Investigating the compounding effects of environmental factors on ecosystem services relationships for the ecological conservation red line areas

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Abstract: Exploring the driving factors of ecosystem services (ESs) trade-offs/synergies is crucial for ecosystem management, especially in ecological conservation red line (ECRL) areas that maintain regional and national ecological security. Soil conservation (SC), water yield (WY) and carbon sequestration (CS) were simulated in the Beijing ECRL areas. Geographical weighted regression was used to explore the trade-offs/synergies, and the geographical detector was applied to quantitatively identify their driving factors. Results show that (1) the SC and CS show marked synergy which characterized more than 80% of each ECRL area; the proportion of the space area of trade-off and synergy between SC and WY, and WY and CS was roughly 3 to 7 and 4 to 6 in each ECRL area, respectively. (2) The synergy of the three pairs of ESs was most sensitive to terrain factors. The precipitation erodibility of soil and its necessity for vegetation make it a determinant of the trade-off between SC and CS; temperature was the determinant in the trade-off between WY and CS, with an explanatory power of 32.8%; potential evapotranspiration was best able to explain the spatial distribution of the trade-off between SC and WY. (3) The interaction between precipitation and other factors had the greatest explanatory power on the spatial relationship between SC and WY. Precipitation and relief amplitude are the main interactive factors respectively affecting the spatial trade-off and synergy between SC and CS. The trade-off

There are no interests to declare.

and synergy between WY and CS were most sensitive to the interaction between climate factors and terrain factors.

Key words: ecosystem services; trade-offs and synergies; quantitative attribution; ecological conservation red line; Beijing

1. Introduction

Ecosystem services (ESs) can be defined as those natural conditions and utilities that ecosystems and ecological processes provide and maintain which are able to sustain human life (Daily, 1997). Globally, it is increasingly recognized that a narrow focus on promoting certain ESs often generates negative outcomes for other ESs, forming a trade-off relationship among ESs (Bennett et al., 2009). For example, preferences for food and timber often come at the expense of flooding and increased soil erosion (MA, 2005). Synergy is a situation in which services are in a positive relationship and co-vary in the same direction (Haase et al., 2012). For instance, the restoration of wetlands helps control floods and regulate the climate (Zedler, 2003). Hence, simulating multiple ESs and elucidating their relationships is imperative for ecosystem management, since only through this approach can synergies be seized upon and trade-offs curtailed (Zheng et al., 2013; Li et al., 2013).

Numerous studies showed that climate, land use intensity, soil and vegetation type, and biodiversity are important driving factors for ESs and their relationships (Pradhan et al., 2017; O'Farrell et al., 2010; Lee & Lautenbach, 2016). Driving factors shared by ESs indirectly affect the relationships among ESs (Bennett et al., 2009). Failure to understand the mechanisms that link driving factors to the supply of ESs may increase the risk of unreasonable management decisions and services degradation (Dade et al., 2019). Despite the importance of drivers and mechanisms for shaping the synergies and trade-offs plausibly arising between ESs, the quantitative identification of the driving factors on the trade-off and synergy requires further study, current research on whether and how driving factors interacted with each other remains weak (Feng et al., 2017).

Extensive urbanization, which entails economic development and fast population growth, has altered atmosphere–hydrosphere–biosphere interactions, thereby impacting the supply of ESs (Li et al., 2016). Early economic development was at the expense of natural resources and ecological environment, resulting in dramatic loss of ESs (Mao et al., 2018). The consumption of resources brought about by the increase of population makes people's preference for supply services higher than regulation, culture and support services, which leads to the emergence of a trade-off relationship between ESs (Zhao et al., 2018). Simultaneously, the concentration of many people in the city has greatly changed the land use pattern. The conversion of forestland, grassland, and cropland to urban land directly changes not only the structure of these ecosystems but also their functioning, which modulates changes in the ESs and their relationships (Tian et al., 2014).

To address the ecosystem degradation caused by rapid industrialization and urbanization, the State Council of China proposed the concept of an "ecological conservation red line" (ECRL) in 2011, aiming to balance the trade-offs among resource utilization, eco-environment protection, and economic development (SCC, 2011). The ECRL denotes a strict control boundary, this delimited in terms of key ecological functional areas as well as ecological environment sensitive areas and vulnerable ones (MEP, 2014). It represents a last stand and resort that would ensure and maintain national ecological security (Xu et al., 2019). As the capital of China, Beijing's rapid urbanization relies on the exploitation of ecological environment and resources, this has, not surprisingly, led to conflict and tensions arising between the ecological environment and urban development (Hubacek et al., 2009). Therefore, how to circumvent or ameliorate this contradiction, and realize a harmonious coexistence between humanity and nature, are core issues that need to be addressed in building Beijing into a world-class capital that is sustainable and livable (Ouyang et al., 2016; Chen et al., 2020). In 2018, the State Council of China approved the "*Beijing Ecological Protection Red Line Delineation Plan*", which contains a defined boundary for diverse ESs: soil conservation, water retention, and biodiversity, among others, thereby creating a framework to implement the idea of integrated research on multiple ESs into the concept of sustainable development.

In recent years, many studies of ECRL have been carried out from the perspective of ESs. For example, Wang and Pan (2017) derived Hangzhou Bay ECRL zones under three scenarios, by calculating the weight index of diverse ESs. Later, Xu et al. (2019) considered five ESs and two ecological vulnerability indicators, and used these as the basis for a coherent framework that defined and classified the ECRL at the Yangtze River Economic Belt. More recently, by integrating ECRL policy, perceptions of ESs by the public, and trade-offs between ESs, Zhang et al. (2020) built a framework to manage the regional ecological environment. Although such work on ECRL areas is based on ESs and considers the relationships between multiple ESs, the spatialization of ES relationships and quantitative attribution analyses of trade-offs and synergies among ESs have not been reported on. In those ECRL areas dedicated to the efficient management of multiple ESs, quantitative attribution research of ES relationships is necessary to weaken the negative effects of trade-offs and fully realize the gains of multiple ESs (Bennett et al., 2009). Simultaneously, whether environmental factors will enhance or weaken the explanatory power of trade-offs and synergies when they work together, or whether these factors are independent of each other, also requires further study. Furthermore, the trade-offs and synergies relationship between ESs can change across regions (Su and Fu, 2013; Bai et ai., 2011), especially in ECRL areas having different leading ecological functions. Therefore, zoning research on the ECRL according to their leading ecological function is of great importance to the zoning management of ecosystems and the construction of ecological civilization.

In this study, we simulated three key ESs that consider local conditions and attributes of the Beijing ECRL areas, namely, soil conservation (SC), water yield (WY), and carbon sequestration (CS). Here, to investigate the patterning of trade-offs and synergies between those ESs across space, the geographical weighted regression (GWR) model was applied. The objective of this study was to quantitatively discern those determinants and their interactions which most influenced the synergies and trade-offs in the ECRL areas, using the geographical detector, to enhance the efficiency of ecosystem management under the premise of preserving ecological functions, keeping the area from decreasing and maintaining the original nature of the ECRL areas.

2. Materials and methods

2.1. Study area

The ECRL areas in Beijing are mainly distributed in its western and northern mountainous areas (), covering a total area of 4290 km^2, accounting for 26.1% of the city's area. Spatially, the ECRL areas in Beijing present a pattern of "two barriers and two zones" (http://www.gov.cn/xinwen/2018-07/13/content_5306150.htm). The "two barriers" refers to the ecological barriers of Yanshan Mountain in the north and Taihang Mountain in the west; the "two zones" correspond to two ecological protection zones, along the Yongding River and Chaobai River-Ancient Canal. According to their leading ecological functions, Beijing's ECRL areas may be divided into four types: (1) soil conservation, (2) water retention, (3) biodiversity maintenance, and (4) important river and wetland. The Beijing ECRL map was obtained from the Beijing Municipal Ecology and Environment Bureau (http://sthjj.beijing.gov.cn) and the mapping of ECRL area types was obtained by digitization.

2.2. Data sources

The digital elevation model (DEM) was downloaded, using 91 Satellite Map Assistant software (Google Earth v6.0.3.). We selected the DEM data with a spatial resolution of 9 m. Land use type, at a 15-m resolution, came from the Beijing Municipal Ecology and Environment Bureau. Monthly normalized difference vegetation index (NDVI) data, at a 30-m resolution, were derived via a linear combination of reflectance values (near-infrared, red band), for which Landsat 8 OLI images of 24 scenes served as the data source. Meteorological site data—35 such sites in Beijing and its surrounding areas—came from the National Climate Center of the China Meteorological Administration (http://data.cma.cn/), and were then spatialized into raster images at a 1-km resolution by using the professional meteorological interpolation software ANUSPLINA v4.4 (http://fennerschool.anu.edu.au/files/anusplin44.pdf). Soil mechanical composition data were provided by the Harmonized World Soil Database (HWSD) (v1.2) (http://webarchive.iiasa.ac.at), while the Soil Data Center, National Earth System Science Data Sharing Infrastructure, National Science and Technology Infrastructure of China (http://soil.geodata.cn) provided the soil depth data. A spatial resolution of 1 km^2 characterized the two soil datasets. From the Resource and Environment Data Cloud Platform, Chinese Academy of Sciences (http://www.resdc.cn), vegetation type data was downloaded, this having a resolution of 1 km.

2.3. Methods

2.3.1. Simulation of SC with RUSLE model

SC was evaluated by the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), which has been applied worldwide. Potential soil erosion is how much soil erosion occurs, in the absence of cover-management and supporting mitigating measures. Accordingly, the potential minus actual soil erosion is the SC. The RUSLE model is expressed as follows:

$$A_c = A_p - A_m = R \times K \times LS \times (1 - C \times P) \tag{1}$$

where, A_c, A_p and A_m are the SC, potential soil erosion, and actual soil erosion ($t \cdot hm^{-2} \cdot yr^{-1}$), respectively; R is the rainfall erosivity factor ($MJ \cdot mm \cdot hm^{-2} \cdot h^{-1} \cdot yr^{-1}$), denoting the potential ability of rainfall to induce erosion, to calculated this, the method of Renard and Freimund (1994) was used; K refers to soil erodibility ($t \cdot hm^{2} \cdot h \cdot hm^{-2} \cdot MJ^{-1} \cdot mm^{-1}$), with soil mechanical composition used to calculate this K factor following the erosion-productivity impact calculator model proposed by Williams et al. (1990); the LS factor refers to the slope aspect, for which the formula developed by Zhang et al. (2013) was used to calculate the L factor while the S factor was generated based on the expression proposed by McCool et al. (1987); the vegetation coverage factor C used the methods of Cai et al. (2000), and; while P is the conservation measure factor; a value of the latter was designated to each land use type following previous research for the North China Plain (Xu et al., 2012). The LS, C, and P factors are dimensionless.

2.3.2. Quantification of WY by the InVEST model

On the basis of the water balance principle coupled to the Budyko framework, Integrated Valuation of ESs and Tradeoffs (InVEST) model derives, via the WY module, the amount of precipitation that remains after a portion of it has undergone evapotranspiration, that is the WY (Sharp et al., 2018). By combining key factors, such as the topography, climate, soil depth and land use of the study area, this model calculates the WY of grid units of different land use/cover in a given study basin, and then summarizes the WY of the whole basin and each sub-basin. The calculation is as follows:

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \cdot P(x) \tag{2}$$

where, $Y(x)$, $AET(x)$, and $P(x)$ are respectively the annual WY, annual actual evapotranspiration, and annual precipitation on grid unit x. The ratio of $AET(x)$ to $P(x)$ was calculated from the Budyko curve (Fu, 1981; Zhang et al., 2004) this way:

$$\frac{AET(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)} - \left[1 + \left(\frac{PET(x)}{P(x)}\right)^{\omega}\right]^{1/\omega} \tag{3}$$

where, $PET(x)$ represents the annual potential evapotranspiration of each grid cell x, which is obtained by the standard Penman–Monteith formula (Allen et al., 1998), and; ω refers to a natural climatic–soil parameter.

2.3.3. Calculation of CS with the CASA model

The Carnegie–Ames–Stanford Approach (CASA) is one of the simulation models that operates on a regional or global scale, able to link remote sensing to spatial databases of climate and vegetation to address the spatiotemporal dynamics of net primary productivity (NPP) (Potter et al., 1993; Mohamed et al., 2004). The CASA model derives NPP by using the absorbed photosynthetically active radiation (APAR) and light-use efficiency (ε) of plants, as follows:

$$NPP_i = APAR_i \times \varepsilon_i \tag{4}$$

$$APAR_t = SOL_t \times FPAR_t \times 0.5 \quad (5)$$

$$\varepsilon_t = T_{\max,t} \times T_{\min,t} \times W_t \times \varepsilon_{\max} \quad (6)$$

where, t denotes the period over which NPP has accumulated; $APAR_t$ ($MJ \cdot m^{-2}$) denotes the photosynthetically active radiation absorbed by vegetation, determined by total solar surface radiation (SOL_t) and the fraction of photosynthetically active radiation ($FPAR_t$); the constant 0.5 indicates the proportion of effective solor radiation accounted for by total solar radiation; ε_t ($gC \cdot MJ^{-1}$) refers to actual light-use efficiency of plants, an outcome jointly determined by both temperature stress—$T_{max,t}$ and $T_{min,t}$ are parameters describing the stress cofeeicients of the highest and lowest temperatures, respectively—and water stress (W_t) as well as the maximum light-use efficiency of vegetation (ε_{max}).

2.3.4. GWR model

GWR model is an extension of traditional regression methods (e.g., ordinary least squares, OLS) whose parameter estimation is not global but local (Fotherigham et al., 2002). Parameters of this model are functions of spatial positioning which can be used to evaluate spatial relationships within a study area. In this study, to uncover spatial relationships between ESs, the GWR model was relied upon. A negative coefficient implies a trade-off relationship between ESs, that is, a case where as one ES increases, the other decreases. Conversely, a positive coefficient indicates a given pair of ESs harbor synergy, in that both services either increase or decrease in tandem. The model takes this form:

$$y_i = \beta_0(\mu_i, v_i) + \sum_{k=1}^{p} \beta_k(\mu_i, v_i) x_{ik} + \varepsilon_i \quad (7)$$

where, y_i, x_{ik}, and ε_i are the dependent variables, independent variables, and random errors, respectively; (μ_i, v_i) refers to the spatial position of point i; k represents the number of independent variables; β_0 (μ_i, v_i) is the intercept at point i, and; β_k (μ_i, v_i) is the regression coefficient.

2.3.5. Geographical detector

Being a relatively novel statistical method, geographical detector is able to not only detect spatially stratified heterogeneity but also reveal its underlying determinants (Wang et al., 2010). It includes four detectors: a factor detector, interaction detector, risk detector, and ecological detector. In this study, the study area is divided into several sub-regions, and the factor detector is used to compare the accumulated dispersion variance of each sub-region with that of the whole study region (Wang and Xu, 2017). The interaction detector was applied to infer whether particular environmental factors, when jointly considered, might either increase or decrease the explanatory power of given trade-offs and synergies (Wang et al., 2016) (Table 1). The q statistic was used here to measure the association between ES trade-offs/synergies and each environmental factor. The larger the q value, the stronger the effect an environmental factor has on ESs trade-offs/synergies, expressed as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \qquad (8)$$

where h=1, 2, …, L refers to the strata of variables; N and σ^2 represent the total number of sample units and the variance, respectively; and N_h and σ_h^2 are respectively the number of sample units and the variance in stratum *h*. The term $\sum_{h=1}^{L} N_h \sigma_h^2$ is the sum of the strata variance, $N\sigma^2$ is the total sum of the variance.

3. Results

3.1. Spatial distribution of ESs

By mapping the supply distributions of three ESs across space in Beijing, their spatial heterogeneity and geographical differences across the ECRL areas could be gleaned (Fig. 2). The SC in the study area ranged from 0.30 to 1698.26 t·hm^{-2}·yr^{-1}, averaging 406.40 t·hm^{-2}·yr^{-1}. The simulation value of SC was similar to 0–1468. 57 t·hm^{-2}·yr^{-1} of Chen et al. (2020) in Beijing and its surrounding areas and 0–1454. 3 t·hm^{-2}·yr^{-1} of Shen et al. (2020) in Beijing-Tianjin-Hebei region. Within the four types of ECRL areas, the lower supply of SC occurred primarily in the water retention ECRL areas.

The range of WY in the study area is 0–576.63 mm and its annual average is 213.05 mm, and the lowest WY value appeared in the Miyun Reservoir in the water retention ECRL areas. This result is consistent with the range of water yield (0–622.47 mm) in Beijing and its surrounding areas reported by Chen et al. (2020). We also calculated the total annual WY of Beijing, which came to 2.761 billion m^3 in 2015 and 3.432 billion m^3 in 2018. This result is close to the total water resources of Beijing in 2015 (2.676 billion m^3) and 2018 (3.546 billion m^3), as reported in the Beijing Water Resources Bulletin (http://swj.beijing.gov.cn/zwgk/szygb/).

Concerning CS, its spatial distribution and that of vegetation type in the study area tends to be consistent. The provisioning of CS was higher in the north and west of the Beijing ECRL areas, where the vegetation consists mostly of forest and grassland with high photosynthesis. According to the CASA model output, Beijing's ECRL areas had a CS that spanned 39.75 to 1041.13 $gC{\cdot}m^{-2}$, which is consistent with the research results of Shen et al. (2020) in the Beijing-Tianjin-Hebei region. The annual average CS in the study area was 467.47 $gC{\cdot}m^{-2}$, which is in line with that (450–600 $gC{\cdot}m^{-2}$) simulated by Yin et al. (2015) in the mountainous areas of Beijing.

3.2. Trade-offs and synergies between the ESs across space

The results obtained from the GWR revealed that, for the three ESs investigated, trade-offs and synergies were present between them on the landscape (Fig. 3). The spatial relationship between SC and WY showed obvious heterogeneity, with a trade-off coefficient ranging from –0.499 to 0, and a synergy coefficient value of 0 to 0.635. In the ECRL areas of Beijing and those with leading ecological functions, the proportion of the space area of trade-off and synergy between SC and WY was about 3 to 7 (Table 2). Especially, in the soil conservation ECRL areas, the spatial synergy between SC and WY accounted for the largest percentage of the area, at 75.71%. The synergistic relationship between SC and CS was most pronounced in each ECRL area, covering more than 80% of space, this suggests that, at least spatially, the relationship between these two ESs is relatively stable. In each ECRL area, the proportion of the space area of trade-off and synergy between WY and CS was roughly 4 to 6. The synergy between WY and CS occupied the largest area in the water retention ECRL areas, reaching 62.42%. At the same time, the WY and CS in the Miyun Reservoir (it being a water retention ECRL areas) shows a concentrated synergy, with a synergy coefficient of 0.613 to 1.410. The lowest WY and CS in the Miyun Reservoir (Fig. 2) made it exhibit a high synergy level.

3.3. Environmental determinants affecting spatial relationships between ESs in ECRL areas

The factor detector results suggest prominent differences behind the spatial heterogeneity of the trade-off/synergy between ESs. Fig. 4 demonstrates the explanatory power (q value) of environmental factors upon the spatial distribution of trade-offs and synergies, with a degree of significance (p-value) below the 5% alpha level (i.e., <0.05). In the ECRL areas of Beijing, environmental factors exert different degrees of influence on the trade-off relationship between SC and WY. The order of their explanatory power, from high to low, was thus: potential evapotranspiration, temperature, vegetation coverage, relief amplitude, elevation, slope, land use type, and precipitation. Relief amplitude was the determinant in the synergistic relationship between SC and WY in ECRL areas of Beijing. In the soil conservation ECRL areas, the spatial trade-off between SC and WY was most sensitive to temperature and potential evapotranspiration, likewise for the ECRL area of Beijing. Since precipitation is most closely related to water in both the water retention ECRL areas and the important river and wetland ECRL areas, it significantly influences spatial relationships in the trade-off and synergy between SC and WY in both those areas. Especially in the water retention ECRL areas, where the leading function is closely related to the water yield, the explanatory power of precipitation on trade-offs/synergy, at 21.43%/14.59%, is significantly higher than that of other environmental factors. For the spatial relationship between SC and WY in the biodiversity maintenance ECRL areas, both a trade-off and synergy are the most obvious responses to elevation, temperature, and potential evapotranspiration.

In the ECRL areas of Beijing, for the spatial trade-off between SC and CS, precipitation provided the most explanatory power for it, being 15.47%, while relief amplitude had the largest q value for the spatial synergy relationship between SC and CS, at 0.114 (Fig. 4). In the soil conservation ECRL areas, environmental factors did not significantly affect the spatial relationship between SC and CS (p-value > 0.05). In the water retention ECRL areas and the biodiversity maintenance ECRL areas, precipitation was still the determinant of the spatial trade-off relationship between SC and CS, consistent with the results of the Beijing ECRL areas. The determinant for the spatial trade-off between SC and CS in the important river and wetland ECRL areas was land use type, which explained 76.44% of the spatial heterogeneity in that trade-off; it was followed by elevation, relief amplitude, potential evapotranspiration, precipitation, and temperature. The spatial synergy between SC and CS in the important river and wetland ECRL areas was most sensitive to precipitation, with a q value of 0.300.

Environmental factors differed in their effects on the spatial trade-off relationship between WY and CS in the ECRL areas of Beijing (Fig. 4). Among them, temperature had the maximum q value, at 0.328, suggesting a decisive role was played by temperature in driving the spatial patterning in that trade-off. For the spatial synergy between WY and CS in the ECRL areas of Beijing, the respective explanatory power of elevation, potential evapotranspiration, temperature, relief amplitude, land use type, vegetation coverage and slope all differed slightly, totaling at least 18%. Regarding the trade-off/synergy between WY and CS in the soil conservation ECRL areas, only one factor attained statistical significance for its spatial distribution: potential evapotranspiration/precipitation. The spatial relationship between WY and CS in the water retention ECRL areas responded to environmental factors to varying degrees, among which the response of spatial trade-off to environmental factors was more significant; their order of q values from large to small is temperature, potential evapotranspiration, precipitation, and elevation. In the biodiversity maintenance ECRL areas, precipitation/elevation was the determinant affecting the spatial trade-off/synergy between WY and CS. In the important river and wetland ECRL areas, the spatial relationship between WY and CS responds most significantly to temperature.

3.4. Dominant interactions affecting trade-off/synergy in ECRL areas

Fig. 5 shows the top three interaction combinations in terms of explanatory power for trade-off and synergy in the ECRL areas of Beijing. Concerning the trade-off and synergy between SC and WY, the interaction between precipitation and other factors was the most significant in the ECRL areas of Beijing, while precipitation alone has a small impact on trade-off and synergy, indicating the superposition of precipitation and other factors could have enhanced the explanatory power of the spatial relationship between SC and WY. The interaction between precipitation and temperature can explain 43.7% of their spatial trade-off, while that between precipitation and potential evapotranspiration explained 26.7% of their spatial synergy. In the soil conservation ECRL areas and important river and wetland ECRL areas, the spatial synergy between SC and WY are greatly affected by potential evapotranspiration. More specifically, we find that the dominant interactions occurred between potential evapotranspiration and elevation, and between potential evapotranspiration and precipitation. In the water retention ECRL areas and biodiversity maintenance ECRL areas, the most explanatory interactions were the superposition of precipitation and another environmental factor, which once again emphasizes the importance of precipitation conditions in these two ECRL areas.

The interaction between precipitation and other factors, as well as the interaction between relief amplitude and other factors, exerted a significant impact on the spatial relationship between those two ESs (Fig. 5). This result is akin to that of the factor detector operating in the ECRL areas of Beijing; that is, precipitation is the determinant for the spatial trade-off, while relief amplitude is the determinant for spatial synergy. For the spatial relationship between SC and CS in the water retention ECRL areas, the interaction between precipitation and temperature explained 51.89% of the trade-off and 21.37% of the synergy, respectively, which was the most powerful interaction combination identified in our study. In the biodiversity maintenance ECRL areas, the interaction between precipitation and other factors has the greatest explanatory power for the spatial relationship between SC and CS, which is related to the factor detector result showing that precipitation is the determinant in this area. In the important river and wetland ECRL areas, the interaction between factors significantly enhanced the explanatory power of single factor for the spatial relationship between SC and CS, among which the dominant interactions accounted for 99% of the spatial trade-off relationship.

For the multiple sets of interactions influencing the spatial trade-off/synergy between WY and CS (Fig. 5), the interaction factors can be classified into two categories: one is climate and the other is terrain. Climate factors, such as precipitation, temperature, and potential evapotranspiration, directly affect the ecological processes of WY and CS and exert an influence on their spatial relationship. Terrain factors, including relief amplitude, elevation, and slope, indirectly regulate the supply of those two ESs via their effects on hydrothermal conditions. When factors work together, it enhances their ability to interpret spatial trade-offs and synergies. For each ECRL area with a different leading ecological function, the spatial trade-off between WY and CS in important river and wetland ECRL areas is dominated by temperature's interaction with other factors, a result clearly different from the other ECRL areas. While in both the water retention ECRL areas and biodiversity maintenance ECRL areas, precipitation's interaction with other factors has the most explanatory power for their trade-off relationships.

4. Discussion

4.1. Determinants and their interactions for spatial trade-off and synergy

Because they are not independent, ESs are often marked by relationships to each other that manifest in strongly non-linear dynamics (Pereira et al., 2005; Kremen and Ostfeld, 2005). Affected by ecological process and pattern, the same environmental factor can differentially influence various ESs, so that the relationships between them change in different directions. For example, precipitation has different effects on the ecological processes underpinning SC and CS in the ECRL areas of Beijing. Previous studies have shown that precipitation, precipitation intensity, and precipitation duration can directly or indirectly trigger soil erosion and reduce SC capacity (Zeng et al., 2017). Further, precipitation is an indispensable condition for vegetation growth in karst areas and increases the CS capacity of vegetation to a certain extent (Li et al., 2014). Therefore, precipitation has the best explanatory power for the trade-off between SC and CS across space. Similarly, under the same precipitation conditions, a higher temperature will increase actual evapotranspiration, resulting in a reduction in WY. Temperature can directly alter both soil temperature and air temperature, thus affecting plant's absorption of water and fertilizer and their growth and dispersal dynamics (Fang et al., 2010). Simultaneously, temperature can affect the synthesis and metabolic processes of vegetation organic matter by affecting plant's photosynthesis, respiration, and transpiration rates, along with other functional traits (Zhao and Running, 2010). In this way, the spatial trade-off relationship between WY and CS in the ECRL areas of Beijing is most sensitive to temperature.

Synergy between ESs is regulated by a variety of influencing factors. In this study, the spatial distribution of synergies between the three ESs was best explained by the terrain factors, precisely because of the macro-control effect of terrain factors and the inner characteristics of each geomorphological type (plains, shallow mountains, and deep mountains in Beijing). This arises when terrain factors control the distribution of water and heat resources in small- and medium-scale spaces, affecting the incident solar radiation, temperature, soil mineralization rate, vegetation distribution and many other environmental conditions and ecological processes, which together directly determine the supply and maintenance of ESs (Wei et al., 2016; Zhao et al., 2018).

Interactions between factors significantly enhanced the explanatory power of single factor for the spatial relationship between ESs. Compared with being a single factor, precipitation and its pairwise interactions have strong explanatory power for the spatial relationship between SC and WY in the ECRL areas of Beijing. Since precipitation figures prominently in both SC's and WY's ecological processes—such as the erosion of precipitation on the soil and the supply of precipitation to the yield of water—the interaction between precipitation and other factors has the greatest explanatory power for the trade-off and synergy between SC and WY. The trade-off and synergy between WY and CS are the most sensitive to the interaction of climate factors and terrain factors, and we found little difference in explanatory power among these interactions. Climate factors directly affect the services provided by ecosystems to humans by influencing key ecological processes, and terrain factors drive the supply and maintenance of ESs by controlling the distribution of environmental conditions and resources at multiple spatial scales. Therefore, the interaction of two types of factors often has a prominent explanatory power on the spatial relationship of ESs. Considering the overall interactions that affected ES trade-offs and synergies in our results, both climate factors and terrain factors should receive more attention in planning the strict protection of Beijing's ECRL areas because they could balance the three key ESs.

4.2. Zoning management of ECRL areas with different leading ecological functions

The difference in the leading ecological function of the ECRL areas determines the direction of development and protection of each ECRL area (Gao et al., 2020). To ensure that the ecological function, area, and nature of each ECRL area remains unchanged, this study explored the determinants and their interactions of the spatial relationship between ESs in the four types of ECRL areas, with the hope of yielding a robust basis for their management in terms of the zoning of each ECRL area. The leading ecological function of soil conservation ECRL areas is to prevent and control soil erosion; to protect, improve and reasonably use soil and water resources, and to maintain and improve land productivity (http://www.mee.gov.cn/gkml/hbb/bwj/201505/W020150519635317083395.pdf). These functions correspond to the three ESs selected in this study, namely, SC, WY and CS, respectively. The factors that affect the formation of these ESs, namely precipitation, potential evapotranspiration, and temperature, are the determinants shaping the trade-off and synergy in the soil conservation ECRL areas. The interaction between these three factors and terrain factors such as slope, elevation, and relief amplitude are very significant for interpreting the trade-off and synergy of ESs in this area; this finding suggests the protection of this ECRL area must consider the combined effect of multi factors integrating terrain factors.

In the biodiversity maintenance ECRL areas, where the leading ecological function is to protect vegetation diversity and species richness, both the terrain and hydrothermal conditions significantly impact the growth of vegetation and its vertical zonal distribution. Thus, the determinant affecting the trade-off/synergy between SC and WY is elevation/temperature. For water retention ECRL areas distributed in the upstream areas of Miyun Reservoir, Huairou Reservoir, and Guanting Reservoir, as well as biodiversity maintenance ECRL areas distributed in the Baihua and Dongling Mountain in the west, the Song, Yudu, and Haituo Mountains in the northwest, and the Labagoumen area in the north, precipitation and its interaction with other factors has the strongest explanatory power on the spatial trade-off relationship among the three ESs; hence, protection of this type of ECRL area requires attention to the distribution of precipitation and the supply of water resources. In the important river and wetland ECRL areas, the determinants and interactions affecting the trade-offs and synergies between the three ESs are different, proving that the protection of ecological functions in this area requires balancing and considering multiple environmental factors, to ensure their comprehensive benefits are maximized.

4.3. Uncertainty analysis and future perspectives

We only evaluated the three ESs closely related to the ECRL areas of Beijing, and the spatial relationship of other services has not been considered yet. At the same time, although the assessment results of these three services have been verified with existing research results in terms of spatial distribution and numerical range, field test data and statistical yearbook data should be used in future research to improve the reliability of the assessment results. Crucially, once an ECRL is delineated, it is imperative that the protective effect of its ecological functions be monitored for a long time, so that various policies and measures can be continuously adjusted according to the actual situation in the field. Therefore, carrying out long-term investigations of ESs and their relationships within the ECRL is required. Moreover, trade-offs in ES can be understood from spatial scale, temporal scale, and reversibility (Rodriguez et al., 2006). Thus, according to the spatial relationship between ESs, the dynamic changes of trade-offs/synergies and their determinants over time and reversibility on a long-term scale can be expended into the future.

5. Conclusions

In this study, a framework is devised that integrate the ECRL with ESs, as well as trade-off and synergy relationships of the latter, for practical use in eco-environment management at the regional scale. The distribution of ESs and their relationships exhibit spatial heterogeneity across the ECRL areas of Beijing. In each ECRL area, the proportion of the space area of trade-off and synergy between SC and WY is about 3 to 7, and the proportion of the space area of trade-off and synergy between WY and CS is roughly 4 to 6. There is a relatively stable spatial synergy between SC and CS, and synergistic relationships account for more than 80% of each ECRL area type.

In the ECRL areas of Beijing, the determinant of the spatial trade-off between SC and WY, SC and CS, and WY and CS is potential evapotranspiration, precipitation, and temperature, respectively. The spatial synergy of these three pairs of ESs is mainly affected by terrain factors. The interaction between precipitation and other factors and that between relief amplitude and other factors, together have the greatest explanatory power for the spatial relationship between SC and CS. The spatial relationship between WY and CS is most sensitive to the interaction between climate factors and terrain factors. These results confirmed that the spatial relationship between ESs and their influencing factors are very complex; hence, the different roles of various environmental factors in the trade-offs and synergies of different pairs of ESs deserve scrutiny and attention. The determinants of the spatial relationship between ESs are also affected by the leading ecological functions of different ECRL areas, which confirmed that the control and management of an ECRL area requires a comprehensive understanding of the natural background of different ECRL areas, beginning with its leading ecological function.

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Table 1 Types of interaction between two covariates

Description	Interaction
$q(X1 \cap X2) < \mathrm{Min}[q(X1), q(X2)]$	Weaken, nonlinear
$\mathrm{Min}[q(X1), q(X2)] < q(X1 \cap X2) < \mathrm{Max}[q(X1), q(X2)]$	Weaken, single factor nonlinear
$q(X1 \cap X2) > \mathrm{Max}[q(X1), q(X2)]$	Enhance, double factors
$q(X1 \cap X2) = q(X1) + q(X2)$	Independent
$q(X1 \cap X2) > q(X1) + q(X2)$	Enhance, nonlinear

Table 2 The area proportion of ES trade-offs and synergies in each type of ECRL area

Regions	SC & WY		SC & CS		WY & CS	
	Trade-offs	Synergies	Trade-offs	Synergies	Trade-offs	Synergies
All ECRL areas of Beijing	32.82%	67.18%	13.71%	86.29%	41.39%	58.61%
Soil conservation ECRL areas	24.29%	75.71%	19.80%	80.20%	48.37%	51.63%
Water retention ECRL areas	35.80%	64.20%	9.90%	90.10%	37.58%	62.42%
Biodiversity maintenance ECRL areas	31.80%	68.20%	16.97%	83.03%	44.19%	55.81%
Important river and wetland ECRL areas	35.61%	64.39%	12.74%	87.26%	40.09%	59.91%

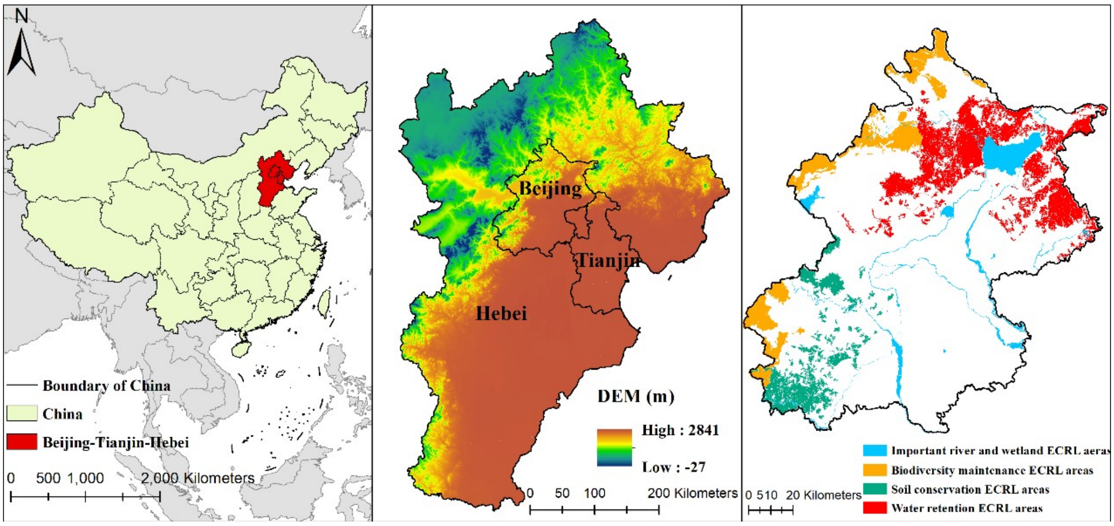

Fig.1 Location and type of the ECRL areas in Beijing

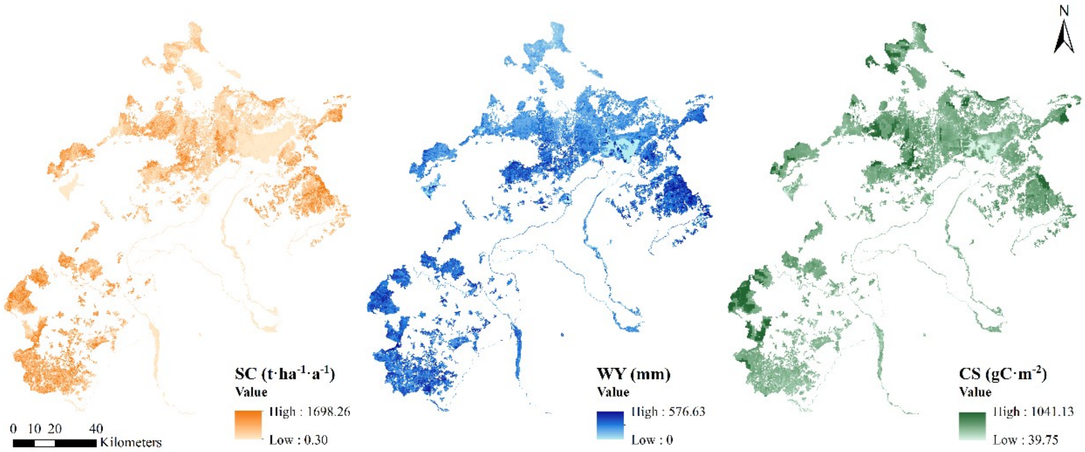

Fig.2 The spatial distribution of SC, WY, and CS in the Beijing ECRL areas

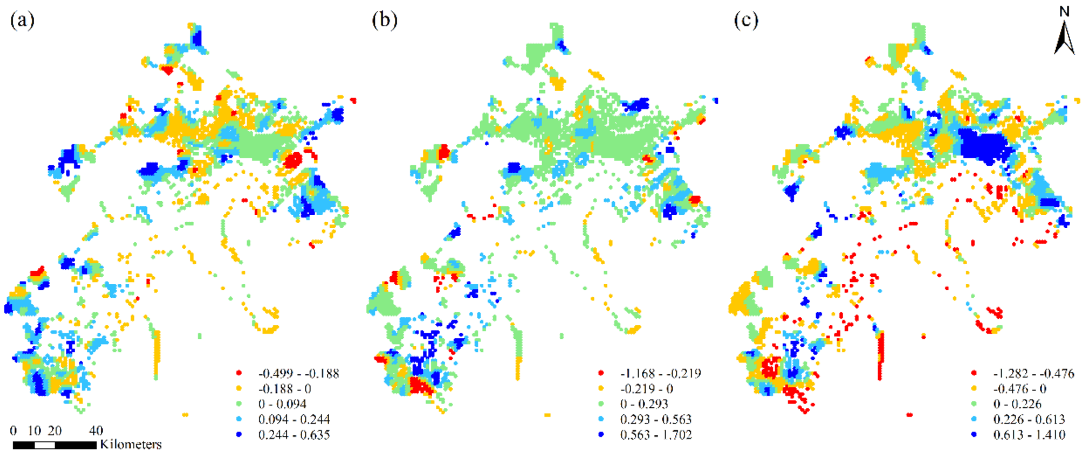

Fig.3 The spatial distribution of relationships between ESs in Beijing's ECRL areas (a) SC and WY, (b) SC and CS, (c) WY and CS

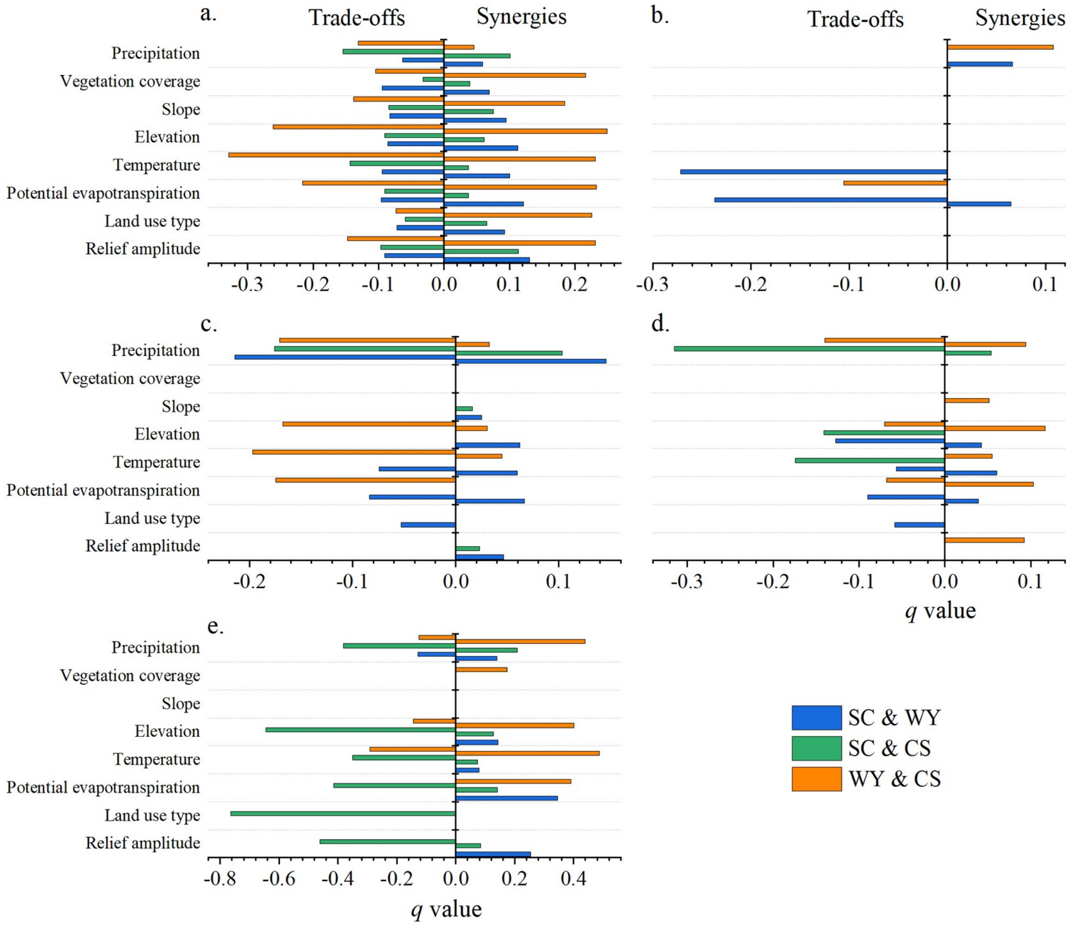

Fig. 4 The q values of factors influencing the spatial trade-offs and synergies of ESs in the ECRL areas of Beijing (a. all ECRL areas of Beijing, b. soil conservation ECRL areas, c. water retention ECRL areas, d. biodiversity maintenance ECRL areas, and e. important river and wetland ECRL areas)

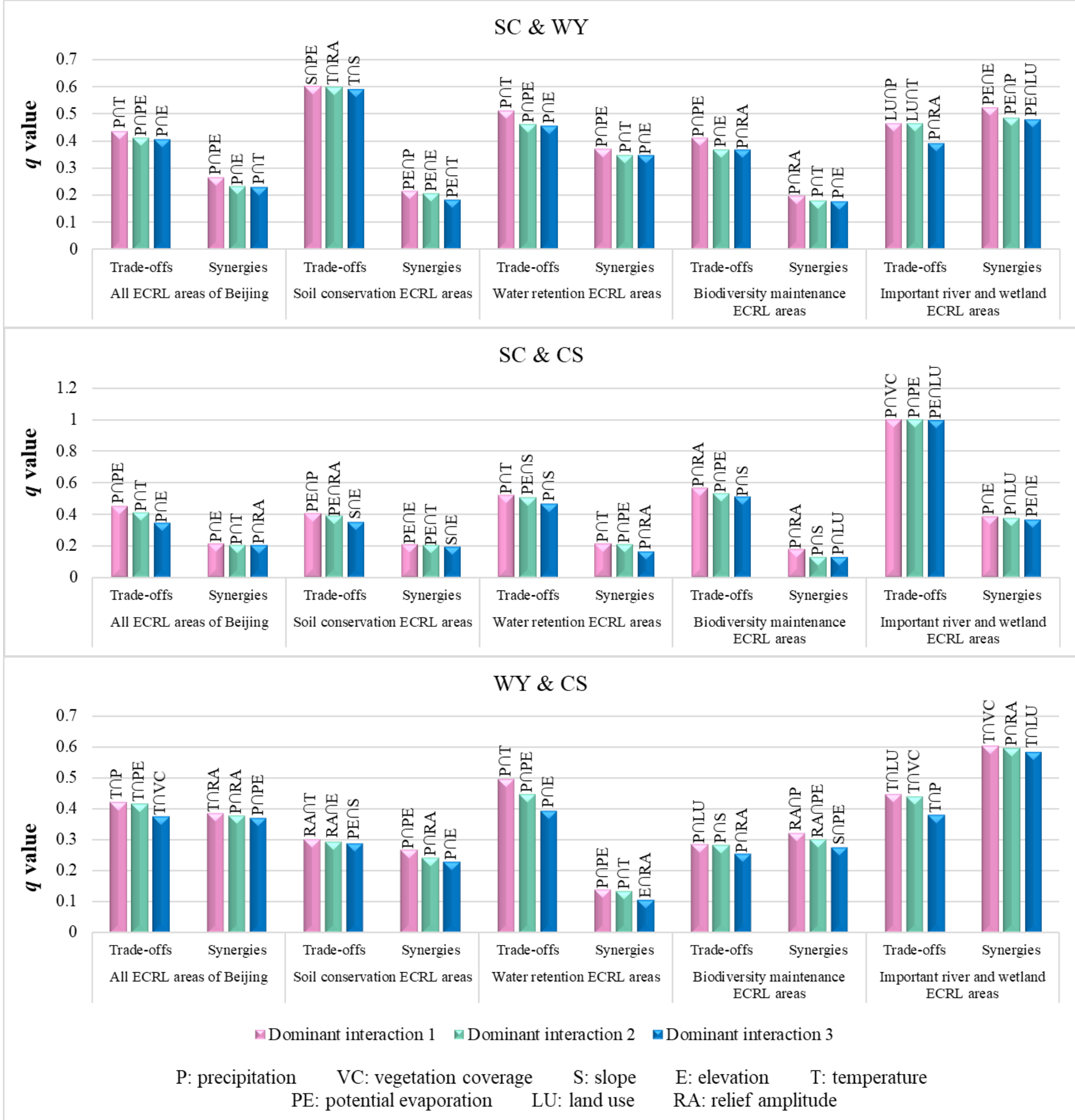

Fig. 5 The dominant interactions affecting the trade-offs/synergies in the ECRL areas of Beijing