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Spatio-temporal Patterns Evolution of Coupling Coordination of Ecosystem Services and New Urbanization in the Beijing-Tianjin-Hebei Region

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Abstract. Clarifying the coupling coordination relationship between ecosystem services and new urbanization is of great significance for promoting high-quality and sustainable development in the region. In this study, 197 county administrative units in the Beijing-Tianjin-Hebei region were selected as the study area, and the ecosystem service value index and new urbanization level from 2005 to 2020 were calculated respectively. The coupling coordination degree model was used to analyze the spatial-temporal correlation pattern evolution of the coupling coordination degree between the two. Results show that: ① The ecosystem service value index in the Beijing-Tianjin-Hebei region first decreased and then increased, showing an overall upward trend, manifested as a spatial pattern of "high in the north and low in the south, high in the west and low in the east", with different spatial distribution patterns of sub ecosystem services; ② The overall level of new urbanization is showing a continuous upward trend, manifested by a spatial pattern from "high in the north and low in the south" to "high in the north and south, low in the middle". ③ The coupling coordination degree shows a steady upward trend, but overall it is in a stage of mild imbalance, manifested as a spatial pattern of "high in the north and low in the south".

Keywords: ecosystem services; new urbanization; coupling coordination degree; Beijing-Tianjin-Hebei region.

1. Introduction

From 1978 to 2023, China's urbanization rate increased from 17.92% to 66.16%. The rapid process of urbanization has seriously interfered with the normal structure and functioning of ecosystems, leading to a decline in ecological and environmental problems. This has an impact on the level of regional ecosystem services and sustainable development, even though it has effectively driven high economic growth. The National New Urbanization Plan (2014-2020), released in 2014 by the State Council and the Central Committee of the Communist Party of China (CPC), explicitly declared that China should set up a low-carbon, ecologically friendly, sustainable economic system and place the building of urbanization and the natural environment on an equal footing to encourage the coordinated and sustainable development of both (Lu *et al*., 2023).

Much research has been done on the interaction between urbanization and ecological services by academics both domestically and internationally. Empirical studies typically concentrate on the province or municipal level as their research units. In their analysis of the spatial differentiation characteristics of urbanization level and ecosystem service value, Yao Xiaowei et al. used the Wuhan city cluster as an example. Research content-wise, the degree of ecosystem services is primarily assessed using the Costanza assessment model (COSTANZA *et al*., 1997). In contrast, the degree of urbanization is primarily assessed using a single dimension, such as data on land use, data on nighttime light, and so forth. The coordination level and coupling relationship between urbanization and ecosystems have been depicted in previous studies using the coupled coordination degree model (Guo, 2019), the gray correlation model (Li, 2019), the responsiveness model (Zhang, 2022), and the interactive coercion model (Lv, 2017). Few studies have used the county area as the fundamental research unit. Furthermore, few studies have examined the coupled and coordinated relationship between the degree of urbanization and ecosystem services from a multi-dimensional perspective.

The majority of earlier research concentrated on examining the relationship between a single dimension of urbanization and ecosystem services or with a particular type of service function (Zhao et al., 2021).

Because of this, the Beijing-Tianjin-Hebei region is used as the research object in this paper, which also builds an index system for new urbanization evaluation and uses the InVEST model to evaluate ecosystem services. It also applies the coupling coordination degree model to analyze the temporal and spatial evolution characteristics of the level of ecosystem services of new urbanization in Beijing-Tianjin-Hebei based on county scales and investigates the coupling coordination relationship between them. To give a theoretical foundation for the ecological preservation and superior development of the Beijing-Tianjin-Hebei region, the paper also examines the coupling coordination relationship between the two as well as the driving mechanism.

2. Materials and methods

2.1. Overview of the Research Area

With 13 prefecture-level cities and 197 county units spread across Beijing, Tianjin, and Baoding, Tangshan, and Langfang in Hebei Province, the Beijing-Tianjin-Hebei region is the third largest urban agglomeration in China. It is situated between longitude 113°04'-119°53' East and latitude 36°01'-42°37' North, covering an area of 218,000 km². The Beijing-Tianjin-Hebei region is situated north of the North China Plain, whose terrain is mostly made up of plains and is high in the northwest and low in the southeast. The region experiences a temperate continental monsoon climate. The Beijing-Tianjin-Hebei region's total GDP is expected to reach 86462.93 billion yuan in 2020, which represents 8.5% of the nation's total GDP and the region's urban population is expected to reach 75,726,900,000, with an urbanization rate of 68.61%, indicating a relatively high level of urbanization.

The Beijing-Tianjin-Hebei region's healthy and ongoing development will, in large part, support China's ecologically and economically sustainable development. But the region's fast economic growth is running into more serious ecological issues like resource scarcity and environmental degradation. For this reason, it's crucial to look at how ecosystem services are interacting with new urbanization in the area.

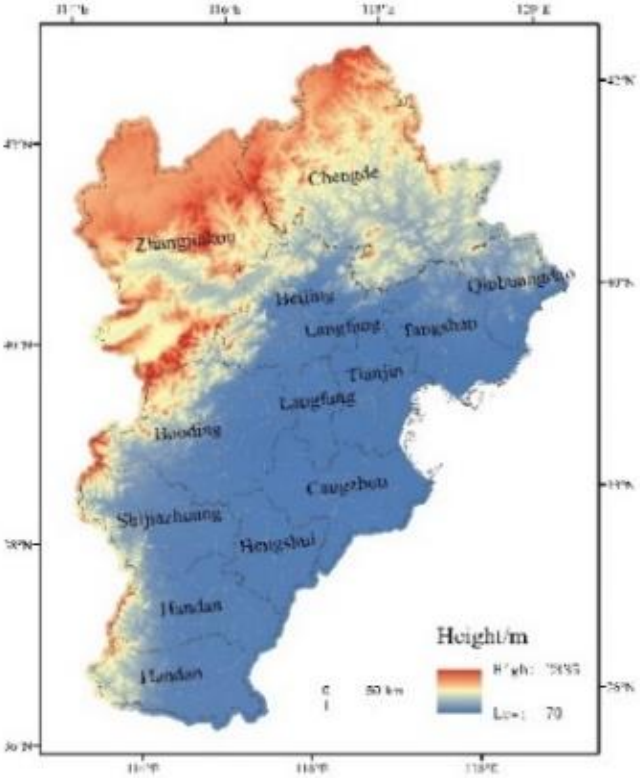

Figure 1. Location of the Research Area

2.2. Data sources

The data used in this study include socio-economic statistics about the environment, economy, and humanities as well as land use, meteorology, vegetation index (NDVI), digital elevation model (DEM), soil, and other spatial data in the Beijing-Tianjin-Hebei region. These are the sources of the data.

(1) The land use data, rainfall data, and evapotranspiration data are respectively from the National Qinghai Tibet Plateau Science Data Center (https://data.tpdc.ac.cn) "Landuse dataset in China (1980-2015)", "1-km monthly precipitation dataset for China (1901-2022)", and "1 km monthly potential evapotranspiration dataset in China (1901-2022)";

(2) Vegetation index data from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn) "Annual Spatial Distribution Data of Vegetation Index (NDVI) " in China, with a resolution of 1km;

(3) DEM data were obtained from the Resource and Environmental Science and Data Center of Chinese Academy of Sciences (https://www.resdc.cn) "National DEM 1km, 500m, and 250m Data" with a resolution of 250m;

(4) The depth data of the root restriction layer comes from DTB_China_1k.tif in the "Depth to bedrock map of China at a spatial resolution of 100 meters", and the effective water content data of plants comes from a spatiotemporal three-level environmental big data platform (http://poles.tpdc.ac.cn) "The Chinese Soil Dataset (v1.1) based on the World Soil Database (HWSD) (2009)";

(5) The socio-economic statistics on population, economy, and number of medical beds were obtained from the "Statistical Yearbook of China's Cities" "Statistical Yearbook of China's Counties" "Statistical Yearbook of China's Regional Economy" for the years 2005, 2010, 2015, and 2020, as well as from the statistical yearbooks of Beijing, Tianjin, and the 13 prefectural-level municipalities in Hebei Province;

(6) PM2.5 data were obtained from Atmospheric Composition Analysis Group (https://sites.wustl.edu/acag/datasets/surface-pm2-5/).

Some of the missing data were calculated by mean interpolation and nearest neighbor method, and the projected coordinate system of the raster and vector data involved in the study was unified by WGS 1984 Albers.

2.3. Research Methods

2.3.1. Valuation of ecosystem services.

Using the InVEST model, this study quantitatively calculates the amount of water produced, food produced, carbon stored, soil conservation, and habitat quality services provided in the Beijing-Tianjin-Hebei region.

For specific calculation methods, please refer to literatures "Spatio-temporal changes of the coupling relationship between urbanization and ecosystem services in the Middle Yellow River" and "Multi spatial scale dynamic response of ecosystem services to urbanization in the Beijing Tianjin Hebei region".

2.3.2. Measuring the level of new urbanization.

With many nuances, urbanization is a multifaceted historical development process and complicated socioeconomic phenomenon. The majority of top-down indicators are used in current research, however, with the adoption of the new urbanization strategy, there has been a lot of focus on the implications of people-oriented urbanization development. This paper builds a new type of urbanization indicators from "top-down" and "bottom-up" dimensions, including population urbanization, land urbanization, economic urbanization, human environment, humanistic environment, and social security, referring to the pertinent results and based on the full consideration of data availability and scientificity.

Table 1. New Urbanization Evaluation Index system

Dimension	Target Layer	Index Layer	Weight	Index Attribute
top-down	population urbanization	proportion of resident population (%)	0.053	positive
	land urbanization	proportion of urban construction land (%)	0.128	positive
	economic urbanization	GDP density (billions/km^2)	0.319	positive
bottom-up	human settlement	per capita disposable income of urban residents (Yuan)	0.178	positive
	cultural environment	PM2.5 contents ($\mu g/m^{-3}$)	0.091	negative
	social security	per capita number of medical beds (sheets)	0.231	positive

2.3.3. Research methods

2.3.3.1 Coupled coordination degree model. The interaction and effect of two or more systems is referred to as coupling. The degree of reciprocal restrictions and interdependence between systems is reflected in the degree of coupling coordination, which can indicate a good or poor coordination status (Chen et al., 2024). The coupling coordination degree model is used in the paper to investigate the relationship between new urbanization and ecosystem services in the Beijing-Tianjin-Hebei region. The calculation formula is as follows.

$$C = 2\sqrt{\frac{f(x)\times g(x)}{[f(x)+g(x)]^2}} \tag{1}$$

$$T = \alpha f(x) + \beta g(x) \tag{2}$$

$$D = \sqrt{C \times T} \tag{3}$$

In these formulas: C is the degree of coupling and $0 \le C \le 1$, the larger the value indicates that the coupling state between the systems is better, and vice versa, the worse the coupling state is; $f(x)$、$g(x)$ are the comprehensive evaluation values of new urbanization and ecosystem services respectively; T is the comprehensive evaluation index of the new urbanization subsystem and ecosystem services subsystem, α、β are the weight values of the two subsystems respectively, taking into account the fact that new urbanization and ecosystem services are of equal importance in the role of coupling coordination, so it is taken α=β=0.5; D is the degree of coupling coordination. Referring to related studies, the degree of coupling coordination is divided into six types: severe dysfunction (0.0~0.1), moderate dysfunction (0.1~0.2), mild dysfunction (0.2~0.3), basic coordination (0.3~0.4), moderate coordination (0.4~0.5) and good coordination (0.5~0.6).

3. Analysis of results

3.1. Spatial and Temporal Patterns of Ecosystem Services and New Urbanization in the Beijing-Tianjin-Hebei Region

3.1.1. Spatial and temporal patterns of ecosystem services

The value of ecosystem services in the Beijing-Tianjin-Hebei region had four trends between 2005 and 2020: an increase in food and water production, a decrease in carbon storage and habitat quality, an increase in the index, and a reduction and then an increase in soil retention.

In particular, the Beijing-Tianjin-Hebei region's ecosystem service value index rose from 0.0825 to 0.0834 between 2005 and 2020, representing an overall 1.12% increase. The county with the biggest

increase was the Jingfuzu Mining District in Shijiazhuang, Hebei Province, with a 66.14% increase. The high-value counties are concentrated in Chengde, Zhangjiakou, and Beijing Municipality in the northern part of the Beijing-Tianjin-Hebei region. In contrast, the low-value counties are primarily located in the North China Plain and the eastern hills in the southern part of the same region. The spatial distribution of the counties follows the trend of "high in the north and low in the south, high in the west and low in the east." The average carbon storage in the counties in the Beijing-Tianjin-Hebei region decreased from 139,638.47t to 138,166.24t, a decrease of 1.05%, and the county with the largest decrease was Yuhua District in Shijiazhuang, Hebei Province, which reached 28.57%. In terms of spatial distribution, counties and districts in the northern and western parts of Beijing-Tianjin-Hebei had higher carbon storage, and counties and districts in the North China Plain had lower carbon storage. The average habitat quality of counties in the Beijing-Tianjin-Hebei region decreased from 2611.62 to 2473.29, a decrease of 5.30%, and the county with the largest decrease was Lubei District in Tangshan, Hebei Province, reaching 59.52%. The spatial distribution shows the trend of “high in the north and low in the south”, and the two counties with the highest values are the Weichang Manchu-Mongolian Autonomous County and the Fengning Manchu Autonomous County in Chengde, Hebei Province. In contrast, the counties with the lowest values are mainly located in the middle of the North China Plain. The average grain output of counties in the Beijing-Tianjin-Hebei region increased from 108,717.10t to 155,071.57t, an increase of 42.64%, and the county with the largest increase was Hongqiao District in Tianjin, reaching 89.23%. The spatial distribution of high-value counties is mainly located in Chengde and Zhangjiakou in Hebei Province, and low-value counties are mainly located in the North China Plain and the eastern hills, and the grain production of counties and districts in the northern part of Beijing has decreased significantly during the study period. The average water production in the counties in the Beijing-Tianjin-Hebei region increased from 8377401.58 mm to 9301462.75 mm, with an increase of 11.03%, and the county with the largest increase was the Jingfuzu Mining District in Shijiazhuang, Hebei Province, with an increase of 237.93%. The spatial distribution shows the trend of "high in the north and south, low in the center", and the water yield in the northern and southern counties of Beijing-Tianjin-Hebei increased during the study period. The average soil retention in the counties in the Beijing-Tianjin-Hebei region increased from 100786.07 t to 100795.40 t, with an increase of 0.01%, and the county with the largest increase was Xushui District in Baoding, Hebei Province, with an increase of 2.27%. The spatial distribution of soil retention was highest in the northern counties of Beijing-Tianjin-Hebei, higher in the western counties, and lower in the North China Plain and eastern counties.

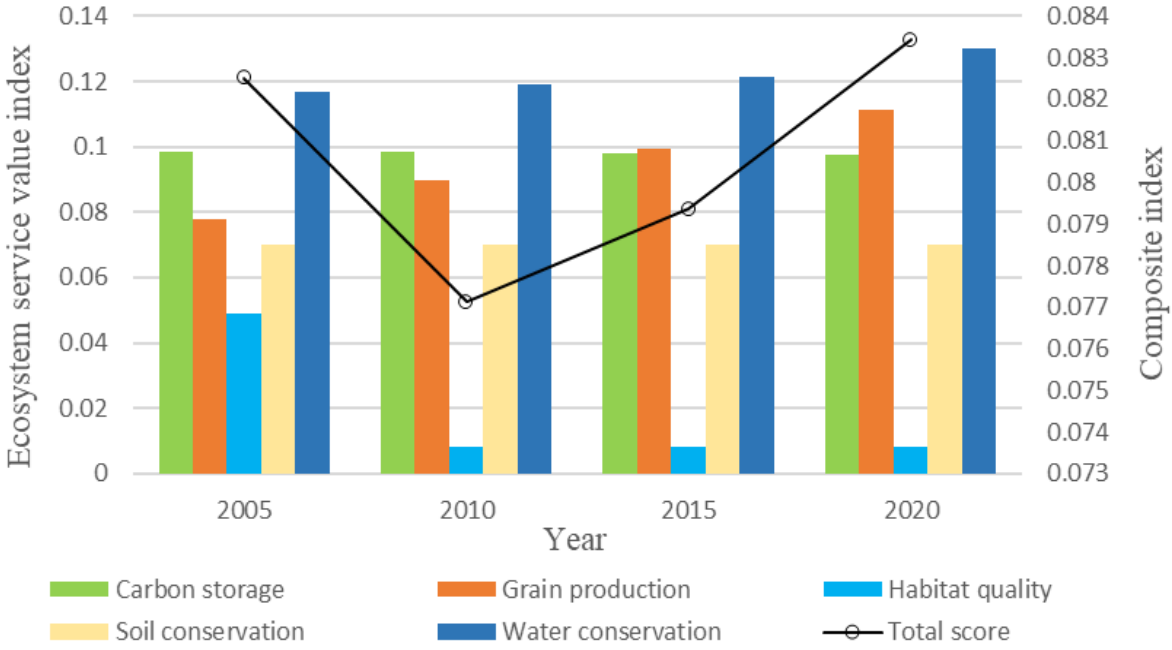

Figure 2. Time-series Changes of County-range Ecosystem Service Value Index in the Beijing-Tianjin-Hebei Region from 2000 to 2020

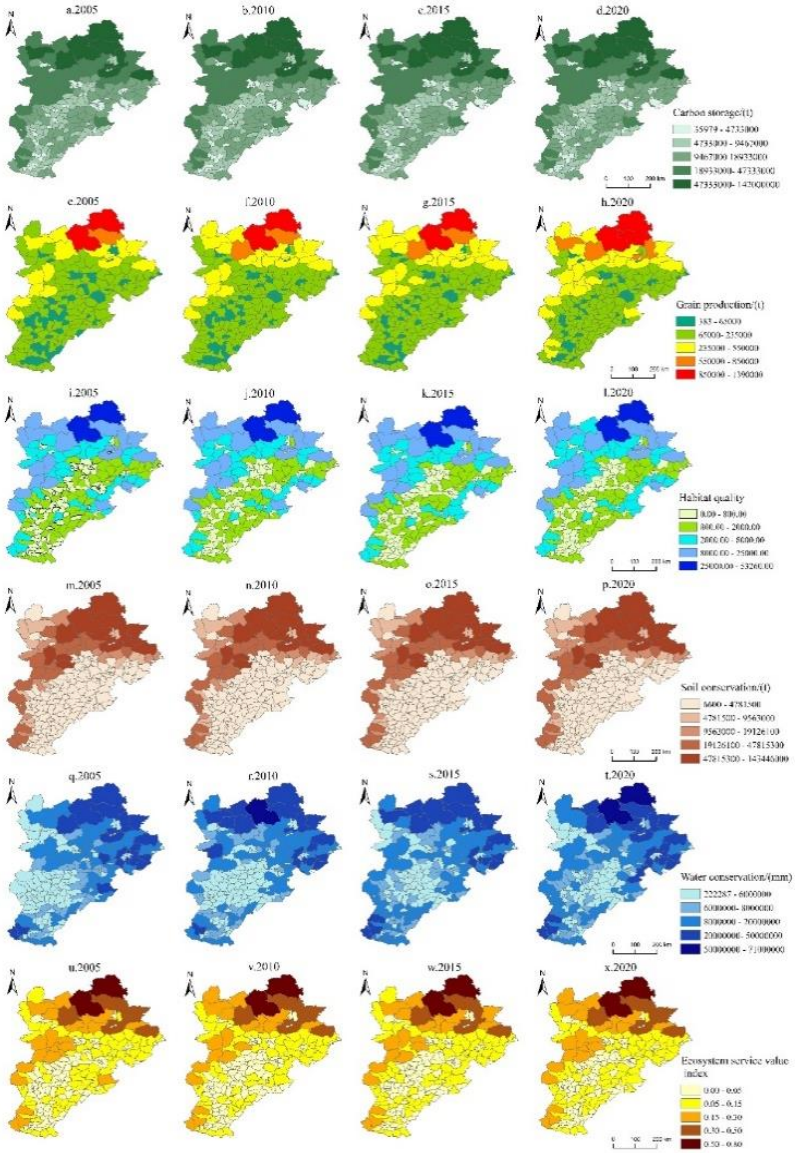

Figure 3. Spatial Distribution of Ecosystem Services in the Beijing-Tianjin-Hebei Region in 2000, 2005, 2010 and 2020

3.1.2. Spatial and temporal patterns of new urbanization

From 2005 to 2020, the level of new urbanization in the Beijing-Tianjin-Hebei region showed a significant growth trend, with the index increasing from 0.0986 to 0.1622, an increase of 64.53%, and the county with the largest increase is Hanshan District in Handan, Hebei Province, reaching 307.06%. The spatial distribution of counties and districts before 2010 showed a trend of "high in the north and low in the south", and after 2010 showed a trend of "high in the north and south, low in the middle". During the study period, the urbanization level of counties and districts in the northeast and southwest of Beijing, Tianjin, and Hebei increased significantly, while the urbanization level of counties and districts in the middle of North China Plain was relatively low.

With the index rising from 0.0361 to 0.0582, an increase of 61.17%, the top-down urbanization level in the Beijing-Tianjin-Hebei region specifically shows a trend of decreasing and then increasing between 2005 and 2020. Guyuan County in Zhangjiakou, Hebei Province, has the largest increase, reaching 247.82%. Top-down urbanization is more prevalent in Beijing and Tianjin's county and district spatial distribution, and the region's total top-down urbanization level rose noticeably over the study period in Beijing, Tianjin, and Hebei.

The index increased from 0.0625 to 0.1650, a 164.05% increase, indicating a considerable growth trend in the bottom-up urbanization level in the Beijing-Tianjin-Hebei region. Bono County in

Baoding, Hebei Province, had the biggest gain, reaching 578.96%. In the Beijing-Tianjin-Hebei region, the overall level of bottom-up urbanization has increased significantly during the study period. The spatial distribution of counties and districts in the North China Plain has a lower level of bottom-up urbanization, while the remaining counties and districts have a higher level.

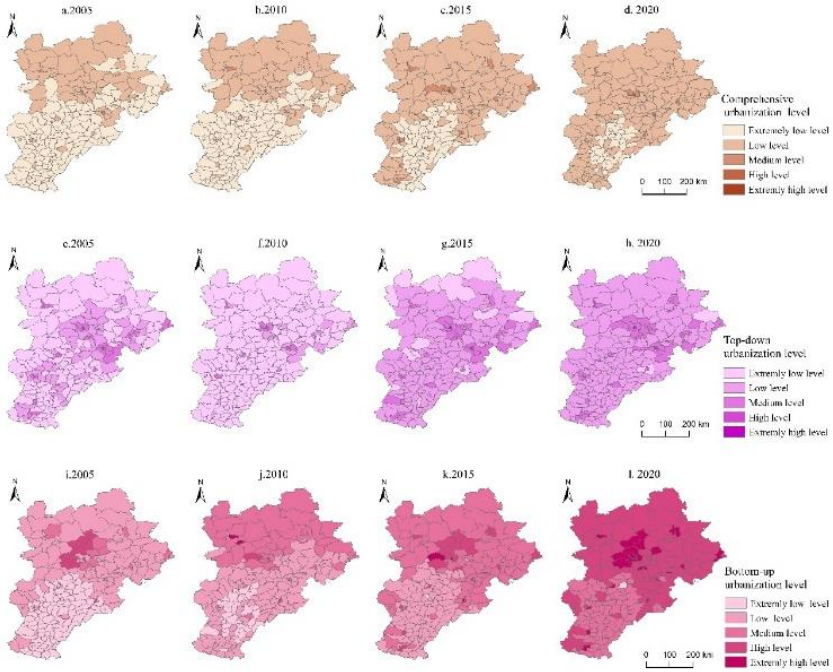

Figure 4. Spatial Distribution of New Urbanization Levels in the Beijing-Tianjin-Hebei Region in 2000, 2005, 2010 and 2020

3.2. Characteristics of Coupled Coordination of Ecosystem Services and New Urbanization

Referring to relevant research, the coupling coordination degree of the study area is divided into six stages: severe imbalance (coupling coordination degree of 0-0.1), moderate imbalance (coupling coordination degree of 0.1-0.2), mild imbalance (coupling coordination degree of 0.2-0.3), basic coordination (coupling coordination degree of 0.3-0.4), moderate coordination (coupling coordination degree of 0.4-0.5), and good coordination (coupling coordination degree of 0.5-0.6).

While it has been in a state of light dysfunction during the study period, overall coupling coordination tends to improve. The average value of the coupling coordination degree of ecosystem services and new urbanization in the Beijing-Tianjin-Hebei region between 2005 and 2020 showed a steady upward trend year by year, from 0.2556 in 2005 to 0.2999 in 2020, an increase of 17.36%.

The only county experiencing serious dislocation during the study period is Heping District in Tianjin, which accounts for 0.51%. Its coupling degree of coordination increased from 0.0438 in 2005 to 0.0936 in 2020. In contrast, the number of counties and districts experiencing moderate dislocation declines more slowly, from 49 in 2005 to 10 in 2020, or 24.87% to 5.08%. With the proportion rising from 48.73% and 18.78% to 56.85% and 25.38%, respectively, the number of counties and districts that are essentially harmonized and slightly dysfunctional grows over time, from 96 and 37 in 2005 to 112 and 50 in 2020. From 12 in 2005 to 20 in 2020, the percentage of counties with moderate coordination fell and then rose, from 6.09% to 10.15%. In Chengde, Hebei Province, there were only two well-coordinated counties and districts in 2005 (1.02%); these were Fengning Manchu Autonomous County and Weichang Manchu Mongolian Autonomous County. By 2020, there were four such counties and districts (1.52%), including Longhua County in Chengde, Hebei Province, and Chicheng County in Zhangjiakou.

The spatial distribution of the degree of coupling coordination in the Beijing-Tianjin-Hebei region between 2005 and 2020 demonstrates the characteristics of "high in the north and low in the south", with the seriously dysfunctional counties primarily found in the central region of the North China

plains, and the well-coordinated counties located in Chengde and Zhangjiakou in the northern part of Beijing-Tianjin-Hebei. The remaining counties in the northern part of Beijing-Tianjin-Hebei belong to the moderate coordination and basic coordination groups. The majority of the counties in Beijing-Tianjin-Hebei's southern region fall under the category of moderate dissonance.

Table 2. The Number and Percentage of Counties in the Beijing-Tianjin-Hebei Region Under Different Levels of Coupling Coordination from 2005 to 2020

	2005	2010	2015	2020
Severe imbalance	1 (0.51%)	1 (0.51%)	1 (0.51%)	1 (0.51%)
Moderate imbalance	49 (24.87%)	43 (21.83%)	23 (11.68%)	10 (5.08%)
Mild imbalance	96 (48.73%)	99 (50.25%)	103 (52.28%)	112 (56.85%)
Basic coordination	37 (18.78%)	41 (20.81%)	46 (23.35%)	50 (25.38%)
Moderate coordination	12 (6.09%)	11 (5.58%)	20 (10.15%)	20 (10.15%)
Good coordination	2 (1.02%)	2 (1.02%)	4 (1.52%)	4 (1.52%)

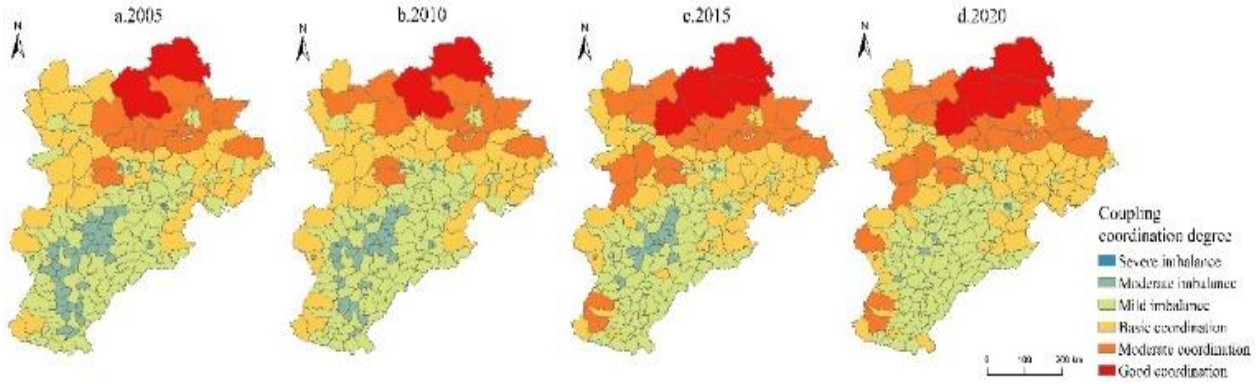

Figure 5. Spatial-temporal Distribution of Coupling Coordination Degree of Ecosystem Services and New Urbanization in the Beijing-Tianjin-Hebei Region in 2000, 2005, 2010 and 2020

4. Conclusion

4.1. Conclusions

1) From 2005 to 2020, the value index of ecosystem services in the Beijing-Tianjin-Hebei region fluctuated upward. It first declined and then grew. Among these, the quality of the habitat and the storage of carbon dioxide declined while the production of food, water, and soil improved. The rest of the sub-ecosystem services and comprehensive service levels exhibit a spatial distribution pattern of "high in the north and low in the south, high in the west and low in the east," except the water production service level, which displays a distribution pattern of "high in the north and south and low in the center."

2) The overall new urbanization index has increased greatly, however, the development degree of new urbanization varies significantly among the counties in the Beijing-Tianjin-Hebei region between 2005 and 2020. Among them, the degree of bottom-up urbanization keeps rising whereas the amount of top-down urbanization first declines before increasing. The degree of new urbanization has shifted from being "high in the north and low in the south" to being" high in the north and south and low in the middle" in terms of spatial distribution.

3) In the Beijing-Tianjin-Hebei region, the degree of coupling and coordination between ecosystem services and new urbanization has grown annually between 2005 and 2020. Although it has been in a state of mild dysfunction, the degree of coupling and coordination has improved. The counties in the Beijing, Tianjin, and Hebei regions displayed an inverted "U" distribution of coupling coordination degree, with the majority of them being mildly dysfunctional, the majority of seriously dysfunctional counties being limited to Tianjin's Heping District, the number of moderately dysfunctional counties gradually declining, and the number of other counties increasing. From the spatial distribution point of view, the coupling coordination degree is a "high in the north and low in the south" distribution trend, the counties and districts north of the North China Plain are mainly in the basic coordination and above stage, and the counties and districts in the North China Plain are mainly in the mildly dysfunctional and below stage.

4.2. Discussions

1) Quickening urbanization's transition to a greener environment. Cities must modernize their approaches to development, and make sure that the pace of urbanization is in line with the ability of local ecosystems to support human populations. Promoting the conversion of high-pollution, high-emission, and high-energy-consumption industries to environmentally friendly ones, optimizing and upgrading the industrial structure, and lessening the adverse effects of new urbanization on the natural environment should be the main goals of urbanization promotion. Utilize the benefits of new urbanization in terms of attracting talent and enhancing economic efficiency.

2) Formulate regional development strategies according to local conditions. In Zhangjiakou, Chengde and Qinhuangdao, where the level of ecological services is relatively high, green industries such as eco-tourism should be actively developed to promote the sustained and healthy development of the local economy; as for Beijing and Tianjin, where the level of urbanization is relatively high, they should pay attention to and improve the ecological environmental shortcomings. Other regions should abandon the old thinking of "pollute first and treat later", and regularly evaluate the development of new urbanization and the ecological environment to promote the sustainable development and ecological civilization of the whole Beijing-Tianjin-Hebei region.

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