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# Trade-offs and Spatial Driving Factors of Ecosystem Regulating Services in Beijing

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**Abstract:** Clarifying the relationships among ecosystem regulating services (ESRs) in Beijing and understanding the influence of natural and socio-economic factors on these relationships can contribute to realizing ecological zoning and guiding informed policymaking based on trade-offs. This study evaluated water conservation (WC), soil conservation (SC), carbon sequestration (CS), wind erosion prevention (WEP), and analyzed the trade-offs of ESRs and its spatial driving factors using root mean square deviation (RMSD), and geographically weighted regression (GWR). Subsequently, the ecosystem management zones at the township scale in Beijing were divided from a trade-off perspective. The results showed that: (1) ESRs in Beijing generally showed synergistic relationships, and only WC and CS showed a weak trade-off. However, the analysis of local spatial relationships found that there were still trade-offs between different services in local regions. (2) The key driving factors affecting the trade-off intensity of ESRs included normalized difference vegetation index (NDVI), elevation, temperature and nighttime light intensity. NDVI inhibited the trade-off between WC and SC throughout the region. Elevation inhibited the trade-off intensity between SC and WEP. Temperature inhibited the trade-off intensity between WC and WEP in the southern plains. Nighttime light exacerbated the trade-off between CS and WEP in the transitional regions between mountains and plains. (3) Based on the trade-off analysis, and considering human well-being, townships in Beijing could be classified into five zones: Comprehensive services enhancement zone, water conservation enhancement zone, soil conservation enhancement zone, carbon sequestration service enhancement zone, and wind erosion prevention enhancement zone. Each zone was characterized by distinct management objectives, trade-off driving factors, and management countermeasures.

**Key words:** ecosystem regulating services; trade-off; spatial driving factors; ecosystem management zoning

## 1 Introduction

Ecosystem services refer to the various benefits that humans obtain from natural ecological processes, including provisioning services, regulating services and cultural services

(Fu et al., 2017). At specific spatiotemporal scale, ecosystem services are interdependent, involving trade-offs and synergistic co-benefits (Dai et al., 2016). Therefore, correctly identifying the trade-offs and effectively managing the natural and socio-economic factors affecting the trade-

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offs of ecosystem services can help achieve a “win-win” scenario for economic development and ecological protection (Pan and Li, 2017). Ecosystem regulating services (ESRs) are closely related to human well-being and form the foundation of ecosystem functions, so it is necessary to analyze the trade-offs of ESRs to provide a scientific reference for achieving synergistic enhancement of ESRs in ecological management.

Trade-off analysis has emerged as a prominent field in ecosystem service research in recent years (Feng et al., 2017). Scholars have conducted extensive studies on ecosystem service trade-offs in watersheds, grasslands and forests (Wu et al., 2017; Zhang et al., 2020; Fang et al., 2021), employing methods such as correlation analysis, spatial overlay analysis, and difference comparison (Wang et al., 2022a; Zhao and Pan, 2022b; Zhu et al., 2023) to measure global or local trade-offs. However, most research has focused on the entire study area, rarely considering the specific regions where trade-offs occur, and often lacking spatial quantification of trade-offs and intensity. Trade-offs in ecosystem services are driven by various natural and socio-economic factors. Measuring the trade-offs and their driving factors is fundamental for ecosystem management and regulation (Su and Liu, 2023), which is crucial for minimizing regional ecosystem service trade-offs by managing driving factors. Scholars have investigated trade-offs in various regions and identified their natural and social driving factors through numerous empirical studies, including identification of dominant factors, analysis of single factor as well as factor interactions, and scaling effects of drivers (Huang et al., 2023; Xia et al., 2023; Li et al., 2024). However, most studies focused on larger scales such as metropolitan areas, city clusters, provinces, cities, etc (Shui et al., 2019; Zhang et al., 2022; Li et al., 2023; Liu et al., 2024), while lacking smaller scale analyses and applications at the township level, which has hampered efforts to construct and protect ecosystems zonally. In terms of research methods, geodetector, an emerging statistical tool for measuring spatial heterogeneity and detecting factors, can quantitatively identify the degree to which driving factors explain the trade-offs between ecosystem services, as well as the interactions between driving factors (Wang et al., 2023b). It has been widely used in the study of driving factors of ecosystem service trade-offs (Chen et al., 2022). However, geodetector mainly measure the explanatory power of natural-social factors on trade-offs (Li et al., 2021), ignoring the spatial differentiation of drivers. In contrast, as a local regression method, geographically weighted regression (GWR) takes into account the spatial heterogeneity of drivers (Zhao and Zhao, 2023), which can compensate for the shortcomings of geodetector. Therefore, this study combined the strengths of geodetector and GWR. The geodetector was utilized to identify the key driving factors influencing the trade-off intensity of ESRs within trade-off regions, and the GWR was employed to clarify the spatial

differences in the impact of key driving factors, which provided a basis for ecosystem zoning management from a trade-off perspective.

As one of China’s megacities, Beijing faces the dual challenges of immense development pressure and fragile ecological conditions (Xu et al., 2019). In recent years, projects such as “Million Acres of Afforestation” and “Construction of Suburban Parks” have contributed to significant improvements in Beijing’s overall ecological environment. However, due to the influence of nature and human activities, Beijing still faces problems such as the inconsistency between water resource security capacity and the development needs of the capital city, serious soil erosion (Wu et al., 2022b), large carbon sink demand, and seasonal wind and sand disturbance. The city’s synergistic supply capacity for regulating services such as water conservation, soil conservation, carbon sequestration, and wind erosion prevention needs to be further improved. Currently, researches on ecosystem services in Beijing have primarily focused on value calculation, supply and demand measurement, protection space identification, and spatial flow (Ma et al., 2017; Zhang et al., 2021b; Wang et al., 2022b). However, only a few scholars have explored the trade-offs between ecosystem services. For instance, Liu et al. (2021) assessed the trade-off and synergy relationships of ecosystem services in Beijing over time; Sun et al. (2018) measured the trade-offs of nine ecosystem services in Beijing from 1984 to 2015 and explored effective land use strategies to mitigate the trade-offs. Although these studies have well analyzed the overall trade-offs of ecosystem services at different time scales, but they have not sufficiently considered the spatial differentiation of trade-offs. Thus, there is a need to conduct spatial analyses of the trade-offs in ESRs and uncover the driving factors of these trade-offs across different geographic regions, and manage ecosystems from a trade-off perspective. Based on this, this study focused on the spatial trade-offs of ESRs with the help of basic data on land use, soil, meteorology, and socio-economics in the study area in 2022, analyzed the trade-offs and identified the local trade-off regions by using bivariate spatial autocorrelation, quantify the trade-off intensity of local trade-off regions by using root mean square deviation (RMSD), geodetector and GWR were used to analyze the spatial driving factors. Finally, the townships in Beijing were divided from a trade-off perspective. The results can provide a reference for regional ecosystem management and regulation.

## 2 Study area and methods

### 2.1 Study area

Beijing (39°26′–41°03′N, 115°25′–117°30′E) is located in the northern part of the North China Plain (Figure 1), covering an area of 16410 km<sup>2</sup>. The topography is higher in the northwest and lower in the southeast, with an average altitude of about 43.5 m, and the mountainous area accounts for

62.0% of the city's area. The climate is a warm temperate, semi-humid, semi-arid monsoon climate characterized by hot, rainy summers and cold, dry winters. The average annual precipitation is 548.86 mm and the average annual temperature is 12.77 °C. The ecosystem is dominated by forests, with an area of 6137.31 km<sup>2</sup> in 2022, accounting for 37.4% of the total ecosystem area, mainly distributed in the

northern part of the region. Beijing is one of the most rapidly urbanizing and industrializing regions in China (Zeng and Li, 2021), and the conflict between ecological protection and economic development is drastic. So how to achieve sustainable growth of ecosystem service provision within urban management is the primary issue in Beijing's urban ecological construction.

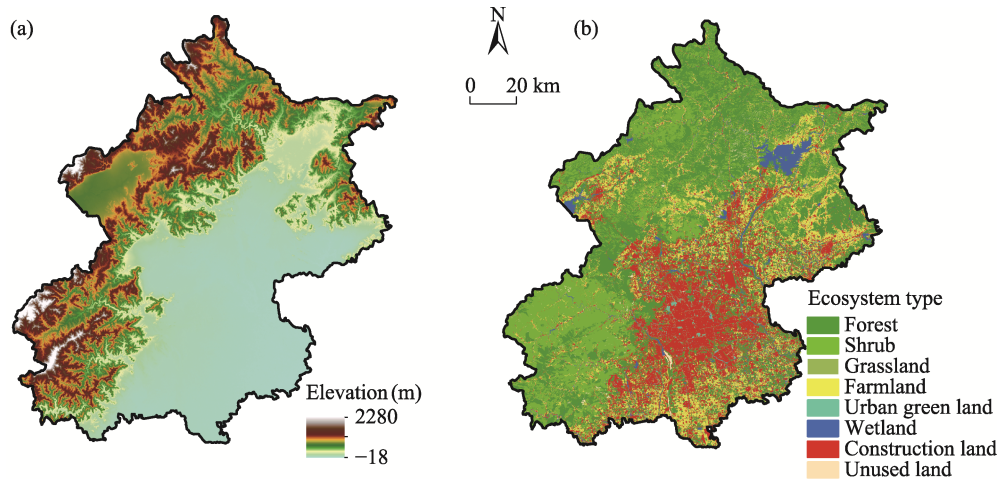


Figure 1 Elevation (a) and ecosystem types in 2022 (b) of the study area

## 2.2 Data sources

The basic research data includes land use data, meteorological data, soil data, terrain data, NDVI data, net primary productivity (NPP) data, nighttime light data, and population data. The land use data and meteorological data were obtained from the Resource and Environmental Science Data Platform, Chinese Academy of Sciences (<https://www.resdc.cn/>). The soil data was sourced from the second national land survey 1:1000000 soil data provided by the Nanjing Soil Research Institute of the Chinese Academy of Sciences (<http://vdb3.soil.csdb.cn/>). The elevation data were obtained from the SRTM elevation data, jointly measured by NASA and the National Survey and Mapping Agency of the Department of Defense (<http://srtm.csi.cgiar.org/srtm-data/>), with a spatial resolution of 30 m. The NDVI data came from the National Tibetan Plateau Data Center (<https://data.tpc.ac.cn/>), with a spatial resolution of 250 m. The NPP data came from the MODIS data set released by NASA (<http://modis.gsfc.nasa.gov/>). Nighttime light data was obtained from the National Center for Environmental Information (NCEI), a subsidiary of NOAA (National Oceanic and Atmospheric Administration). The population data came from the LandScan population spatial distribution data set released by the U.S. Department of Energy's Oak Ridge National Laboratory (<https://landscan.ornl.gov/>). After collecting these datasets, they were uniformly processed in ArcGIS 10.6. The unified projection coordinates are Kravosky\_1940\_Albers, the linear unit is meter, and the unified spatial resolution is 30 m.

## 2.3 Ecosystem regulating services evaluation

In this study, four typical regulating services (water conservation, soil conservation, carbon sequestration, and wind erosion prevention) were selected to quantitatively evaluate the physical quantity in Beijing in 2022. The calculation methods are as follows (Table 1).

## 2.4 Analytical methods of trade-offs in ecosystem regulating services

### 2.4.1 Bivariate spatial autocorrelation

Bivariate spatial autocorrelation was employed to reveal the correlation between attribute values of spatial units and the attribute values of their neighboring spatial units (Chen et al., 2017). In this study, 500 m fishing nets were created in ArcGIS, and nets with null values for the four ESRs were deleted. Finally, 65479 fishing nets were obtained, and the trade-offs between ESRs of the fishing net unit were analyzed.

Global Moran index: it was used to reflect the overall trade-offs of ESRs in the study area.

$$I_{xy} = \frac{n}{\sum \sum w_{ij}} \times \frac{\sum \sum w_{ij} (x_i - \bar{x})(y_j - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2} \sqrt{\sum (y_j - \bar{y})^2}} \quad (1)$$

In the formula,  $I_{xy}$  is the global Moran index, greater than 0 is a synergistic relationship, and less than 0 is a trade-off relationship;  $n$  is the number of fishing nets;  $x_i$  is the  $x$  attribute value of fishing net  $i$ ;  $y_j$  is the  $y$  attribute value of neighboring fishing net  $j$ ;  $\bar{x}$  and  $\bar{y}$  are the mean values of attributes of the regulating services  $x$  and  $y$ ;  $w_{ij}$  is the

Table 1 Calculation methods of regulating services

Regulating services	Calculation methods	Index interpretation
Water conservation (WC)	Water balance equation (Zhang et al., 2021a): $Q_{wc}=P-R-ET$	$Q_{wc}$ is the water yield (mm); $P$ is the annual rainfall (mm); $R$ is the annual surface runoff (mm); $ET$ is the annual evapotranspiration (mm)
Soil conservation (SC)	RUSLE (Wang et al., 2023a): $Q_{sc}=R \times K \times LS \times (1-C \times P)$	$Q_{sc}$ is soil retention (t); $R$ is rainfall erosivity factor; $K$ is soil erodibility factor; $LS$ is slope and slope length factor; $C$ is vegetation cover factor; $P$ is soil retention measure factor
Carbon sequestration (CS)	Based on the Net Ecosystem Productivity (NEP) (Cao et al., 2023): $Q_{cs}=MCO_2/MC \times NEP$	$Q_{cs}$ is carbon sequestration (t); $MCO_2/MC=44/12$ , represents the coefficient of conversion of C to CO <sub>2</sub> ; $NEP$ is net ecosystem productivity (t)
Wind erosion prevention (WEP)	RWEQ model (Gregory et al., 2004): $Q_{wep}=S_t-S_p$	$Q_{wep}$ is the amount of wind erosion prevention (t); $S_t$ and $S_p$ respectively represent the potential wind erosion and actual wind erosion (t), and the calculation method refers to Huang et al. (2022)

spatial weight matrix between  $i$  and  $j$ .

Local Moran index: it was used to estimate the divergence characteristics of two attributes between local spatial units and to draw Local Indicators of Spatial Association (LISA) distribution maps based on the  $z$  test ( $P < 0.05$ ). GeoDa software was employed to conduct the bivariate spatial autocorrelation analysis. The different aggregation types in the LISA distribution map indicated trade-off or synergy areas, where high-high aggregation and low-low aggregation were synergy areas, and high-low aggregation and low-high aggregation represented trade-off areas. Others were considered not significant (Wang et al., 2022c).

### 2.4.2 Root mean square deviation

Bivariate spatial autocorrelation distinguished the trade-offs and synergies of ESRs as a whole and identified the trade-off regions, but it was difficult to express the intensity of regulating services interactions. Therefore, the *RMSD* was used to measure the intensity of trade-offs in these regions, expanding the measure of the trade-offs to the uneven rate of change in magnitude by measuring the average difference between the standard deviation of ecosystem services and the standard deviation of average ecosystem services (Lu et al., 2014).

In order to eliminate the influence of different dimensions for multiple ecosystem services, the max-min standardization method was first used to unify the dimensions:

$$ES_{std} = \frac{ES_i - ES_{min}}{ES_{max} - ES_{min}} \quad (2)$$

The *RMSD* was calculated as follows:

$$RMSD = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (ES_{std} - \overline{ES_{std}})^2} \quad (3)$$

In the formula,  $ES_{std}$  is the standardized value of a certain regulating service;  $ES_i$  is the calculated value;  $ES_{max}$  and  $ES_{min}$  are the maximum and minimum values of a certain regulating service, respectively;  $\overline{ES_{std}}$  is the average of the standardized value of a certain regulating service for all units;  $n$  is the number of regulating services;  $i$  is a certain

service; *RMSD* is the root mean square deviation, with a larger value indicating a higher trade-off intensity between ESRs (Zhang et al., 2023). In this study, based on relevant literature (Wu et al., 2022a) and the natural breakpoint method, an  $RMSD \leq 0.1$  was regarded as a weak synergy,  $0.1 < RMSD \leq 0.2$  was regarded as weak trade-off,  $0.2 < RMSD \leq 0.4$  was regarded as moderate trade-off, and  $RMSD > 0.4$  was regarded as strong trade-off.

### 2.5 Analysis of driving factors of trade-off intensity among ecosystem regulating services

The driving factors were first standardized and three key driving factors affecting the trade-off intensity of ESRs in trade-off regions were identified by geodetector. Then, using the trade-off intensity of ESRs as the dependent variables and the key driving factors as the independent variables, the spatial effect of the key driving factors on the trade-off intensity was analyzed by GWR in ArcGIS Pro.

#### 2.5.1 Geodetector

Geodetector is a statistical method to explore the spatial differentiation of variables and reveal the driving forces behind them (Wang and Xu, 2017). It is based on the idea that if an independent variable  $x$  affects a dependent variable  $y$ , then their spatial distributions should be convergent. The formula is:

$$q = 1 - \frac{1}{N\sigma^2} \sum_{i=1}^L N_i \sigma_i^2 \quad (4)$$

In the formula,  $q$  is the detection power of the independent variable on the dependent variable,  $q \in [0, 1]$ , a larger  $q$  indicates a stronger explanatory power of the independent variable  $x$  on the dependent variable  $y$ ;  $N$ ,  $\sigma$  are the total sample size and variance of the study area, respectively;  $L$  is the number of detection partitions;  $N_i$ ,  $\sigma_i^2$  are the sample size and variance of different partitions, respectively.

Natural and anthropogenic factors have been demonstrated to significantly influence ecosystem service trade-offs (Zhao and Pan, 2022a). Therefore, several factors including topography, climate, vegetation, and anthropogenic

activities (Table 2) were considered for attributing trade-offs. With the trade-off intensity levels as the dependent variables and the driving factors as the independent variables, the GD package was utilized to select the classification methods and

levels with the greatest explanatory power in R (Yang et al., 2023). And then this study quantitatively analyzed the explanatory power of factors on the trade-off intensity of ESRs and identified the key driving factors.

Table 2 Driving factor description

Driving factor type	Driving factor name	Driving factor description
Terrain factors	Elevation (Ele)	Obtained from elevation data
	Slope	The degree of steepness and gentleness of the ground surface is obtained through surface analysis in ArcGIS
Climatic factors	Precipitation (Pre)	The total annual precipitation is obtained by Kriging interpolation based on the daily precipitation data of 50 meteorological stations in Beijing and surrounding areas.
	Temperature (Temp)	The annual average temperature is obtained by Kriging interpolation based on the daily temperature data of 50 meteorological stations in Beijing and surrounding areas.
Vegetation factors	NDVI	An indicator of vegetation growth status
Anthropogenic factors	Population density (Pop)	The number of people within the fishing net divided by the area of the fishing net
	Nighttime light intensity (Nli)	Obtained from nighttime light data
	Proportion of construction land (Pc)	Proportion of construction land in each fishing net

### 2.5.2 Geographically weighted regression

GWR, an extension of ordinary linear regression, can better analyze the local characteristics of regulating services trade-off relationships (Zuo and Gao, 2022). GWR was employed to analyze the impact of key driving factors on the trade-off intensity of ESRs. The formula is:

$$y_i = \beta(\mu_i, \nu_i) + \sum_{k=1}^m \beta_k(\mu_i, \nu_i) x_{ik} + \varepsilon_i \quad (5)$$

In the formula,  $y_i$ ,  $x_{ik}$ , and  $\varepsilon_i$  are dependent variables, independent variables and random errors respectively;  $(\mu_i, \nu_i)$  represents the position of fishing net  $i$ ;  $m$  is the number of key driving factors;  $\beta(\mu_i, \nu_i)$  is the intercept;  $\beta_k(\mu_i, \nu_i)$  is the regression coefficient of fishing net  $i$ .

### 2.6 Ecosystem management zoning at the township scale from a trade-off perspective

First, the 500 m fishing net scale was extrapolated to the township scale to calculate the proportion of land area in each township accounted for by each regulating service aggregation type. Next, the analysis results of the regulating service trade-offs were overlaid with the township distribution space. For townships where the regulating service aggregation types were all low-low aggregations, the management objective was to comprehensively improve various regulating services. Other townships were partitioned into ecosystem management zones based on the proportion of areas with low regulating services aggregations. If two or more low regulating services had the same area proportions, the physical volume of the regulating services after standardization within the township is compared, and the districts are divided based on the service with the lowest physical volume. Afterwards, the townships in Beijing were divided into five types of ecological management zones: 1) Com-

prehensive services enhancement zone. The types of regulating service aggregation in these townships are all low-low aggregation, and the management objective is to synergize the enhancement of various regulating services. 2) Water conservation enhancement zone. The area with the aggregation type of low water conservation and high levels of other services in these townships accounted for the highest proportion. The management objective is to improve the water conservation level. 3) Soil conservation enhancement zone. The area with the aggregation type of low soil conservation and high levels of other services in these townships accounted for the highest proportion. The management objective is to improve the soil conservation capacity. 4) Carbon sequestration service enhancement zone. The area with the aggregation type of low carbon sequestration and high level of other services in these townships accounted for the highest proportion. The management objective is to improve the carbon sequestration level. 5) Wind erosion prevention enhancement zone. The area with the aggregation type of low wind erosion prevention and high level of other services in these townships accounted for the highest proportion. The management objective is to strengthen the windbreak and sand fixation capacity. Finally, the mean values of the regression coefficients of the key driving factors for the aggregation type with the highest area within the zone were calculated. An average value greater than 0 indicated that the factor promoted trade-offs, identifying it as the trade-off driving factor of the zone.

## 3 Results

### 3.1 Trade-offs of ecosystem regulating services in Beijing

Based on the quantitative assessment of ESRs in Beijing in 2022, the trade-offs between ESRs were measured. The re-

sults of the global bivariate spatial autocorrelation analysis (Table 3) showed that synergies were dominant among services, with SC and CS having the highest degree of synergy, but WC and CS presented a weak trade-off. Overall, the Pearson correlation coefficient was slightly larger than the Moran index, mainly because the spatial weight matrix was taken into account in the calculation of the Moran index, which made the trade-off relationship has some spatial lags. But the Pearson correlation analysis results were basically consistent with the trade-offs reflected by the bivariate Moran index. The relative sizes of the indices were as follows: SC-CS>SC-WEP>WC-SC>CS-WEP>WC-WEP>WC-CS, which indicated that global bivariate spatial autocorrelation analysis can well measure the overall trade-offs of ESRs.

### 3.2 Trade-off intensity of ecosystem regulating services in Beijing

#### 3.2.1 Identify regulating service trade-off regions

Through local bivariate spatial autocorrelation analysis, this study identified the local trade-off regions of regulating services in Beijing (Figure 2). The trade-off regions between WC and SC, CS were mainly manifested in the urban sub-centers and in the northern mountainous areas with a mixture of forests, shrubs, and sparse forests. Synergistic fishing nets for WC and WEP accounted for 50.93% of the significant fishing nets, mainly distributed across the southern plains as well as in the townships of Xiong'erzhai, Huangsongyu, Shandong Zhuang of the Pinggu District and the townships of Nankou, Liucun and Shisanling of the Changping District. The trade-off regions were relatively concentrated in the districts of Mentougou, Fangshan and the northern part of Huairou. SC and CS mainly showed a synergistic relationship, with the number of fishing nets accounting for 74.49% of the total. The trade-off regions were mainly concentrated in the townships of Tanghekou, Labagoumen Manchu, Changshaoying Manchu in the north, and the townships of Gaoling, Gubeikou and Xinchengzi in the northeast, characterized by low-high aggregation. The trade-off regions between SC and WEP were mainly distributed in the southwest and parts of the central and northern

Table 3 The results of global trade-offs analysis

Trade-offs	Moran index	Pearson correlation coefficient
WC-SC	0.172***	0.183***
WC-CS	-0.069***	-0.068***
WC-WEP	0.056***	0.118***
SC-CS	0.396***	0.404***
SC-WEP	0.231***	0.290***
CS-WEP	0.130***	0.150***

Note: \*\*\* indicates  $P < 0.001$ .

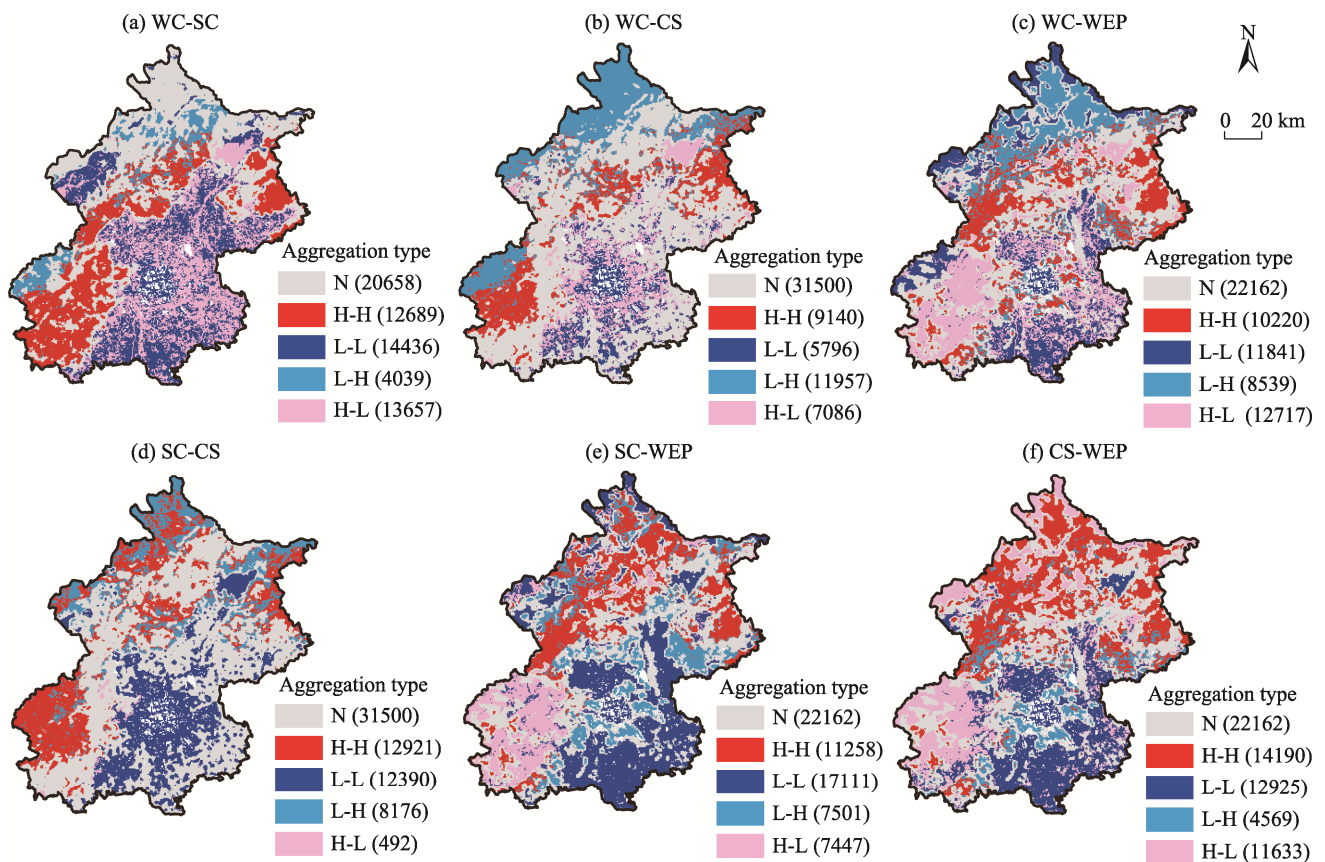


Figure 2 Spatial agglomeration characteristics of ecosystem regulating services trade-offs in Beijing

Note: N: Not significant; H-H: High-high aggregation; L-L: Low-low aggregation; L-H: Low-high aggregation; H-L: High-low aggregation. Numbers in bracket indicated the number of nets.

regions, with low-high and high-low aggregation accounting for more than 17%. CS and WEP were mainly synergistic, with localized trade-off regions concentrated in the districts of Mentougou and Fangshan in the southwest. This study clarified the regions where trade-offs occurred and provided a basis for regional zoning management.

### 3.2.2 Trade-off intensity of ecosystem regulating services in trade-off regions

The trade-off intensity of the local trade-off regions was calculated and visualized (Figure 3). The results showed that regions with strong trade-offs between WC and SC, CS were mainly distributed in the Miyun Reservoir and the construction land aggregations of Dongba, the townships of Wangsiying and Dougezhuang in the Chaoyang District, where lower soil conservation and carbon sequestration capacity were observed due to limited vegetation cover. The average trade-off intensity between SC and CS was 0.388, with strong trade-offs concentrated in the townships of Labagoumen Manchu, Tanghekou, and Baoshan in the northern part of Huairou, as well as in the townships of Gubeikou and Xinchengzi in the northeastern part of Miyun, and Zhangshanying town in the Yanqing District. Although these townships had a high capacity for carbon sequestration due to the extensive distribution of forests, the dramatic undulating topography of the mountainous areas resulted in relatively

low levels of soil conservation. The average trade-off intensity between CS and WEP was 0.296, represented a moderate trade-off, and the trade-off intensity gradually increased from the city center to the periphery. In summary, regulating services in Beijing were generally dominated by synergistic relationships, but some townships exhibited widespread strong trade-off regions. These townships should be the focus of future ecosystem protection and restoration.

### 3.3 Spatial driving factors of trade-off intensity among ecosystem regulating services

#### 3.3.1 Identification of key driving factors

The driving factor analysis results based on geodetector showed (Table 4) that different driving factors had different effects on the trade-off intensity of ESRs in the trade-off regions. NDVI explained the trade-offs between most services. Slope had a stronger explanatory power on the trade-off intensity between WC and SC, WC and CS, SC and WEP. Climate factors played a better role in explaining the intensity of the trade-offs between WC and WEP, as well as CS and WEP. The explanatory power of anthropogenic factors was smaller than that of natural factors. Considering the  $q$  value and the collinearity of the driving factors, the key driving factors influencing trade-off intensity in the trade-off regions were identified (Table 5).

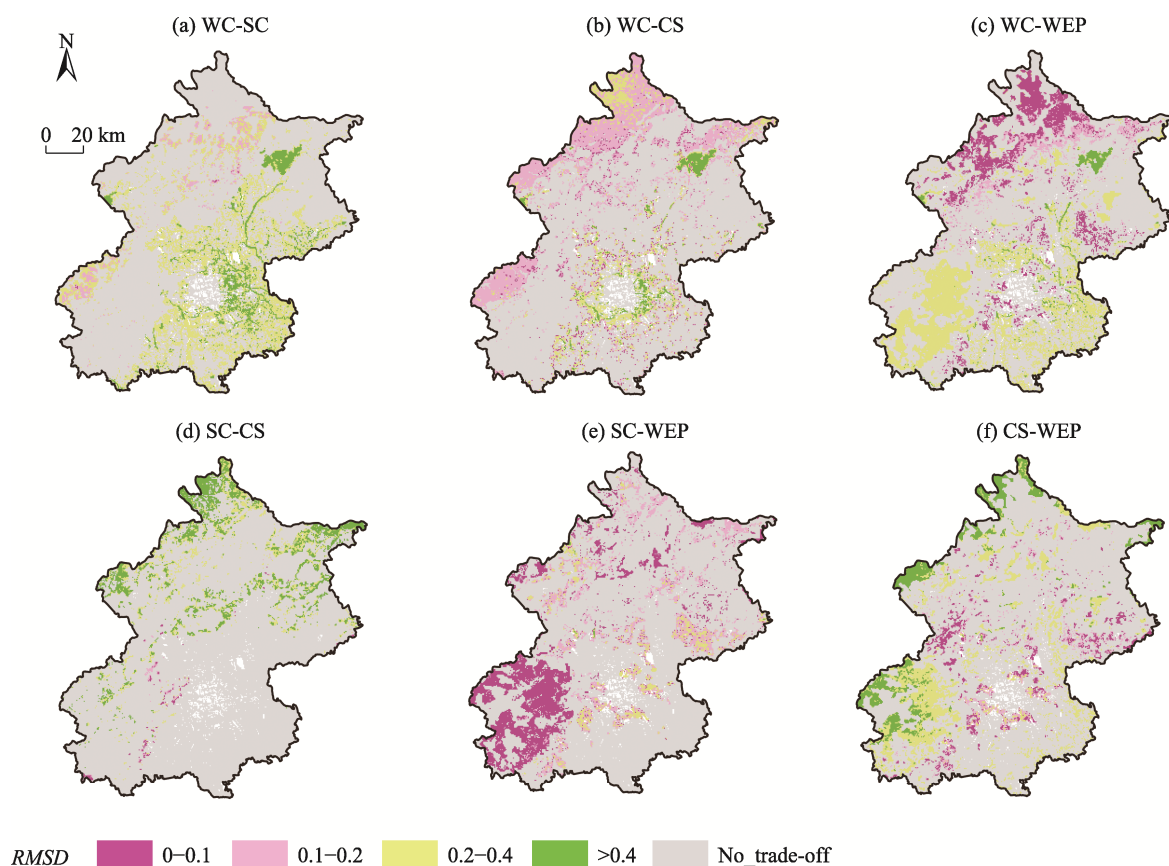


Figure 3 Spatial distribution pattern of trade-off intensity of ecosystem regulating services in Beijing

Table 4 The explanatory power of driving factors on the trade-off intensity in trade-off regions

Trade-offs	Terrain factors		Climatic factors		Vegetation factors	Anthropogenic factors		
	Ele	Slope	Pre	Temp	NDVI	Pop	Nli	Pc
WC-SC	0.268	0.360	0.183	0.203	0.308	0.049	0.154	0.093
WC-CS	0.173	0.235	0.127	0.137	0.296	0.135	0.128	0.100
WC-WEP	0.172	0.181	0.431	0.438	0.100	0.035	0.193	0.042
SC-CS	0.023	0.024	0.085	0.153	0.036	0.071	0.063	0.020
SC-WEP	0.384	0.589	0.224	0.234	0.343	0.174	0.332	0.311
CS-WEP	0.295	0.178	0.229	0.308	0.226	0.138	0.277	0.171

### 3.3.2 Analysis of spatial driving factors based on geographically weighted regression

Based on the identified key driving factors, ordinary least square regression (OLS) and GWR were performed on the trade-off intensity in the trade-off regions. The results indi-

cated that the difference between the Akaike information criterion (AIC) of the OLS and GWR was greater than 3 (Table 5), and the adjust  $R^2$  of the GWR was larger, indicating that the simulation results of the GWR were more reasonable (Shen et al., 2019).

Table 5 Ordinary least square regression and geographically weighted regression results

Trade-offs	Key driving factors	OLS		GWR		AIC difference
		AIC	Adjust $R^2$	AIC	Adjust $R^2$	
WC-SC	Slope, NDVI, Ele	-55450.48	0.673	-59782.88	0.746	4332.40
WC-CS	NDVI, Slope, Ele	-42133.43	0.410	-46618.24	0.535	4484.81
WC-WEP	Temp, Pre, Nli	-38276.98	0.391	-51032.53	0.667	12755.55
SC-CS	Temp, Pre, Nli	-20648.63	0.172	-25003.06	0.500	4354.43
SC-WEP	Slope, Ele, NDVI	-44460.93	0.496	-51889.53	0.695	7428.60
CS-WEP	Temp, Ele, Nli	-27939.27	0.409	-38410.18	0.691	10470.91

The analysis of GWR revealed (Figure 4) that natural factors and anthropogenic factors had varying impacts on trade-off intensity across different spaces. Slope inhibited the trade-off intensity between WC and SC in the northwest, and NDVI inhibited the trade-off between WC and SC throughout the region. This indicates that as the slope in mountainous areas increases, vegetation is better protected, resulting in greater evapotranspiration from vegetation and reduced water conservation, whereas steeper topography leads to less soil conservation.

NDVI exacerbated the trade-off intensity between WC and CS in the north but inhibited it in other regions. Overall, Ele exacerbated the trade-off, suggesting that the higher elevation regions in the north had more carbon sequestration due to abundant vegetation, while increased evapotranspiration from vegetation led to less water conservation.

Temperature inhibited the trade-off intensity between WC and WEP in the southern plains, while precipitation played an exacerbation role, indicating that high temperatures increase evapotranspiration and precipitation, thereby improving the water conservation capacity. Nighttime light generally inhibited the trade-off between SC and CS, indicating that vegetation near human settlements can be better managed and maintained, promoting a synergistic increase in SC and CS.

Ele generally inhibited the trade-off intensity between SC

and WEP, while NDVI inhibited the trade-off in the southwest and exacerbated it in the other regions, suggesting that as the elevation increases, vegetation is better protected, enhancing soil conservation and windbreak functions. In the transitional areas between mountains and plains, nighttime light exacerbated the trade-off between CS and WEP, indicating that human activities have encroached on farmland and shrub ecosystems.

### 3.4 Countermeasures for zoning management of ecosystems at the township scale in Beijing from a trade-off perspective

Townships or streets in Beijing can be categorized into five distinct zones based on ecosystem management objectives (Figure 5). These zones include: 48 townships in comprehensive services enhancement zone, 23 townships in water conservation enhancement zone, 164 townships in soil conservation enhancement zone, 71 townships in carbon sequestration service enhancement zone, and 37 townships in wind erosion prevention enhancement zone. The trade-off of ESRs in different zones reflects the ecological characteristics and the local disturbance of human beings, thus affecting the human well-being of these townships. Therefore, a regulatory chain of “trade-offs—human well-being—zoning management” was established, and management countermeasures for each zone were proposed.

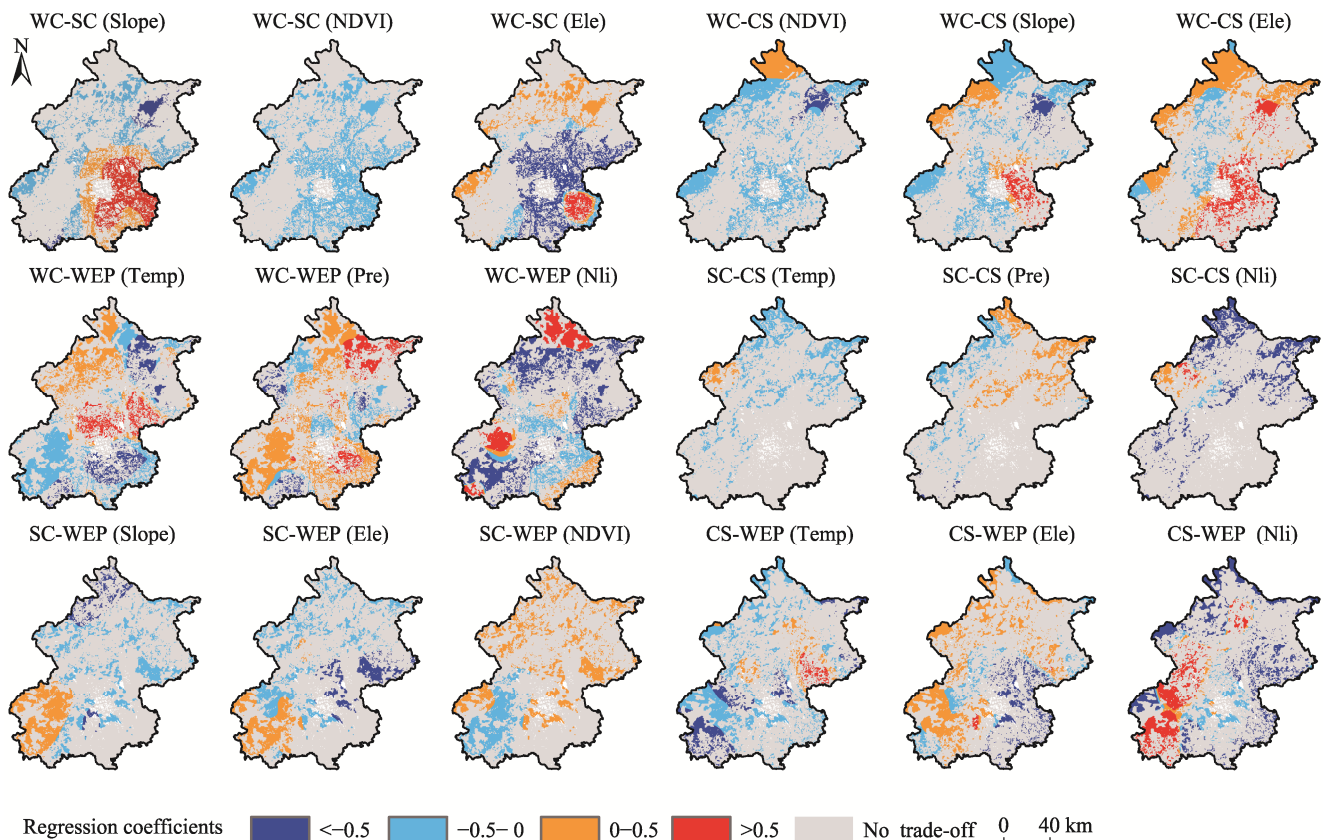


Figure 4 Spatial distribution of regression coefficients for key driving factors

The townships or streets in the comprehensive services enhancement zone were concentrated in the central area of the city. The zone was characterized by high population density and concentrated demand for ecosystem regulating services. The proportion of construction land in this area was high and land resources were tight, causing the supply capacity of various regulating services to be generally low, even though there were no trade-offs in this zone. The human well-being goal of the zone was to adjust the quantity of service supply to match human needs, future efforts should focus on reasonably increasing green space through the development of small green spaces, pocket parks, metope greening, and other similar initiatives to enhance the provision of regulating services.

Most townships in the water conservation enhancement zone were located in northern Huairou and northeastern Yanqing. The driving factors for the trade-off were elevation and precipitation. The vegetation in this zone was mainly mixed forests composed of oak (*Quercus*) and pine (*Pinus*). The high vegetation coverage contributed to strong soil conservation and carbon sequestration capabilities. However, the large leaf area increased evapotranspiration, resulting in low water conservation capacity while other services were high. Therefore, townships in this zone should improve water conservation capacity to ensure the safety of drinking water. In the future, these townships should adopt

protective measures such as closing the hillside for forest cultivation and constructing nature reserves to form locally climax vegetation communities through natural succession, and retaining litter to enhance water-holding capacity. If artificial vegetation restoration is required, local shrub species that consume less ecological water should be selected to improve the water conservation capacity of regional vegetation.

These townships in the soil conservation enhancement zone were widely distributed across the eastern plains and mountainous areas with smaller slopes. The main ecosystems in this zone were farmland and grassland, and the trade-offs were driven by NDVI, precipitation, and slope. The soil conservation supply capacity of these townships was low, while other services were high. On one hand, the small slopes in the eastern plains made the potential for soil erosion and actual soil erosion low. On the other hand, in the mountainous areas, actual soil erosion was more likely to occur due to the effects of rainfall and slope. Therefore, the human well-being goal of this zone is to control soil erosion, ensure agricultural production, reduce river siltation and non-point source pollution of water bodies. For townships with extensive basic farmland in plain areas such as the districts of Tongzhou, Shunyi, and Daxing, soil erosion can be suppressed in the future through the High-standard Farmland Construction, Conservation Tillage, and the establishment of farmland protective forest and grass con-

struction. For mountainous townships of the districts such as Miyun, Pinggu, and Changping, where ordinary farmland and grassland dominate, increasing the vegetation coverage by reverting farmland to forests and grassland or restoring grassland can help inhibit runoff processes and improve the erosion resistance of farmland and grassland.

These townships in the carbon sequestration service enhancement zone were mainly distributed in the western part of Changping and the junction of Shijingshan, Haidian, Mentougou and Fengtai. The driving factor behind the trade-offs included elevation and nighttime light intensity. In Shijingshan, Haidian, Mentougou, and Fengtai, human activities were frequent, and a large proportion of the land was used for construction. Meanwhile, in the high-altitude area of western Changping, such as the townships of Nankou and Liucun, shrubs and sparse forests were widely distributed, resulting in a low level of carbon sink but a high level of other services. Therefore, the human well-being goal of this zone is to neutralize carbon emissions and inhibit the greenhouse effect by increasing vegetation coverage. In the future, townships in the plain areas should focus on “Construction of Suburban Parks”, increasing the proportion of mixed forests through mixed planting, replanting, and other models. Forest management should aim to increase the proportion of evergreen coniferous forests. Streets in urban areas should enhance the carbon sequestration capacity of ecosystems and neutralize the carbon dioxide emitted by human activities through small and micro greening methods such as planting wall-climbing plants, edge greening, greening in gaps, and roof greening. Other townships should aim to achieve a reasonable ratio of trees to bushes and improve the carbon sequestration level of the ecosystem through projects such as the mountain ecological restoration and forest cultivation.

These townships in the wind erosion prevention enhancement zone were primarily located in the Mentougou District and the western of Fangshan District, with sporadic distributions in the districts of Shunyi, Daxing, and Changping. The trade-off driving factors included precipitation, elevation, slope, and nighttime light intensity. Although the potential for wind erosion in this zone was comparable to other regions, higher actual wind erosion had resulted in lower windbreak and sand fixation capabilities. Thus, the human well-being goal of this zone is to control wind erosion, provide clean air, and protect respiratory health. For townships with favorable conditions in terms of topography, soil, water source and vegetation, it is recommended to utilize native plant species to create a community structure that integrates trees, shrubs and grasses. This structure would enhance the vegetation’s ability to prevent wind and stabilize the soil, thereby reducing wind erosion. In townships where vegetation construction is challenging, it is advisable to build appropriate engineering sand barriers using engineering measures based on the evaluation of terrain and climate conditions to mitigate wind erosion.

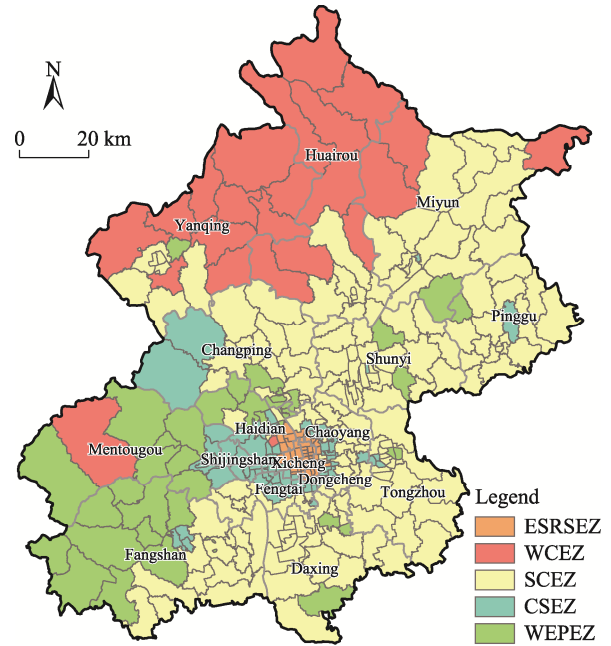


Figure 5 Ecosystem management zones in Beijing

Note: ESRSEZ: Comprehensive services enhancement zone; WCEZ: Water conservation enhancement zone; SCEZ: Soil conservation enhancement zone; CSEZ: Carbon sequestration enhancement zone; WEPEZ: Wind erosion prevention enhancement zone.

#### 4 Discussion

Based on a 500 m fishing net scale, this study identified the local trade-off regions of regulating services in Beijing and analyzed the spatial differentiation of trade-off intensity within these regions. It was found that the synergies among regulating services in Beijing were generally more significant than the trade-offs, aligning with existing research results (Li et al., 2022b). The global bivariate spatial autocorrelation reflects the average degree of correlation between the regulating services of all fishing nets and neighboring nets in Beijing. However, the spatial correlation and type of agglomeration of fishing nets and neighboring nets vary across space due to the effects of natural and human activities, resulting in varying trade-off intensities across different locations. For instance, the urban sub-center has abundant precipitation and higher water conservation. However, due to the aggregation of construction land and reduced vegetation coverage, the trade-offs between WC and SC, CS, WEP were relatively high. SC and CS were both positively correlated with vegetation coverage and had an obvious synergistic relationship (Han et al., 2024). The local high trade-off regions were primarily located in the northern and north-eastern mountainous areas, where had strong carbon sequestration due to the prevalence of forests and gardens. However, the steep terrain exacerbated the risk of soil erosion, resulting in a trade-off between low SC and high CS. CS and WEP, as a whole showed a synergy, and the result was consistent with existing studies (Xue and Yang, 2022). But in the southwestern Mentougou District and Fangshan

District, the Brown soil and Argosol as the main soil type reduced the risk of wind erosion because of their larger soil particles (Nan et al., 2014). Therefore, CS and WEP presented a moderate to strong trade-off.

Beijing's complex topography and varying levels of economic development result in spatial heterogeneity in the effects of driving factors on the trade-off intensity of ecosystem regulating services (ESRs) across different regions. This study combined the advantages of geodetector and GWR to perform a quantitative analysis of driving factors alongside spatial analysis. This approach helped to clarify the effects of spatially natural and anthropogenic factors on the trade-off intensity of ESRs in trade-off regions. The results indicated that NDVI, elevation, temperature and nighttime light intensity were the key driving factors affecting the localized trade-off intensity of ESRs in Beijing. However, Feng et al. (2021) found that the ecosystem service trade-offs in the Beijing-Tianjin-Hebei region were mainly affected by land use type, vegetation cover and evapotranspiration. This difference is likely because elevation and temperature affect regional evapotranspiration conditions, and changes in land use type are influenced by nighttime light. Vegetation can affect the capabilities of water conservation, soil conservation, carbon sequestration, wind erosion prevention through transpiration, photosynthesis and its own structure (Li et al., 2022a), making it a crucial factor in the trade-offs of regulating services. Topographic factors such as elevation and slope affect vegetation by changing soil and vertically distributed water and heat conditions (Ji et al., 2019), indirectly affecting the supply of regulating services. Temperature explained most of the trade-offs among ESRs, consistent with existing research results (Gao and Zuo, 2021). It is worth noting that in the background of global warming, rising temperature has a significant negative impact on the water conservation capacity in the southern part of the study area, which should be alleviated by certain human measures. In addition, nighttime light intensity was also an important factor affecting the trade-off intensity of ESRs. Liu et al. (2023) also found that anthropogenic factors such as GDP and nighttime light had a significant impact on the value of ecosystem services in the Beijing-Tianjin-Hebei region, indicating that human activities had positive or negative impacts on the coordinated supply of regulating services by affecting land use types and landscape patterns.

The study clarified the trade-off intensity and driving factors of localized regulating services in Beijing. In the future, urban management can focus on local trade-off regions in townships when implementing projects such as the "Plain Afforestation Project" and the "Construction of Suburban Parks", and control the trade-off driving factors to promote synergies among different regulating services. This study also analyzed the intensity of trade-offs and the spatial driving factors of ESRs in the local area. However, due to

limitations in methods and data, the gradient effects and interactions of driving factors were not systematically analyzed. Additionally, while the study identified the regions where trade-offs occurred, it neglected the trade-offs resulting from uneven changes in synergies, which indicated that the ecosystem zoning management countermeasures based on the trade-off analysis results need optimization. In the future, research should further consider the spatiotemporal differences of services at multiple spatiotemporal scales and conduct more in-depth analyses of the trade-offs among various services and their driving mechanisms to continuously improve zoning management measures.

## 5 Conclusions

Based on the actual situation in Beijing, this study analyzed the trade-off relationships among four kinds of ecosystem regulating services (WC, SC, CS, and WEP). Bivariate spatial autocorrelation was used to identify the local trade-off regions of regulating services, and the trade-off intensity was measured by RMSD in these regions. Geodetector and GWR were used to analyze the spatial effect of key driving factors, and an attempt was made to conduct ecosystem zoning management at the township scale based on the trade-off perspective. The main conclusions are as follows.

(1) The regulating services in Beijing were generally synergistic, with SC and CS showing the highest degree of synergy, while a weaker trade-off relationship existed between WC and CS. The analysis of local relationships showed obvious spatial heterogeneity in trade-off intensity. The Miyun Reservoir and the urban sub-center construction land aggregation were identified as strong trade-off regions between WC and SC, CS. The trade-off between SC and CS was higher in the northern and northeastern mountainous areas. The trade-off intensity between CS and WEP showed a distribution pattern that gradually increased from the urban center to the periphery.

(2) The key driving factors of local trade-offs in regulating services in Beijing included NDVI, elevation, temperature, and nighttime light intensity, with spatial differences in the effect of different factors on the intensity of regulating service trade-offs. NDVI inhibited the trade-off between WC and SC throughout the region, but exacerbated it in northern mountainous regions. Elevation generally inhibited the trade-off intensity between SC and WEP. Temperature inhibited the trade-off intensity between WC and WEP in the southern plains. In transitional regions between mountains and plains, nighttime light exacerbated the trade-off between CS and WEP.

(3) Based on a trade-off perspective, the 343 townships in Beijing were divided into five ecosystem management zones: comprehensive services enhancement zone, water conservation enhancement zone, soil conservation enhancement zone, carbon sequestration service enhancement zone, wind erosion prevention enhancement zone. Through

the regulatory chain of “trade-offs-human well-being-zoning management”, the driving factors and management countermeasures for regulating service trade-offs in each zone were clarified to provide a reference for territorial spatial planning and ecosystem management.

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## 北京市生态系统调节服务权衡关系及其空间驱动因素

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**摘 要:**厘清北京市生态系统调节服务关系以及自然和社会经济因素对调节服务关系的影响, 有助于实现基于权衡关系的生态分区与管理对策制定。本研究在对水源涵养、土壤保持、固碳、防风固沙四项调节服务评估的基础上, 通过均方根偏差、地理加权回归等方法开展服务间权衡关系及其空间驱动因素分析, 并基于权衡视角划分了北京市乡镇尺度的生态系统管理分区。结果表明:(1)总体上, 各项调节服务以协同关系为主, 仅水源涵养与固碳呈现较弱的权衡关系, 局部空间关系分析显示不同服务之间在局部区域仍存在权衡关系。(2)调节服务权衡强度的关键驱动因素包括 NDVI、高程、温度和夜间灯光强度。NDVI 加剧了北部山区水源涵养与固碳权衡强度; 高程总体上抑制了土壤保持与防风固沙权衡强度; 温度抑制了南部平原水源涵养与防风固沙的权衡; 夜间灯光加剧了山区平原过渡地带固碳与防风固沙的权衡。(3)基于权衡关系分析结果, 考虑人类福祉, 将北京市乡镇分为服务全面提升区、水源涵养提升区、土壤保持提升区、固碳服务提升区、防风固沙提升区, 明确了分区的管理目标、权衡驱动因素、管理对策。

**关键词:** 生态系统调节服务; 权衡; 空间驱动因素; 生态系统管理分区