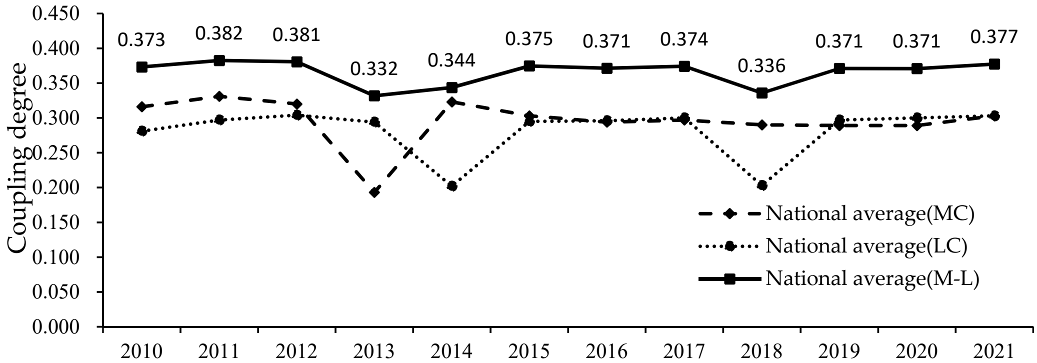

Figure 5. Average coupling degree of the ML, LC, and M-L systems in 12 years.

3.3. Spatial Evolution Pattern of Collaborative Value

3.3.1. Spatial Evolution Pattern of Coupling Coordination Degree

To investigate the spatiotemporal characteristics of the coupling coordination evolution of urban modernization and low-carbon development in 31 provinces from both temporal and spatial dimensions, the coupling coordination degree of each province was averaged according to the three stages divided in the previous research period, and the spatial evolution pattern results were obtained by comparing the level division in Table 2 (see Table 4).

Table 4. Spatial evolution pattern of the coordination degree of national urban modernization and low-carbon coupling.

Period	Coordination Level	Eastern	Central	West	Northeast
2010–2012	Highly coordinated	Jiangsu and Guangdong			
	Moderate coordination	Beijing, Shanghai, Zhejiang, and Shandong			Liaoning
	Mild synergy	Tianjin, Hebei, and Fujian	Anhui, Henan, Hubei, and Hunan	Guangxi and Sichuan	
	Mild disorders		Shanxi and Jiangxi	Inner Mongolia, Chongqing, Yunnan, and Shaanxi	Jilin and Heilongjiang
	Moderate imbalance	Hainan		Guizhou, Gansu, Qinghai, Ningxia, and Xinjiang	
	Severe imbalance			Tibet	
2014–2017	Highly coordinated	Jiangsu and Guangdong			
	Moderate coordination	Beijing, Shanghai, Zhejiang, and Shandong			
	Mild coordination	Hebei and Fujian	Anhui, Henan, Hubei, and Hunan	Guangxi, Chongqing, and Sichuan	Liaoning
	Mild disorders	Tianjin	Jiangxi	Inner Mongolia and Shaanxi	Heilongjiang
	Moderate imbalance	Hainan	Shanxi	Guizhou, Yunnan, Gansu, Ningxia, and Xinjiang	Jilin
	Severe imbalance			Tibet and Qinghai	
2019–2021	Highly coordinated	Guangdong and Jiangsu			
	Moderate coordination	Beijing, Shanghai, Zhejiang, and Shandong	Henan and Hubei		
	Mild coordination	Hebei and Fujian	Anhui, Jiangxi, and Hunan	Guangxi and Sichuan	
	Mild disorders	Tianjin	Shanxi	Inner Mongolia, Chongqing, Guizhou, and Shaanxi	Liaoning
	Moderate imbalance	Hainan		Yunnan, Gansu, Qinghai, Ningxia, and Xinjiang	Jilin and Heilongjiang
	Severe imbalance			Tibet	

The benefits and drawbacks of coupling coordination between urban modernization and low-carbon development in 31 provinces are as follows: good coordination in the east, mild coordination in the middle, mild imbalance in the northeast, moderate imbalance in the west, and severe imbalance. The coupling state between provinces and regions eventually fades, establishing a regional coordinated development trend. The coupling coordination degree of 31 provinces remained essentially similar across the three periods, ranging from severe imbalance to moderate coordination. At the same time, the eastern region serves as a meeting point for provinces with a higher degree of coordination. From 2010 to 2012, 17 provinces had mild coordination and mild imbalance, accounting for 54.8% of the total. From 2014 to 2017, 15 provinces had mild coordination and mild imbalance, accounting for 48.4% of the total. From 2019 to 2021, 14 provinces had mild coordination and mild imbalance, accounting for 45.2% of the total. According to the general trend analysis, provinces with good coordination in the eastern area are reasonably steady and continue to lead. In several central provinces, the coupling and coordination situation is favorable. The western provinces' situation is essentially unchanged. The state of coupling of several provinces in Northeast China has decreased.

3.3.2. Test for Spatial Correlation

The spatial autocorrelation coefficient global Moran's I is utilized for analysis to extensively study the spatial correlation characteristics of coupling coordination degree between nearby provinces based on the 12-year three stage coupling coordination degree data [3]. According to Table 5, the global Moran value of the coupling coordination degree is the lowest at 0.166 and the highest at 0.380 from 2010 to 2021; the z- and *p*-values of 12 years passed the significance test, and in addition to a few years (such as 2018), they also passed the 1% significance test, indicating a significant positive spatial autocorrelation between urban modernization and low-carbon coordinated development.

Table 5. Global Moran's I values of national coordination degree.

Year	Moran Index I	z-Value	*p*-Value	Year	Moran Index I	z-Value	*p*-Value
2010	0.256	2.500	0.006	2016	0.292	2.810	0.002
2011	0.328	3.118	0.001	2017	0.326	3.106	0.001
2012	0.351	3.320	0.000	2018	0.166	1.720	0.043
2013	0.380	3.572	0.000	2019	0.345	3.270	0.001
2014	0.289	2.784	0.003	2020	0.267	2.593	0.005
2015	0.289	2.788	0.003	2021	0.287	2.765	0.003

From 2010 to 2013, the global Moran's I increased year by year from different years, with it reaching a peak of 0.380 in 2013, 0.124 more than 0.256 in 2010. From 2014 to 2017, it increased year by year again; however, in the third stage, it fluctuated. In 2018, it dropped to 0.166, which only met the 5% confidence level of spatial correlation. In subsequent years, the Moran's I gradually stabilized to 0.287. In this stage, the spatial correlation of the coordination degree of urban modernization and low-carbon coupling in 31 provinces of China weakened year by year.

The spatial correlation investigation revealed that there is a specific clustering center in the coupling coordination degree of this article. This paper uses ARCGIS 10.7 software to examine the spatial correlation change characteristics of coordination degree based on existing data to investigate the location of clustering space. The convergence of coupling coordination degrees across provinces (see Table 6) and their evolutionary properties (see Figure 6) were examined.

Table 6. Spatial correlation changes of low-carbon coupling coordination degree in national cities.

Spatial Association Mode	2010–2021
HH	Shanghai, Jiangsu, Zhejiang, Fujian, and Shandong
LL	Gansu, Qinghai, Ningxia, and Xinjiang

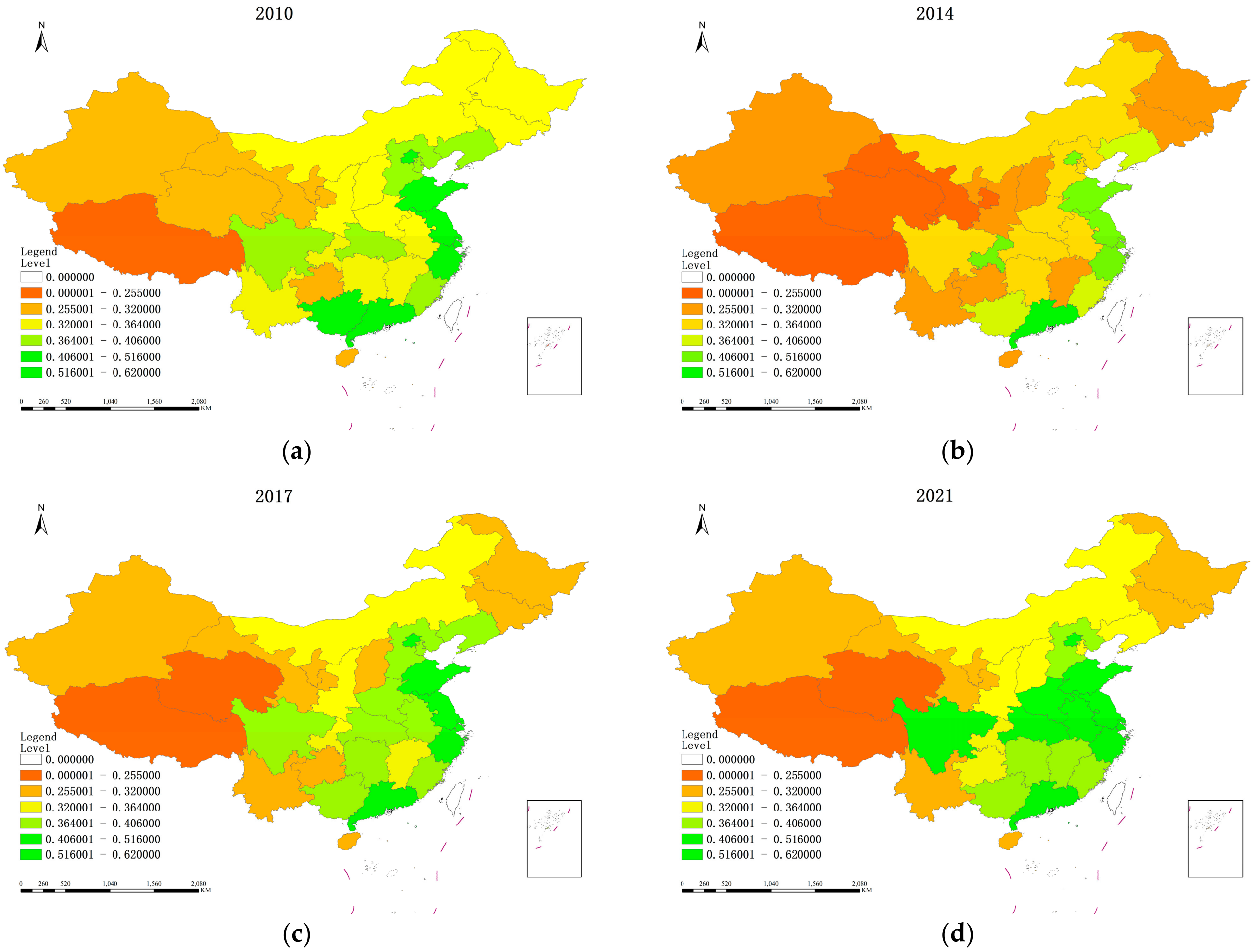

Figure 6. Evolutionary distribution of coordination degree between modernization and low-carbon coupling in 31 provinces. Four representative years: (**a**) degree distribution of national coupling coordination in 2010; (**b**) degree distribution of national coupling coordination in 2014; (**c**) degree distribution of national coupling coordination in 2017; and (**d**) degree distribution of national coupling coordination in 2021.

Table 6 shows that the spatial correlation features are mostly defined by HH and LL clustering. From 2010 to 2021, HH agglomeration mainly occurred in the Shanghai, Jiangsu, Zhejiang, Fujian, and Shandong regions, with the spatial distribution consistent with eastern urban agglomerations such as the Yangtze River Delta, indicating a high degree of coupling and coordination among these cities themselves and surrounding cities. LL agglomeration is distributed in the western region, taking the Gansu, Qinghai, Ningxia, and Xinjiang regions as examples. These provinces have a low degree of cooperation, and surrounding cities have a low degree of coordination as well.

On the one hand, the eastern region has built a solid foundation for innovation-driven development through the construction of numerous science and technology innovation centers, combined with demonstration zones for reform in various fields, creating a good development “soft environment” that can be replicated and promoted nationally. On the other hand, the eastern coastal zone, which is part of the HH cluster region, has taken the initiative in developing advanced low-carbon technologies, coupling and coordinating low-carbon growth with urban modernization. The western provinces have a low level of coordinated development between urban modernization and low-carbon development, resulting in LL agglomeration in space, are relatively underdeveloped in terms of transportation, lack the foundation for urban economic development and low-carbon green energy, degrade the ecological environment, and have limited resource elements.

4. Influencing Factors of Coupling Coordination

Four influencing factors have been identified after taking into account the city's actual situation. These are: (1) the per capita disposable income of urban residents (yuan) is chosen for economic governance because it is a reliable indicator of peoples' living standards and purchasing power [35]; (2) the policy direction chooses the local general public budgeting income (100 million yuan), which can reflect both the level of urban modernization and the local government's ability to maintain the regular operation of institutions and assure the supply of public services; (3) a comprehensive indicator that reflects the "effort level" of education and innovation investment in each province—the proportion (%) of education expenditure in total financial expenditure for talent selection is directly related to the accomplishment of the development goals of education technology innovation in each province [36]; and (4) the choice of per capita park green space area (square meters) for quality of life is a crucial indication for gauging the coordinated growth of contemporary cities and low-carbon development [37]. The degree of influence of four influencing factors in 31 provinces on their coupling coordination degree was calculated in this article using the gray correlation model. The top four indicators with the greatest impact degree were simultaneously determined and arranged by the provinces in which they are located. Table 7 presents the results of sorting the indicators with the greatest occurrence.

Table 7. Gray correlation degree of influencing factors in different regions.

Area	Province	Influencing Factors				Top Four Impact Indicators				Ranking of Regional Indicators
		Economic Dominance	Policy Direction	Talent Literacy	Quality of Life					
Eastern	Beijing	0.632	0.652	0.613	0.651	M4	L2	M5	M8	L2
	Tianjin	0.565	0.529	0.619	0.640	M5	L9	M3	L2	M6
	Hebei	0.637	0.630	0.571	0.639	M6	L4	M8	L1	L6
	Shanghai	0.572	0.597	0.620	0.580	L1	L6	M10	M7	M3
	Jiangsu	0.565	0.624	0.608	0.631	L9	L6	L2	L4	M5
	Zhejiang	0.632	0.630	0.563	0.655	L4	M9	L2	M6	M8
	Fujian	0.624	0.631	0.645	0.612	L6	M10	M6	M3	M10
	Shandong	0.564	0.609	0.725	0.576	M10	M6	M3	L9	L4
	Guangdong	0.651	0.648	0.600	0.679	L2	M8	M2	M4	L9
	Hainan	0.683	0.584	0.652	0.614	M9	L6	M5	M2	\
Central	Shanxi	0.654	0.642	0.647	0.680	L3	L2	M8	M7	M4
	Anhui	0.735	0.730	0.685	0.652	L1	M2	M4	M7	M2
	Jiangxi	0.721	0.591	0.691	0.764	L2	M2	M5	L8	M7
	Henan	0.732	0.735	0.530	0.688	M4	M2	L4	M8	\
	Hubei	0.664	0.690	0.547	0.639	M11	M4	L4	M6	\
	Hunan	0.696	0.708	0.574	0.681	L5	L1	M4	M7	\
West	Inner Mongolia	0.526	0.591	0.590	0.582	M3	L6	L9	M8	M2
	Guangxi	0.570	0.579	0.710	0.578	M10	L9	L5	L3	M10
	Chongqing	0.665	0.568	0.687	0.583	M10	M2	L8	M9	M6
	Sichuan	0.739	0.713	0.655	0.658	M2	M10	M4	L3	L3
	Guizhou	0.791	0.771	0.692	0.733	L1	M6	M8	M1	M3
	Yunnan	0.652	0.626	0.638	0.607	M2	M3	L9	M10	M9
	Tibet	0.815	0.647	0.681	0.749	M2	L8	L2	M12	L5
	Shaanxi	0.615	0.593	0.551	0.620	L3	M6	M11	L5	L9
	Gansu	0.728	0.696	0.623	0.658	M2	M6	M4	L3	\
	Qinghai	0.706	0.579	0.738	0.617	M10	M2	M6	M9	\
	Ningxia	0.694	0.606	0.710	0.586	M10	M2	L5	L8	\
	Xinjiang	0.712	0.565	0.653	0.624	M2	L6	M3	M10	\
Northeast	Liaoning	0.563	0.603	0.714	0.600	M8	L9	M10	L8	M8
	Jilin	0.566	0.508	0.671	0.525	L9	M8	M10	M3	M10
	Heilongjiang	0.541	0.550	0.675	0.554	L9	M3	M8	M10	L9

Economic supremacy and the degree of their coupling coordination have the largest gray correlation degree, with an average of 0.652. The level of economic evaluation has the largest influence on the coordinated development of urban modernization and low-carbon coupling, as shown by the highest correlation degree among multiple provinces, which is as high as 0.810. According to the average gray correlation degree of the various regions, the eastern region has a value of 0.613, the central region is at 0.700, the western region has a value of 0.684, and the northeast region has a value of 0.577. This suggests that, compared to other regions, the central and western regions' per capita disposable income level has a greater influence on the coordinated development of urban modernization and low-carbon coupling. The rationale behind this is that, given how central cities are developing, rapid and high-quality economic improvement can raise the city's status and influence in a variety of ways, encourage structural industry transformation toward a low-carbon economy, and further encourage the coupling and coordinated growth of the two.

With an average of 0.641, the gray correlation effect of talent literacy on coupling coordination degree is second only to economic assessment criteria. From a regional perspective, the average gray correlation degree is 0.622 in the eastern region, 0.612 in the central region, 0.661 in the western region, and 0.687 in the northeast. This suggests that, compared to other regions, the northeast and western regions' coordinated development of urban modernization and low-carbon coupling is more dependent on the ratio of education expenditure to total fiscal expenditure. The reason is that the current state of education in the northeast and western areas is plagued by issues including inadequate educational investment, poor worker quality, and the decline of fundamental education. As a result, education has a more significant effect on how urban modernization and low-carbon green energy are coupled and coordinated.

The average gray correlation degree between the quality of life and the degree of coupling coordination between the two is 0.634, showing that the level of quality of life has also considerably boosted the degree of coupling coordination of urban modernization and low-carbon development. The average gray correlation degree in the eastern region is 0.628, the average in the central region is 0.684, the average in the western region is 0.633, and the average in the northeast region is 0.560, indicating that the per capita park green space area in the central and western regions plays a greater role in the coordinated development of urban modernization and low-carbon coupling than in other regions. The reason for this is because, in comparison to the eastern and northeastern regions, the degree of urban living environment is relatively low, and its development and changes are more sensitive to coupling coordination.

The degree of the gray correlation influence of policy direction on coupled co-dispatch is relatively low compared to the former, but it does reach a correlation level of 0.627, indicating that this factor is beneficial for improving the coupling coordination degree of the two as a means of ensuring public services and regulating urban development di-rection. The average gray correlation degree in the eastern region is 0.613, 0.683 in the central region, 0.628 in the western region, and 0.554 in the northeast region, indicating that the level of local general public budgeting income plays a greater role in the coordinated development of urban modernization and low-carbon coupling in the central region than in other regions. The reason for this is that the central region's social and economic development is relatively rapid, and the scale of local government fiscal revenue is large enough to fully exploit the benefits of fiscal revenue, inject sufficient resources into urban Low-carbon economic planning, and promote synergy between the two.

Different indicators have differing amounts of regional impact, as seen from a regional perspective. The indicators L2, M6, L6, M3, etc., have been significantly impacted in the eastern region, showing that changes in industrial structure, as well as per capita costs for urban energy conservation and environmental protection, have a greater impact on the coupling coordination degree. The central region's indices M4, M2, and M7 show a greater degree of effect, indicating that the region's coupling and scheduling can be more significantly influenced by residents' economic dominance and population makeup. The indicators that have been most significantly impacted in the western region are M2, M10, M6, and L3, indicating that in order to improve the coupling and coordination of urban green development, efforts need to be made not only in the economic and educational aspects but also in the construction of urban infrastructure and the improvement of residents' quality of life.

5. Conclusions and Suggestions

5.1. Conclusions

The study used a coupling coordination comprehensive evaluation model, the spatial autocorrelation coefficient, and the gray correlation degree model to analyze the spatiotemporal evolution characteristics of urban modernization and low-carbon coupling development in 31 provinces based on the coupling mechanism of these two development types in numerous Chinese provinces. The following conclusions were drawn:

(1) The coupling coordination degree of 31 provinces varied over the course of the 12-year study period, clearly displaying temporal evolution characteristics. The majority of the provinces have the highest coupling coordination degree in the first stage and the lowest coupling coordination degree in the second stage, according to the variation trend of the average coupling coordination degree of each province. It returns to a specific coupling level in the third stage (the average coupling coordination degree for the entire nation in the three stages is 0.379, 0.359, and 0.364, respectively). In three stages, several provinces in Northeast China show a decreasing trend. The coupling coordination degree has the traits of leading in the east, finishing in the west, and being centered in the middle and northeast from the standpoint of spatial heterogeneity. Overall, during the study period, the coupling level increased, but 2018 saw significant swings.

(2) The coupling and coordination between the two during the inquiry had a sizable spatial relationship. First, using the natural discontinuity approach, the coupling coordination degree values of each province were separated into six groups in accordance with the clustering principle. Second, over the course of the three research periods, the coupling coordination levels of the 31 provinces were summarized in chronological order. The Moran index was then utilized to confirm the spatial association between urban modernization and low-carbon development using spatial correlation testing. Finally, the findings show that there is a distinct center of coupling, coordination, and agglomeration between the two. Agglomeration has the following unique features: some eastern provinces (such as Shanghai, Jiangsu, Zhejiang, etc.) exhibit HH agglomeration characteristics, whereas other western provinces (such as Gansu, Qinghai, etc.) exhibit LL agglomeration characteristics.

(3) Economics, talent, life, and policy evaluation are the four variables that have the biggest effects on linked collaborative scheduling. Due to the numerous elements examined in this article, a significant number of provinces and regions are taken into consideration, and the location of the provinces affects the impact of numerous influencing factors on the coupling coordination of the provinces. As a result, from a broad perspective, the impact of various factors on the eastern region is well balanced; in the central region, policy evaluations have a stronger influence on the cooperation and coordination between the two. The western and northeastern regions are most affected by talent evaluation and life assessment.

5.2. Suggestions

Using a coupling coordination degree model, this study assesses the urban modernization and green low-carbon comprehensive development of 31 Chinese provinces from 2010 to 2021. The spatial heterogeneity of coupling coordination degree is confirmed from the standpoint of the spatial autocorrelation coefficient when combined with the significance test of the Moran index. At the same time, significant variables that determine the degree of coupling coordination in various provinces are quantified. The following concrete manifestations are based on the complete coupling coordination degree of 31 provinces nationwide across the three research periods: currently, the core of urbanization development does not prioritize humanistic literacy [20], and by enhancing humanistic literacy, numerous provinces may significantly enhance the coupling coordination of urban modernization and low-carbon development, and the northeast and western areas' economic development is constrained by locality, and the spatial spillover impact of economic development in diverse regions is generally minimal [38]. Other regions are not significantly impacted by the eastern region's effective economic development because different provinces have not fully utilized the value of policy guidance and other aspects, and local governments have not given enough attention to the coordinated development of the ecological environment and economic situation [39]. The aforementioned inquiries are representative and differ in various provinces.

In response to the aforementioned problems, this article suggests the policy recommendations below from the perspective of individual development in various regions, combined with elements like economic development, ecological environment, cultural literacies, and governmental regulation, in order to promote the coordinated development of urban modernization and low-carbon development:

(1) The eastern provinces should make the transformation of the low-carbon industry a top priority [40]. This area has had rather rapid technological progress and innovation. High-quality demographic traits and degrees of scientific research not only support one another in economic development but also establish powerful partnerships in the development of low-carbon industrial innovation, raising everyone's standard of living [24]. Large-scale low-carbon transformation can have structural consequences, encourage investment in environmentally friendly enterprises in the region, and support the coordination and coupling of low-carbon urbanization development. They should utilize the idea of "people-oriented" to coordinate the growth of diverse components, capitalize on the driving force of favorable regions, and advance comprehensive development [20].

(2) The central provinces should keep stepping up their efforts to strengthen their economies [41]. A collaborative model of business, academia, and research can be established in this area by utilizing the benefits of asset investment and gathering educational resources. The government should also stimulate the development of low-carbon societies, take part in some economic pilot zones, and speed up the development of inland vertical and horizontal opening channels to the outside world. In addition, we will continue to raise the level of intense use of urban resources while also accelerating the elimination of outmoded production capacity, implementing industrial structural reform, and maintaining the ecological and green development pattern [27].

(3) In the western and northeastern regions, infrastructure development and education should be given primary attention. First and foremost, the western region needs to use all of its energy resources. It can improve the supply capacity of strategic resources in numerous places, create competition in the resource market on a broad scale, and draw a lot of investment capital due to the abundance of clean energy and its strong industrial supporting capabilities. They should use educational resources in other disciplines, promote the use of renewable energy, and diversify capital investment in the education sector [38]. In order to achieve economic complementarity and industrial structural complementarity between the east and the west, the northeast region plays a critical strategic role. The northeast region has a lot of space for improvement in terms of low-carbon development patterns. At the same time, we will actively change the economic development model, increase the treatment of wastewater and waste gas, and accomplish comprehensive environmental improvement with the aid of government regulations and financial support. This should promote low-carbon development and urban upgrading in the end.

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