

Multi-scale coupling analysis of urbanization and ecosystem services supply-demand budget in the Beijing-Tianjin-Hebei region, China

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Abstract: Rapid economic development and human activities have severely affected ecosystem function. Analysis of the spatial distribution of areas of rapid urbanization is the basis for optimizing urban-ecological spatial design. This paper evaluated the spatial distribution of urbanization in the Beijing-Tianjin-Hebei (BTH) region, and then quantified the ecosystem services (ES) budget in the region based on an ES supply and demand matrix. The results showed that (1) urbanization patterns in the BTH region were relatively stable from 2000 to 2015, with clear patterns of low levels of urbanization in the northwest and high levels in the southeast; (2) areas with positive ES budget values were found throughout the region, except in built-up areas, with high ES supply areas concentrated in the northwest, and high ES demand areas in the southeast; (3) at both the county and prefecture-city levels, urbanization had negative, positive, and negative correlations with ES supply, demand, and budget, respectively; (4) the coupling coordination degree (CCD) increased, with high CCD values in the southeast. Based on these results, policy recommendations include strengthening rational land-use planning and ecosystem management, promoting the coordinated development of the economy and ecological function, and coordinating the provision of production-life- ecological functions.

Keywords: urbanization; ecosystem services; supply-demand; coupling; Beijing-Tianjin-Hebei region

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1 Introduction

Ecosystem services (ES) are the products and services that humans can directly or indirectly obtain from ecosystem structure, function, and processes (Costanza *et al.*, 1997). The Millennium Ecosystem Assessment (MEA, 2005) states that ES include supporting, regulating, provisioning, and cultural services, and reports that more than half of ecosystems have experienced degradation as a result of human activities. Since the beginning of the 21st century, more than half of the world's population has been living in urban areas, and the process of global urbanization is accelerating (Chen *et al.*, 2019; Wang *et al.*, 2020). Urbanization promotes the rapid development of society, economy, and culture, but also leads to environmental problems, such as a shortage of cultivable land and destruction of ecosystem function. Such changes can lead to challenges in resource utilization and environmental protection (Liu *et al.*, 2017; Liu *et al.*, 2020; Wiederkehr *et al.*, 2020). In China, land use is constantly being converted by construction, and ecosystem imbalance occurs frequently (Peng *et al.*, 2020). In this context, assessment of ES in relation to urbanization is an effective tool to support decision-making processes for sustainable land use. This approach has important practical significance for coordinating regional sustainable development, optimizing land-use planning, and ensuring ecological security.

With the rapid progression of urbanization and economization, landscapes have undergone significant changes. Consequently, there is an urgent need to analyze the effects of urbanization on ES (Wu *et al.*, 2019). Previous studies have used statistical indicators (Schrandt *et al.*, 2021) and spatial econometric models (Wang *et al.*, 2021) to explore the relationships between urbanization and ES and diverse relationships have been found, including negative (Aguilera *et al.*, 2020), positive (Deng *et al.*, 2021), and non-linear correlations (Peng *et al.*, 2017). In addition, the degree of spatial coupling between urbanization and ES is generally low (Zhou *et al.*, 2017; Cui *et al.*, 2019). Most researchers have analyzed these relationships using only a single dimension of urbanization. Few studies have attempted to comprehensively examine the coupling and coordination of relationships between urbanization and ES from multiple dimensions.

From the perspectives of production and consumption, ES can be divided into two aspects: supply and demand (Uthes and Matzdorf, 2016). Specifically, ES supply refers to the ability of ecosystems to provide products and services for humans; ES demand refers to the sum of ecosystem products and services used by humans. Previous studies have mainly focused on changes in ES supply in relation to urbanization (Galcía-Nieto *et al.*, 2018), and there is little discussion of the relationships between urbanization and ES demand. An exploration of the overall effects of urbanization on ES is needed.

The ES supply-demand budget reflects the balance between natural and human socio-economic systems (Peng *et al.*, 2022). In recent years, research on ES supply-demand budgets has emerged. Uthes and Matzdorf (2016) measured ES supply and demand using questionnaires and an optimization method to explore the government budget allocation in rural Germany. Bukvareva *et al.* (2017) established a comprehensive index to evaluate the ES of air and water purification in Russia, which shows the practicability of this method in estimating inter-regional ES budgets. Ala-Hulkko *et al.* (2019) used spatial accessibility analysis to measure crop supply and demand in the European Union, considering cultivated land types and population density. Burkhard *et al.* (2012) developed an ES matrix model to

calculate ES supply, demand, and overall budget, based on the potential impact of land use/cover change (LUCC) on ES and an expert scoring method. The ES matrix model has been widely used in studies of ES supply-demand budgets. Tao *et al.* (2018), Guan *et al.* (2020), and Sun *et al.* (2020) have verified that the method can quickly and effectively evaluate ES supply and demand under LUCC and encourage spatial visualization. While there is a wealth of research on ES supply-demand budgets, few studies have addressed the long-term dynamics of ES budgets in a comprehensive way (Pang *et al.*, 2017). There is an urgent need to use long-term time series data to explore ES in different areas.

The Beijing-Tianjin-Hebei (BTH) region is the capital economic center of China, as well as an important ecological barrier of the North China Plain. As a result of grassland ecosystem degradation and desertification, ecosystem services and the ecological carrying capacity of the BTH region are low (Zhou *et al.*, 2021). With rapid urbanization, the BTH region has become one of the areas in China with the greatest pressure on natural resources and the environment (Chu *et al.*, 2017; Wang *et al.*, 2021). Ecological protection and restoration have become core issues in the coordinated development of the BTH region (Zhao *et al.*, 2018). It is urgent, therefore, to understand the influence of urbanization on ES and formulate a reasonable urbanization development strategy.

To address this need of the BTH region and meet the research gap of coordinated analysis between urbanization and ES, we evaluated the ES supply, demand, and supply-demand budget using an ES matrix model. The spatio-temporal evolution of urbanization and ES in the BTH region from 2000 to 2015 were analyzed. A coupling coordination degree (CCD) model was used to analyze the relationships between urbanization and ES. The results can provide a reference for decision-makers in terms of ecological protection and sustainable development in BTH and other similar areas.

2 Methods and materials

2.1 Study area

The BTH region is located in the northern part of the North China Plain (36°05'N–42°40'N, 113°27'E–119°50'E) (Figure 1). The provincial administrative units include Beijing, Tianjin, and Hebei. The area is about $21.8 \times 10^4 \text{ km}^2$, accounting for 2.3% of China's land area. At the end of 2019, the population was 113 million, and the regional GDP was 8.46×10^{16} yuan, accounting for 8.80% and 8.58% of national totals, respectively. There is significant spatial variation in the topography of the BTH region; the northwestern part has high elevation, while the southeastern part is low. The region includes a variety of geomorphic types. Grasslands, basins, and mountains are common in the north and northwest. The eastern region is dominated by mountains and hills. Due to its proximity to the Bohai Bay, the western region is dominated by wetlands and the central and southern regions are dominated by plains. The area has a warm temperate continental monsoon climate and the period from mid-April to late September is a major rainy season.

2.2 Methods

This study conducts the study according to the framework as shown in Figure 2. Firstly, we prepared the data including land use/cover data, social-economic data and night lighting data.

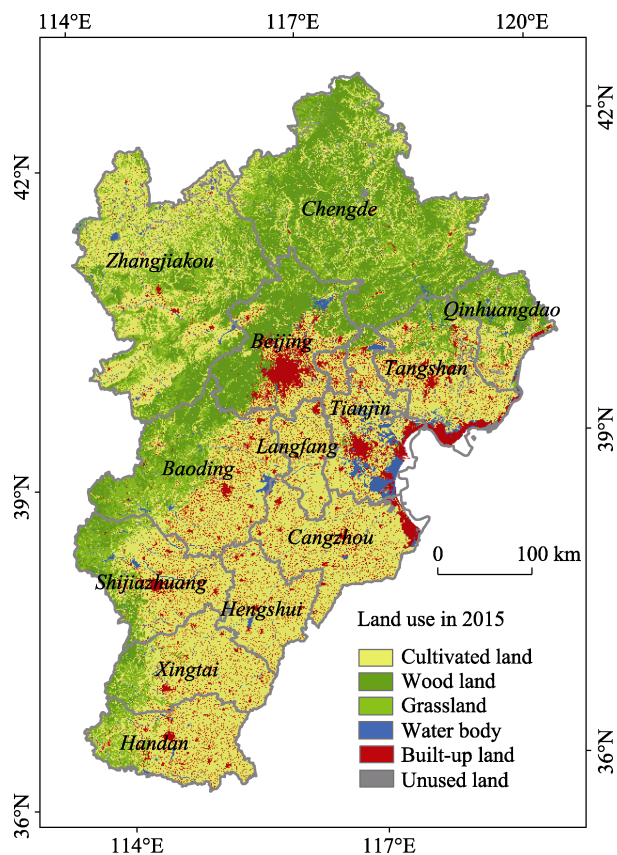


Figure 1 Geographical location and land use of the Beijing-Tianjin-Hebei region

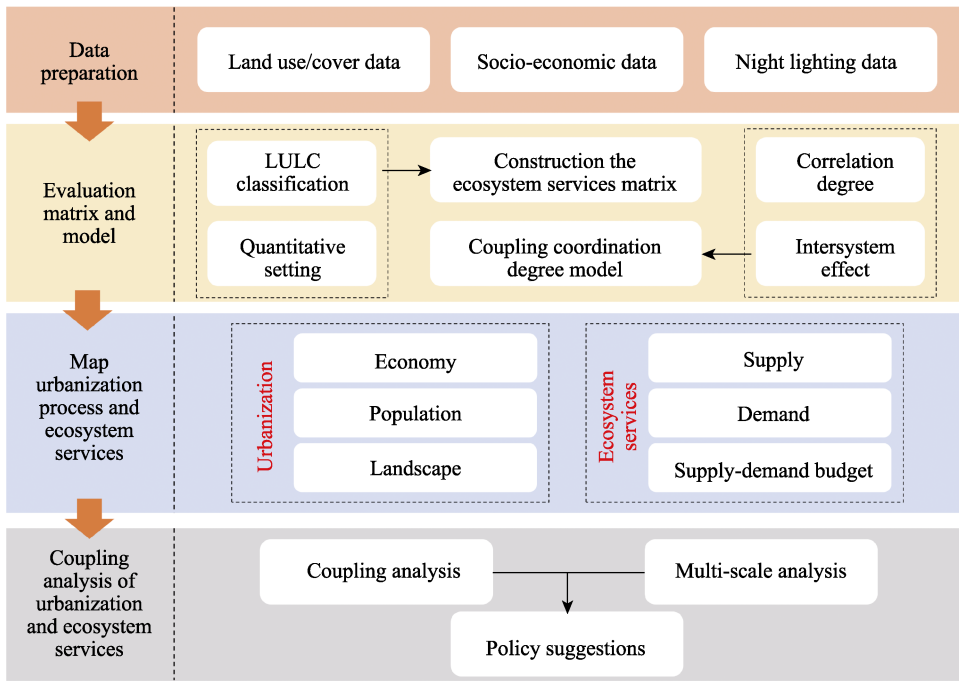


Figure 2 The overall framework of this study

Secondly, we analyzed the ecosystem services matrix and coupling degree model. Then, we mapped the urbanization process and ecosystem services. Finally, we carried out the multi-scale coupling analysis of urbanization and ecosystem services in the BTH region.

2.2.1 Urbanization indices

Urbanization is multi-dimensional and includes a series of complex evolutionary processes, such as population migration, urban land expansion, industrial structure adjustment, capital agglomeration, and a change in consumption habits (Inostroza and Zepp, 2021). Typically, single-dimension indices such as LUCC (Zhou and Chen, 2018), population urbanization rate (Yuan *et al.*, 2018), or nighttime lighting data (Wang *et al.*, 2020) are used to measure the level of urbanization. However, these metrics do not provide an overarching picture of the characteristics and level of urbanization.

Referring to the existing research (Dadashpoor *et al.*, 2019; Bian *et al.*, 2021), this study comprehensively characterized urbanization using three dimensions. First, economic urbanization refers to the flow of capital and technology from rural areas to cities. This study uses regional GDP to represent economic urbanization. Second, population urbanization is the process of regional human capital accumulation and this paper used population density to characterize population urbanization. Third, landscape urbanization refers to the gradual expansion of urban land to cover the regional space. The digital number (DN) for nighttime light intensity was used to reflect regional patterns of landscape urbanization (Dakhliya *et al.*, 2021).

2.2.2 Ecosystem service supply-demand budget

This paper established ES bundles suitable for the BTH region. Specifically, the ES bundles included nine regulating services (local climate regulation, global climate regulation, flood protection, groundwater recharge, air quality regulation, erosion regulation, nutrient regulation, water purification, and pollination), eleven provisioning services (crops, livestock, fodder, capture fisheries, aquaculture, wild foods, timber, wood fuel, energy (biomass), biochemicals/medicine, and freshwater) and two cultural services (recreational and aesthetic values, intrinsic value of biodiversity) (Peng *et al.*, 2020). Based on the above, ecosystem service types and six land use/cover types were combined in ES supply, demand, and budget matrix tables (Figure 3). Each matrix table comprised 132 subunits and 18 summative units. The initial values of the ES supply and demand matrix elements were determined with reference to the research of Burkhard *et al.* (2012). Furthermore, referring to the research of Costanza *et al.* (2014), Xie *et al.* (2008), and Zhan *et al.* (2019), this paper compiled the ES supply and demand matrix tables for the BTH region. The values for each subunit ranged from 0 to 5; the higher the value, the higher the supply or demand level of the corresponding LUCC type per unit area. The ES budget matrix was calculated as ES supply minus ES demand, and its values reflect the surplus, deficit, or balance of supply and demand.

For region i , the level of ES supply of type j was calculated using the following formula:

$$\text{ES supply}^{ij} = \sum_{m=1}^6 K_m^i V_{mj}$$

where ES supply ^{ij} is the supply level of ES type j in region i ; K_m^i is the area ratio of specific land use/cover types in region i ; and V_{mj} is the corresponding element value in the

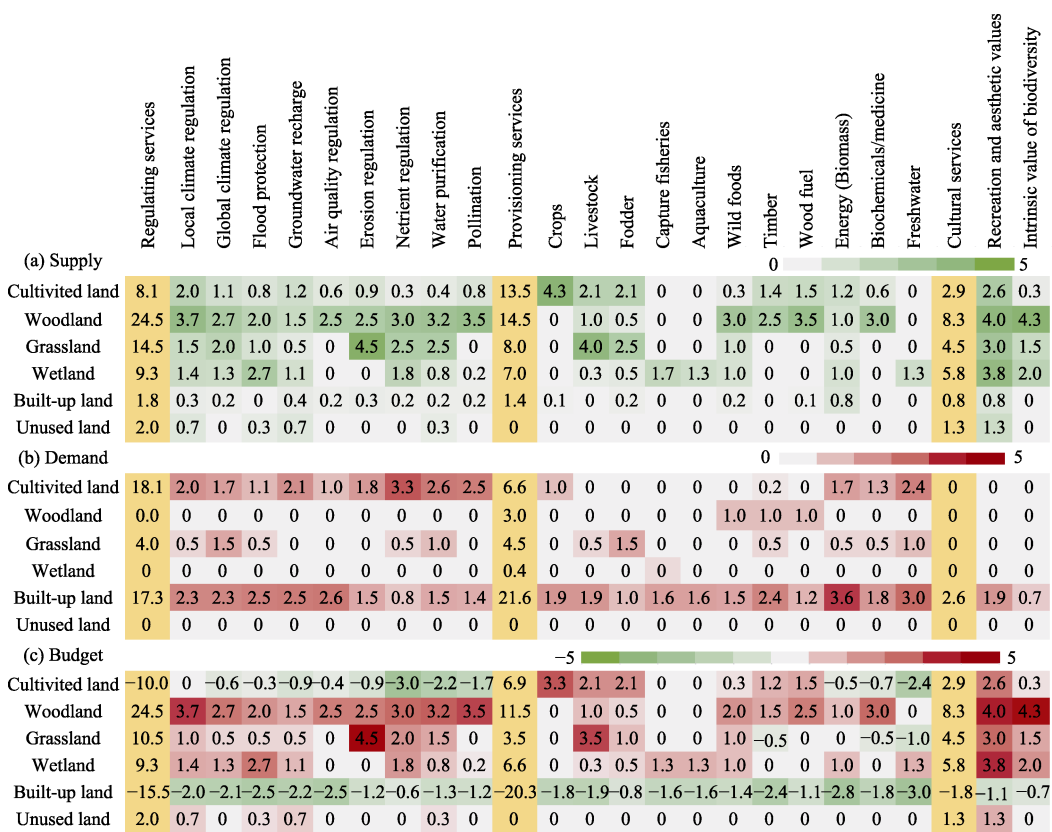


Figure 3 Matrix of ecosystem service demand (a), supply (b), and budget (c) for different land cover types

ES supply matrix table. This method is also applicable to the calculation of ES demand level. The research goal was to explore the overall state of ES in the BTH region. Therefore, for ES supply, demand, and supply-demand budget, this study only show the summative results for regulating services, provisioning services, and cultural services.

2.2.3 Coupling analysis

CCD can be used to describe the correlation between two or more systems (Shi *et al.*, 2020). This paper used the following equations to calculate the CCD between urbanization level and ecosystem service budget (Gan *et al.*, 2020; Liu *et al.*, 2021).

$$CCD = (C \times T)^{\frac{1}{2}}$$
$$C = \left[\frac{UL \times ESB}{\left(\frac{UL + ESB}{2} \right)^2} \right]^{\frac{1}{2}}$$
$$T = \alpha \times UL + \beta \times ESB$$

where *CCD* is the coupling coordination degree between urbanization level and ecosystem service budget, with a range from 0 to 1; *C* is the coupling degree; *T* is the comprehensive evaluation index, which presents the overall effect and level; and α and β are the proportion-al contributions to the system ($\alpha + \beta = 1$).

2.3 Data sources and materials

The basic data used included land use/cover, socio-economic, and nighttime light data. Land use/cover data for 2000, 2005, 2010, and 2015 were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (<http://www.resdc.cn>). This data set is generated by artificial visual interpretation, and the spatial resolution is 1 km. The socio-economic data were divided into two parts: population density and GDP density, both of which were obtained from the Environmental Science Data Center of the Chinese Academy of Sciences. The gridded population data were generated using a multi-factor weight distribution method to overlay the population data on a spatial grid, with administrative region as the basic statistical unit, which shows the spatial properties of the population. Similar to the population data, the gridded GDP data considered the influence of many factors, including residential density, nighttime light brightness, and land-use type. The widely used nighttime light intensity image data were obtained from the National Centers for Environmental Information (<https://www.ngdc.noaa.gov/ngdc.html>), including DMSP/OLS and NPP/VIIR data (Gerace and Montanaro, 2017). This paper used DMSP/OLS data for 2000, 2005, 2010, and 2013 and performed spatial correction (Ali *et al.*, 2019).

3 Results and analysis

3.1 Urbanization process

The development of multi-dimensional urbanization in the BTH region from 2000 to 2015 is shown in Figure 4. There were no significant changes in the pattern of population urbanization in the region from 2000 to 2015, especially from 2000 to 2010. The areas of highest urbanization were mainly located in the center of the BTH region, and areas with low urbanization were distributed in the northwest. Population urbanization has a causal relationship with development of the regional economy and landscape change. The results support this theory and the spatial distribution of the regional economic and landscape indices was generally similar to that of the population index. In addition, the high value areas for economic and landscape development clearly reflect the agglomeration effects of urbanization. Beijing, Tianjin, Shijiazhuang, and other urbanized regions has higher urbanization levels from all the population, GDP and landscape perspectives. GDP increased evidently from 2000 to 2015, with Beijing and Tianjin dominated in this area. Urbanization process accelerated, especially in southwest China.

3.2 Ecosystem services supply-demand budget

Based on the LUCC data and the ecosystem service matrix, this paper quantified and mapped the supply, demand, and budget of the three ES categories (regulating, provisioning, and cultural services). Figure 5 shows the quantitative maps for 2015, representing the distribution of ES supply, demand, and supply-demand budget. There was considerable spatial variation in ES in the BTH region. In terms of the total ES supply, high ES supply areas were concentrated in the northwest, including northwest Hebei. Low ES supply areas were located in the southeast, including Beijing, Tianjin, and southeast Hebei. The three categories of ES showed similar spatial patterns. Regulation services and provision services have

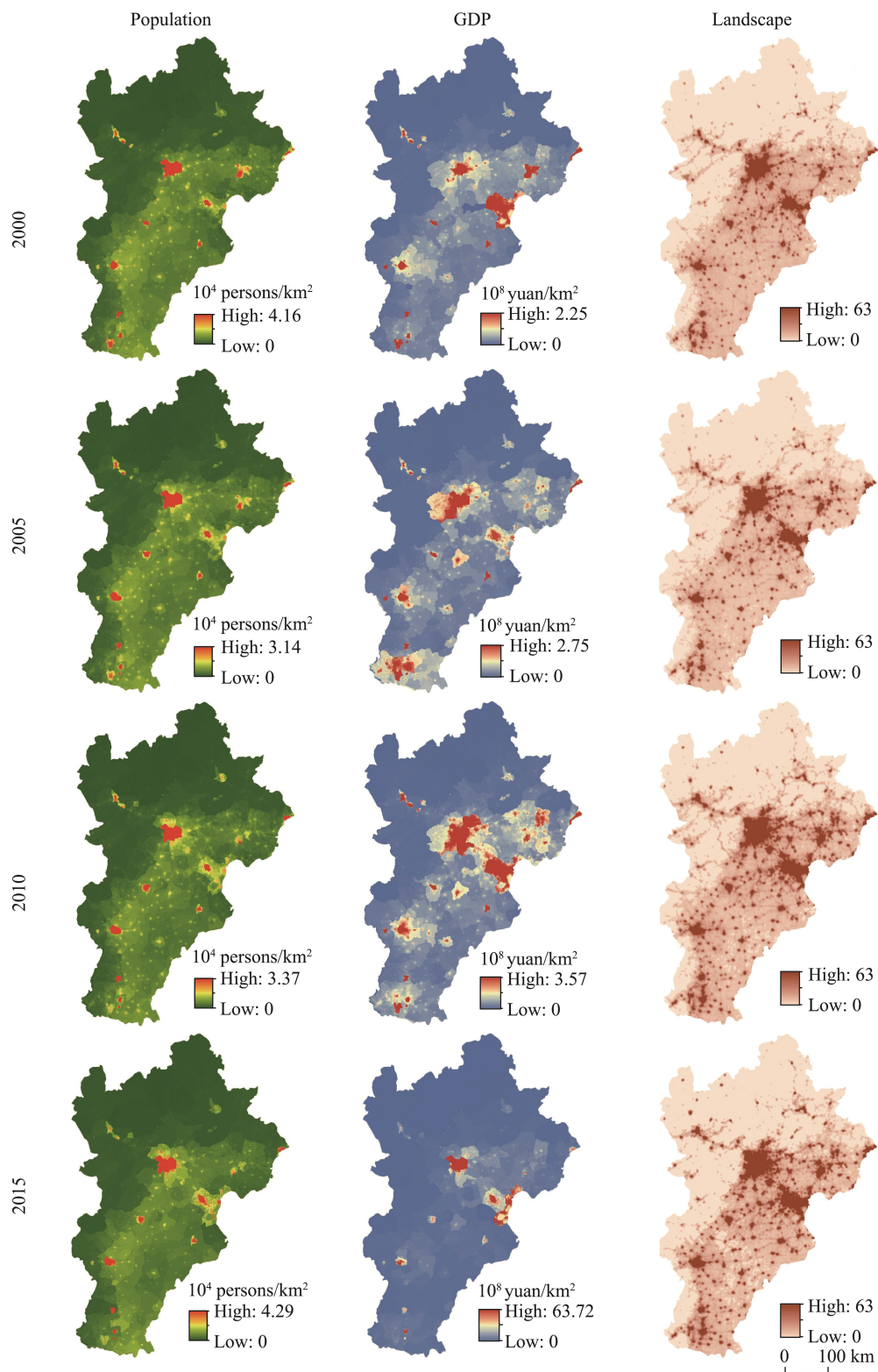


Figure 4 Temporal and spatial variation in urbanization indices in the Beijing-Tianjin-Hebei region from 2000 to 2015

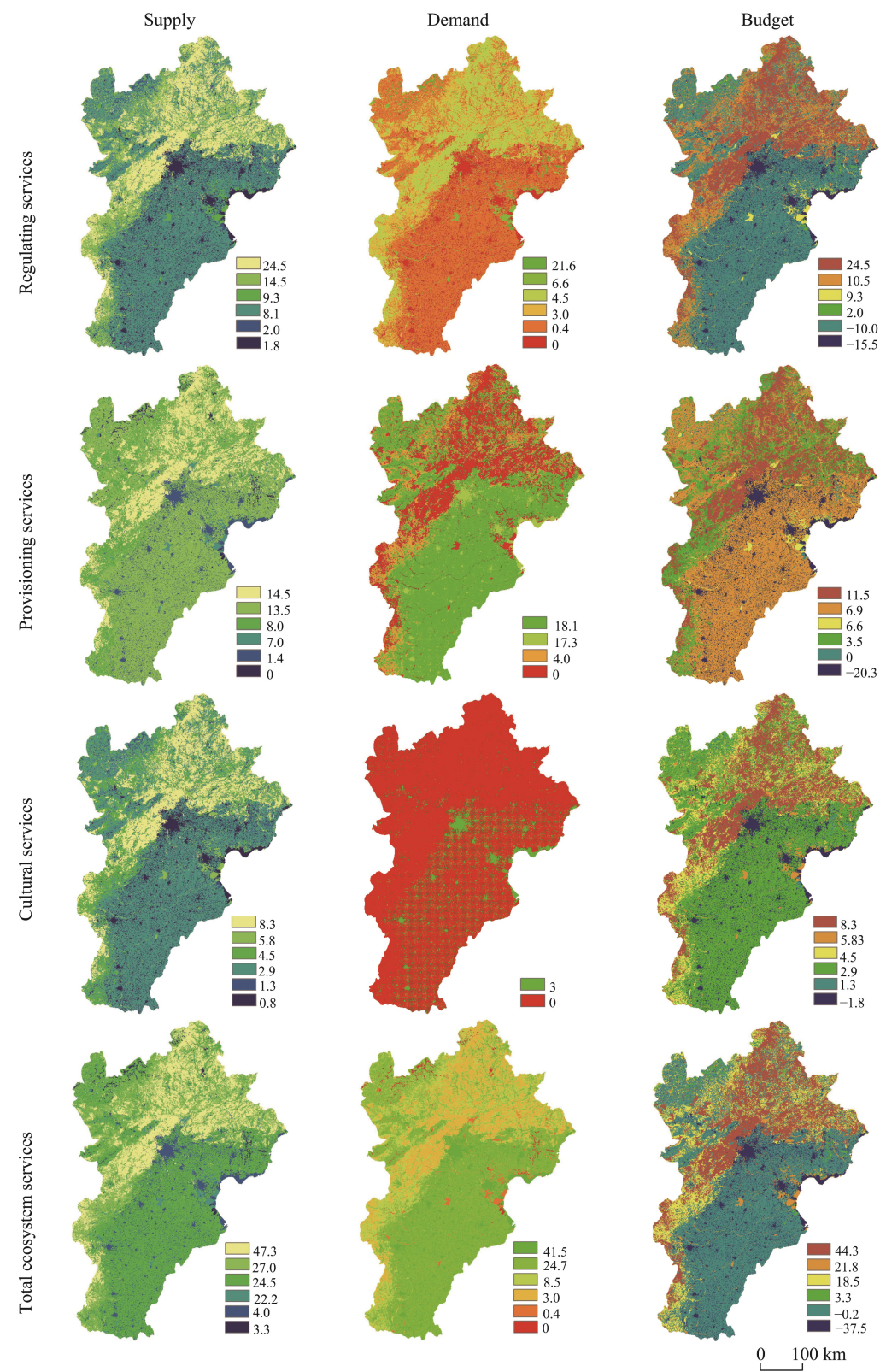


Figure 5 Spatial variation in ES supply, demand, and budget in the Beijing-Tianjin-Hebei region in 2015

relative high values on the whole. Wood land can provide more ES owing to the rich biodiversity and ecosystem structure. Rapidly urbanized areas had the lowest ES supply levels. ES demand had the opposite spatial distribution to that of ES supply. Densely populated areas have higher demand for ES. Areas in the southeast with dense populations and rapid economic development had greater ES demand. Areas in the northwest with the most grassland and woodland had lower ES demand. As for the ES budget, positive ES budget values were distributed throughout the BTH region, but with lower representation in built-up areas and cultivated land. ES budget is positive in the northwest of the BTH region, while negative in the southeast region. Moreover, the three categories of ES supply, demand, and budget showed similar spatial patterns.

3.3 Coupling analysis of urbanization and ecosystem services supply-demand budget

This study used GDP density, population density, and landscape type as the three main indicators of urbanization. Figure 6 shown the relationships at the county scale. There were negative relationships between ES supply and urbanization, and between ES budget and urbanization. The strongest relationships, based on the coefficients, were between population density and ES supply, demand, and budget. Population density has the most evident relationships with and ES supply ($\beta=-1.048$) and ES budget ($\beta=-1.095$). There was a positive relationship between urbanization and ES demand, with the greatest coefficient of 1.143 of population density. Similar relationships existed at the prefecture-city scale (Figure 7). There were evident negative relationships between urbanization and ES supply and budget, while positive relationships between urbanization and ES demand, at prefecture-city scale. However, landscape index has the strongest relationships with ES supply, demand and budget, with the coefficients of -0.539 , 0.528 , and -0.546 , respectively.

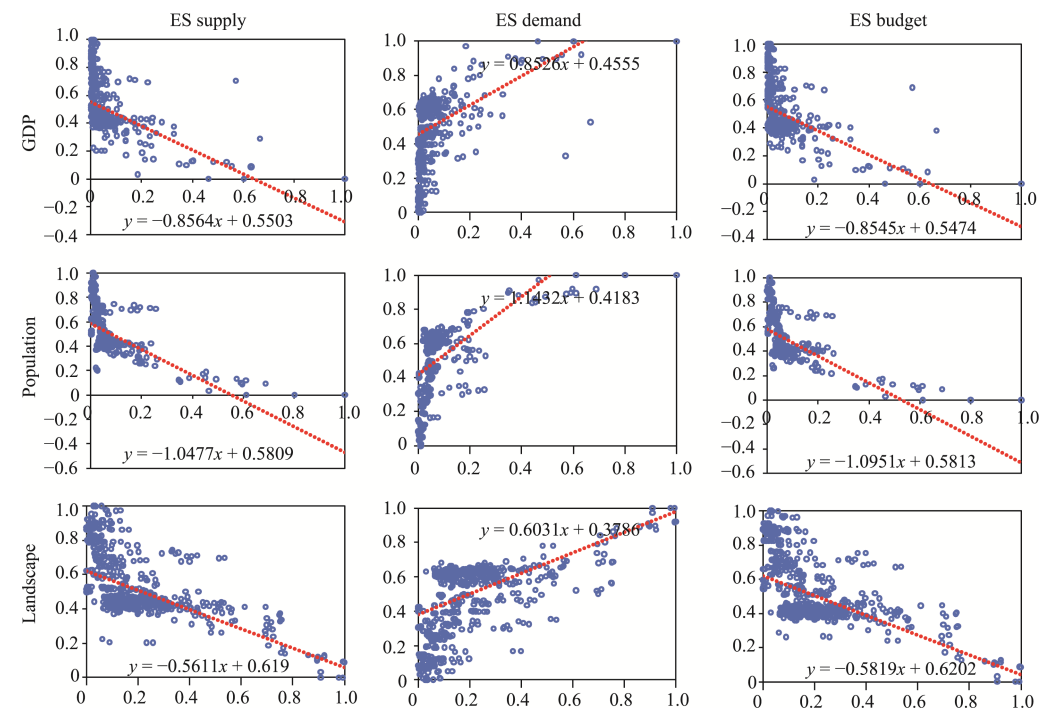


Figure 6 Relationships between urbanization indexes and ES supply, demand, and budget at the county scale

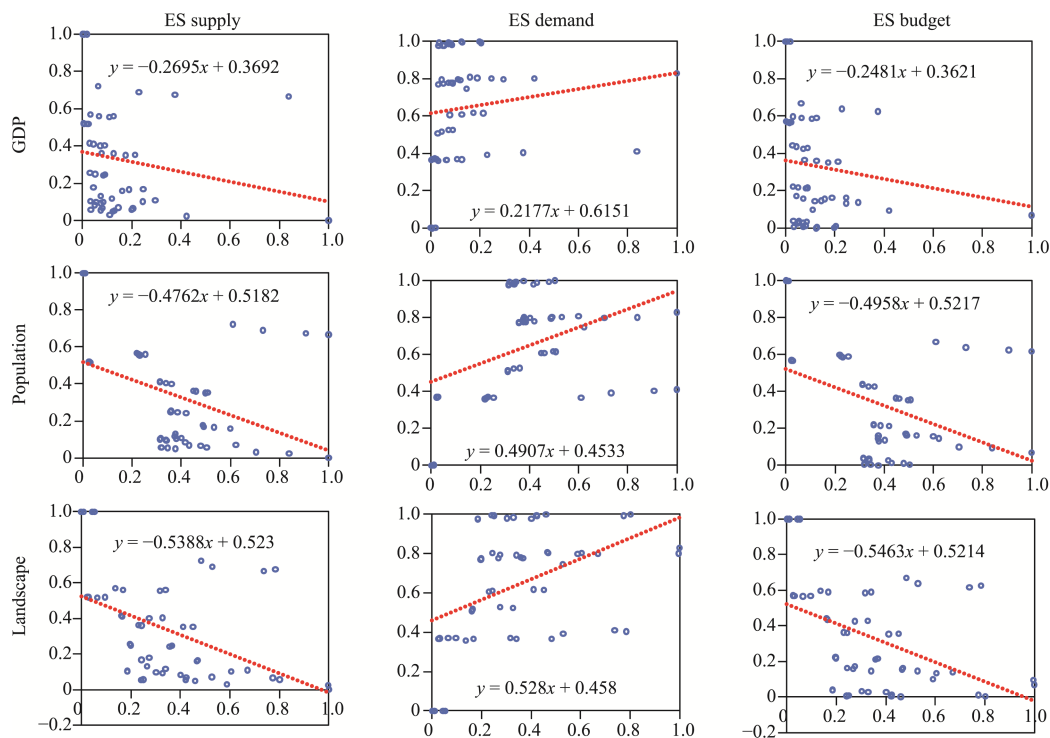


Figure 7 Relationships between urbanization indexes and ES supply, demand, and budget at the prefecture-city scale

The coupling analysis of urbanization and the ES supply-demand budget showed similar spatial patterns at both county and prefecture-city scales from 2000 to 2015. As shown in Figure 8, the spatial patterns were similar in 2000, 2005, 2010 and 2015, and the overall coupling degree improved from 2000 to 2015. Some high values were distributed in cities with high urbanization levels. In 2000, the mount of CCD more than 0.6 only 1 unit (Beijing) in ES supply, 7 units (Qinhuangdao, Tangshan, Baoding, Cangzhou, Shijiazhuang, Xingtai, and Handan) in ES demand, and 0 unit in ES budget. In contrast, in 2015, the mount of CCD more than 0.6 are 4 units (Beijing, Tianjin, Qinhuangdao, and Changping) in ES supply, 19 units (Qinhuangdao, Tangshan, Baoding, Cangzhou, Shijiazhuang, Xingtai, and so on) in ES demand, and 0 unit in ES budget. From the perspective of spatial pattern, the CCD values present banded distribution. The counties with a lower coupling degree were mainly distributed in the northwest areas, while those with a higher coupling degree were in the southeast. The spatial patterns at the prefecture-city scale were similar to those at the county scale (Figure 9). The coupling degree of the prefecture-cities in the BTH region improved from 2000 to 2015. The high urbanized areas, such as Beijing, Tianjin, and southern cities in Hebei, have relatively high CDD values.

4 Discussion

Over the past few decades, urbanization has been advancing rapidly in China. Cities have been losing ecological space, and sustainable urbanization has been difficult to maintain. Facing rapid urbanization process, this study explored the relationship between ES budget

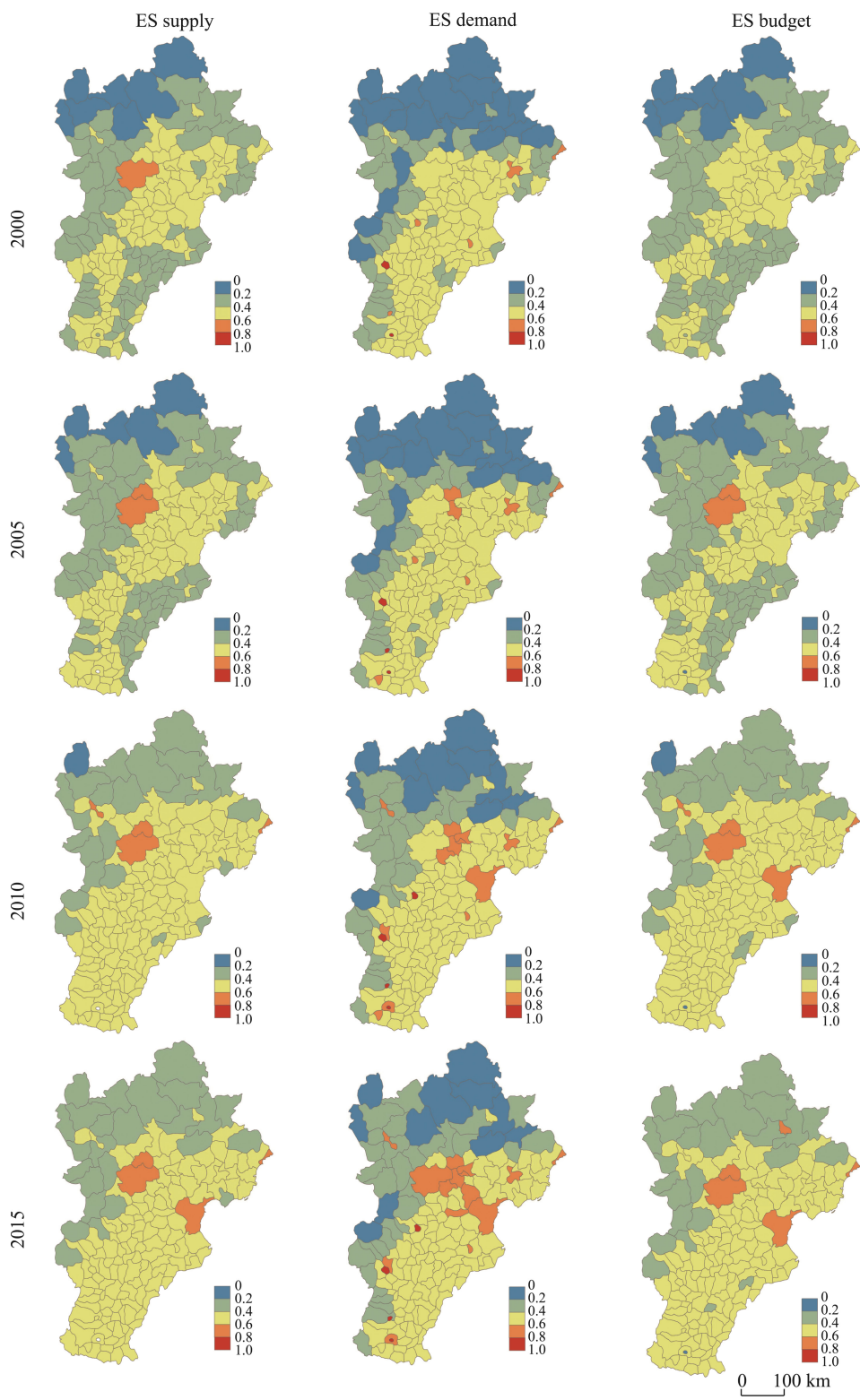


Figure 8 Spatial variation in coupling levels of urbanization and ecosystem services supply-demand budget at the county scale in the Beijing-Tianjin-Hebei region

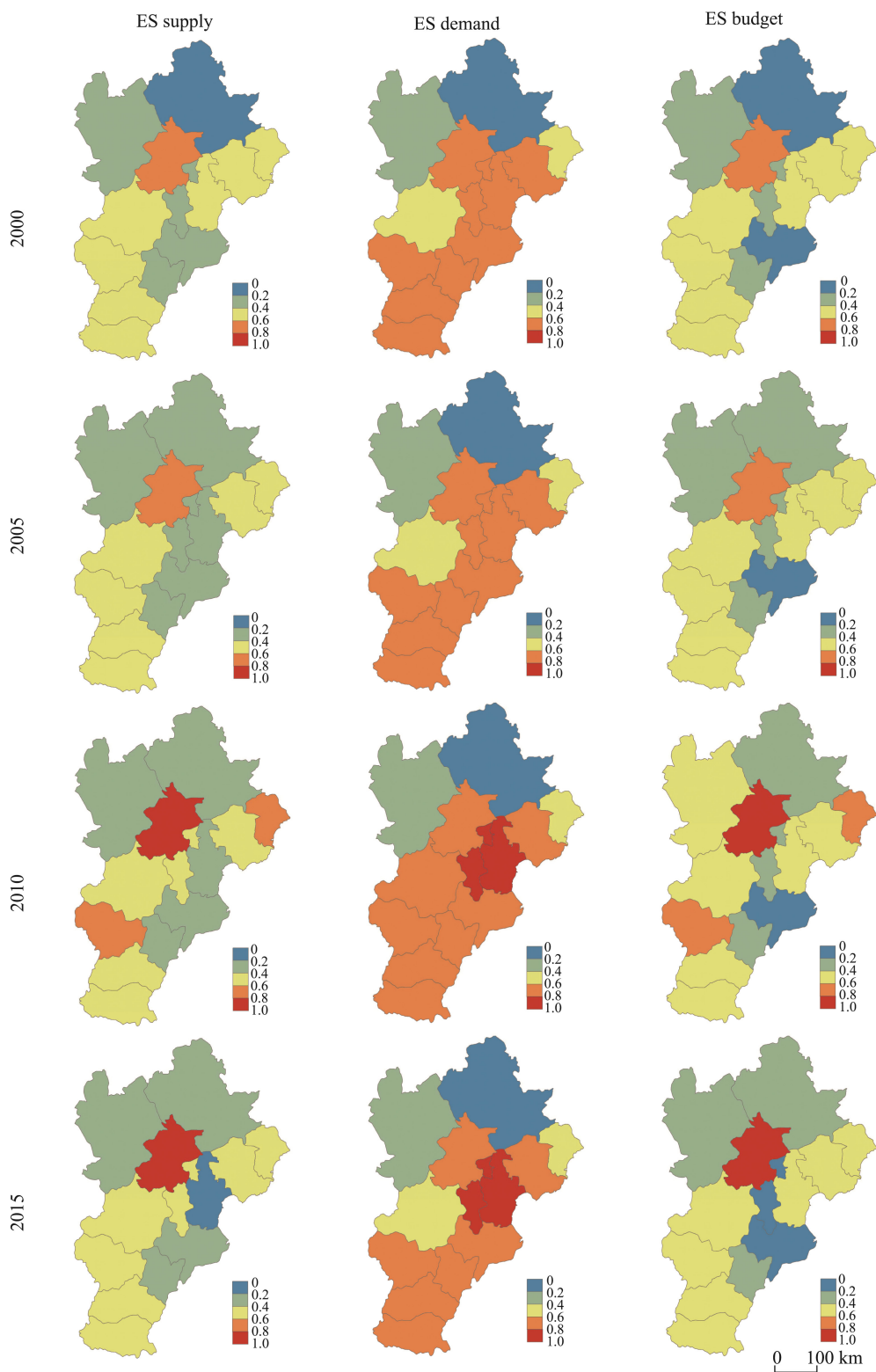


Figure 9 Spatial variation in coupling levels of urbanization and ecosystem services supply-demand budget from 2000 to 2015 at the prefecture-city scale in the Beijing-Tianjin-Hebei region

and urbanization level. Furthermore, we conducted multi-scale coupling analysis to quantify the correlations. According to the results, we found that urbanization is evident from the perspectives of population, economic and landscape. The development trends are consistent with those of others (Wang *et al.*, 2021; Peng *et al.*, 2017). The spatial pattern of ES demand and supply is based on the LUCC in the BTH region. It's reason that the urbanized area with high ES demand, and ecological area with high ES supply. As for the correlations, negative, positive, and negative relationships exist between urbanization levels and ES supply, demand, and budget, respectively. These is mainly because that ES demand is mainly caused by the increasing living standard and urbanization level, and the ES supply is mainly dominated by the ecological land. These results are credible to provide scientific evidences for policy makers.

As shown in this study, there is a negative correlation between urbanization and ES supply-demand budget, which reflects the irrationality of land-use change as a result of human intervention. The process of urbanization crowds out natural spaces, leading to a decline in typical ecosystem services such as productivity and water conservation, and limits the sustainable development of the BTH region. To overcome this obstacle, ecological protection and environmental optimization must be given equal weight to urban development. Expanding the area of ecological land contributes to improving the ES value in the BTH region. Green roof, ecological garden and grain to green are effective projects to expand the ecological area. Meanwhile, with the process of urbanization, controlling its negative effects should be paid more attention. The spatial planning should take ES supply and demand into account for sustainable development. In terms of and ecological restoration in the BTH region, regional government agencies should take agricultural needs and ecological protection into account during the process of urbanization and construction, in order to optimize ecological security. During the construction of cities, it is important to establish ecological compensation mechanisms and optimize the spatial design of urban-ecological networks to incorporate inter-regional land multifunctionality. In addition, policies related to land use should be designed according to local conditions but consideration must also be given to coordinated development of areas of rapid urbanization.

5 Conclusions

Urbanization is an important driver of changes in ecosystem types and services. In this study, an ES matrix was used to analyze ES supply, demand, and budget in the BTH region from 2000 to 2015. GDP, population density, and nighttime light brightness were used as indicators of different dimensions of urbanization. Multi-scale coupling analysis was used to quantify the correlations between urbanization and ES supply, demand, and budget and identify regional differences. The results provide a reference for ecosystem management and environmental protection in the BTH region.

The main research conclusions are as follows. (1) The effects of population agglomeration and factor agglomeration are important drivers shaping patterns of urbanization in the BTH region. Between 2000 and 2015, spatial patterns of urbanization in the BTH region remained stable, and the areas with the highest levels of urbanization were mainly located in the central part of the region. (2) From 2000 to 2015, ES supply in the BTH region was high in the northwest and low in the southeast, while ES demand showed the opposite pattern. Areas

with positive ES supply-demand budget values were found throughout the BTH region, but the ES budget of built-up areas requires attention. (3) There were negative, positive, and negative correlations between urbanization levels and ES supply, demand, and budget, respectively, in the BTH region. The urban-ecological coupling degree in the BTH region increased during the study period. Spatially, areas with a high coupling degree were concentrated in the southeast of the region.

Conflicts of interest

The authors declare no conflicts of interest.

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Appendix

Table S1 165 counties in the Beijing-Tianjin-Hebei region

No.	County	Province	No.	County	Province	No.	County	Province
1	Weichang	Hebei	43	Tangshan	Hebei	85	Pingshan	Hebei
2	Kangbao	Hebei	44	Tongzhou	Beijing	86	Lingshou	Hebei
3	Fengning	Hebei	45	Dachang	Hebei	87	Hejian	Hebei
4	Guyuan	Hebei	46	Changli	Hebei	88	Lixian	Hebei
5	Longhua	Hebei	47	Laishui	Hebei	89	Xingtang	Hebei
6	Chengde	Hebei	48	Baodi	Tianjin	90	Dingzhou	Hebei
7	Pingquan	Hebei	49	Xianghe	Hebei	91	Cangxian	Hebei
8	Zhangbei	Hebei	50	Daxing	Beijing	92	Boye	Hebei
9	Shangyi	Hebei	51	Luannan	Hebei	93	Suning	Hebei
10	Chicheng	Hebei	52	Fengnan	Hebei	94	Anguo	Hebei
11	Luanping	Hebei	53	Wuqing	Tianjin	95	Xinle	Hebei
12	Chongli	Hebei	54	Ninghe	Tianjin	96	Cangzhou	Hebei
13	Chengde	Hebei	55	Langfang	Hebei	97	Xianxian	Hebei
14	Huairou	Beijing	56	Laiyuan	Hebei	98	Haixing	Hebei
15	Wanquan	Hebei	57	Zhuozhou	Hebei	99	Anping	Hebei
16	Kuancheng	Hebei	58	Tanghai	Hebei	100	Raoyang	Hebei
17	Zhangjiakou	Hebei	59	Yixian	Hebei	101	Zhengding	Hebei
18	Miyun	Beijing	60	Gu'an	Hebei	102	Mengcun	Hebei
19	Xinglong	Hebei	61	Shuiqing	Hebei	103	Shuozhou	Hebei
20	Xuanhua	Hebei	62	Tianjin	Tianjin	104	Luquan	Hebei
21	Yanqing	Beijing	63	Xincheng	Hebei	105	Botou	Hebei
22	Qinglong	Hebei	64	Dingxing	Hebei	106	Gaocheng	Hebei
23	Huai'an	Hebei	65	Baxian	Hebei	107	Wuji	Hebei
24	Huailai	Hebei	66	Xiong'an	Hebei	108	Nanpi	Hebei
25	Qianxi	Hebei	67	Xushui	Hebei	109	Yanshan	Hebei
26	Funing	Hebei	68	Jinghai	Tianjin	110	Jingjing	Hebei
27	Zhuolu	Hebei	69	Rongcheng	Hebei	111	Shenzhou	Hebei
28	Zunhua	Hebei	70	Mancheng	Hebei	112	Wuqiang	Hebei
29	Pinggu	Beijing	71	Shunping	Hebei	113	Wuyi	Hebei
30	Changping	Beijing	72	Tangxian	Hebei	114	Jinzhou	Hebei
31	Qian'an	Hebei	73	Wen'an	Hebei	115	Xinji	Hebei
32	Shunyi	Beijing	74	Fuping	Hebei	116	Shijiazhuang	Hebei
33	Qinhuangdao	Hebei	75	Anxin	Hebei	117	Dongguang	Hebei
34	Yangyuan	Hebei	76	Renqiu	Hebei	118	Fucheng	Hebei
35	Jixian	Tianjin	77	Baoding	Hebei	119	Luancheng	Hebei
36	Lulong	Hebei	78	Qingyuan	Hebei	120	Jingxian	Hebei
37	Fengrun	Hebei	79	Qiyang	Hebei	121	Yuanshi	Hebei
38	Beijing	Beijing	80	Dacheng	Hebei	122	Zhaoxian	Hebei
39	Sanhe	Hebei	81	Qingxian	Hebei	123	Hengshui	Hebei
40	Yuxian	Hebei	82	Wangdu	Hebei	124	Wuqiao	Hebei
41	Luanxian	Hebei	83	Gaoyang	Hebei	125	Ningjin	Hebei
42	Yutian	Hebei	84	Huanghua	Hebei	126	Jixian	Hebei

(To be continued on the next page)

(Continued)

No.	County	Province	No.	County	Province	No.	County	Province
127	Zanhuang	Hebei	140	Guangzong	Hebei	153	Shexian	Hebei
128	Zaoqiang	Hebei	141	Renxian	Hebei	154	Guantao	Hebei
129	Gaoyi	Hebei	142	Qinghe	Hebei	155	Handan (county)	Hebei
130	Boxiang	Hebei	143	Pingxiang	Hebei	156	Feixiang	Hebei
131	Xinhe	Hebei	144	Xingtai	Hebei	157	Guangping	Hebei
132	Gucheng	Hebei	145	Nanhe	Hebei	158	Handan (urban)	Hebei
133	Lincheng	Hebei	146	Shahe	Hebei	159	Handan (suburb)	Hebei
134	Longyao	Hebei	147	Wu'an	Hebei	160	Cixian	Hebei
135	Nangong	Hebei	148	Linxi	Hebei	161	Chengan	Hebei
136	Neiqiu	Hebei	149	Jize	Hebei	162	Daming	Hebei
137	Julu	Hebei	150	Quzhou	Hebei	163	Weixian (Handan)	Hebei
138	Xiangtai	Hebei	151	Qiuxian	Hebei	164	Linzhang	Hebei
139	Weixian (Xingtai)	Hebei	152	Yongnian	Hebei	165	Laoting	Hebei

Note: 165 counties ordered from north to south.

Table S2 13 prefecture-level cities in the Beijing-Tianjin-Hebei region

No.	City	Province	No.	City	Province
1	Handan	Hebei	8	Tianjin	Tianjin
2	Xingtai	Hebei	9	Beijing	Beijing
3	Shijiazhuang	Hebei	10	Zhangjiakou	Hebei
4	Baoding	Hebei	11	Tangshan	Hebei
5	Hengshui	Hebei	12	Qinhuangdao	Hebei
6	Cangzhou	Hebei	13	Chengde	Hebei
7	Langfang	Hebei			

Note: 13 cities ordered from north to south.