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Synergies and Trade-Offs among Different Ecosystem Services through the Analyses of Spatio-Temporal Changes in Beijing, China

Qiurong Xu [1,*], Ruipeng Li [1], Jia Yu [1,2] and Pei Zhang [3]

1 School of Environmental and Geographical Science, Shanghai Normal University, Shanghai 200234, China
2 Key Innovation Group of Digital Humanities Resource and Research, Shanghai Normal University, Shanghai 200234, China
3 The First Institute of Surveying and Mapping of Hebei Province, Shijiazhuang 050031, China
* Correspondence: qiurongxu@shnu.edu.cn

Abstract: Increasing global urbanization has not only resulted in economic development but it has also caused a number of ecological issues, such as haze, global warming, and storm surges, which can end up hindering the development of human society in the long term. One method of maintaining the long-term growth of human ecosystems is by considering ecosystem services (ES) when making decisions over land use. This study provides information to aid with decision making in the maintenance of Beijing's ES provision in the long term. Firstly, three key ES, namely, carbon storage (CS), habitat quality (HQ), and water yield (WY), were evaluated by the InVEST model. Then, the spatial patterns of synergies and trade-offs among three ES at the city and grid scales were explored through the correlation coefficients analysis and geographically weighted regression (GWR). Finally, the strength of trade-offs among ES was calculated based on root mean squared error (RMSE), and the potential ecological risk areas are recognized. We discovered that (1) the total carbon storage decreases from 3.74 million tons in 2000 to 3.66 million tons in 2020, and HQ has the same trend, with its average value decreasing from 0.72 to 0.67; in contrast, water yield is more stable, increasing slightly from 8.22×10^{10} m^3 in 2000 to 8.23×10^{10} m^3 in 2020. (2) The synergies and trade-offs of ES are spatially heterogeneous. Among them, the correlation coefficients at the city-level indicated synergistic relationships among the three ES, but CS-WY and WY-HQ always have trade-off relationships at the grid level, where 37.88% of WY-HQ and 14.59% of CS-WY were trade-offs in 2020. (3) At the urban-rural interface, the trade-offs among ES are stronger than those in other regions. In rural-urban areas, the RMSE in CS-HQ, CS-WY and WY-HQ always had high values (>0.5), accounting for 16.72%, 9.33%, and 26.94% of the entire area, respectively; these areas are identified as potential ecological risk areas, which will be the focus area for future ES regulation. These findings provide opportunities for clear trade-offs among ES and promote positive synergies. In addition, land-use management may use the results to guide ecosystem service use, identify critical areas, and ensure regional sustainability in urban development.

Keywords: ecosystem services; trade-off; synergy; spatial heterogeneity

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1. Introduction

Ecosystem services (ES) are benefits derived from nature and are usually grouped into four categories (provisioning, regulating, supporting and cultural services) [1]. The Millennium Ecosystem Assessment revealed that ES protect both biodiversity and genetic diversity, offer benefits relevant to human well-being, and significantly influence ecological stability, social cohesion, and economic growth [2,3]. An ecosystem can provide several different ES simultaneously. In order to gain more access to a particular ES, humans are changing the inner composition of ecosystems (e.g., land-use changes) to utilize the resources of the ecosystem [4]. In recent years, ES have deteriorated, and conflicts have arisen as a result of increasing urbanization and exploitative human activities [5]. Examples include water scarcity [6], air pollution [7,8], soil erosion [9], reduced vegetation productivity [10,11], and reduced biodiversity [5]. People are becoming increasingly aware of the importance of protecting the natural environment, and the ultimate goal of ES research is to help decision makers develop ecological conservation plans more efficiently and effectively.

Understanding the factors involved in ES is crucial for achieving sustainable management [12]. Certain policy makers exploit the benefits of only one ES, ignoring the relationships between others, which can ultimately lead to their significant decline. ES do not exist independently but are a bundle of multiple ES. Despite the expectation that multiple ES can be simultaneously maximized, there are often complex and dynamic relationships among them [13]. Therefore, the synergies and trade-offs among ES are needed to be explored before making decisions on ecological conservation [14], rather than simply chasing a single benefit.

In the past few decades, the interactions between ES have received increasing attention [15,16]. The main research methods used to determine the relationships among ES are statistical methods [17], spatial analysis [18], scenario simulation [19,20], and clusters of ES [21,22]. Trade-offs and synergies are two types of interactions between ES [23]. With trade-offs, one service improves while another declines over time—for example, most communities in the Lanzhou region feature habitat quality and ecological recreation trade-offs [24]—and synergistic effects occur when services increase or decline simultaneously—for example, the degradation of natural habitats can reduce the soil and water conservation capacity [25]. Many researchers have investigated the synergies and trade-offs between ES using descriptive methods, regression analysis, and correlation coefficients analysis [26]. Among these methods, paired correlation coefficients have been widely employed to examine interactions between ES. For instance, Pan et al. explored the relationships between four typical ES in Jiajiu using correlation coefficients [18], whereas correlation and significance testing were applied in Huainan CMA-HGT region, and five ES trade-offs were investigated [27]. Statistical analysis methods have revealed the relationship mechanisms between ES, but the results lack spatial information [12]. Several studies are therefore now attempting to use spatial analysis to explicitly highlight the relationship between ES, such as spatial overlay analysis [28] and cold–hotspot analysis [29]. However, these approaches do not consider the spatial heterogeneity of landscapes. To demonstrate distinct regionally patterns of trade-off/synergy, geographically weighted regression (GWR) was used [30]. The above methods measure the degree of statistical dependence between two ES, but do not quantify the degree of trade-off between three or more ES. The root mean squared error (RMSE) approach has been proven to effectively quantify ES trade-offs between two or more ES [31,32]; however, few studies have spatially accounted for their strengths, an issue that requires further exploration [28,33]. Thus, it is crucial to describe the relationships and strengths between ES quantitatively using continuous spatial results for ecosystem management.

This study aimed to develop a comprehensive and rational way of evaluating the trade-offs and synergistic relationships among ES. A correlation coefficients analysis was used to identify global relationships between ES in Beijing, as this method considers no-effect relationships. A GWR was introduced to reveal the spatio-temporal heterogeneity of ES synergies and trade-offs. A RMSE was used to identify the strength of trade-offs among ES. With a low environmental carrying capacity, Beijing is a region representative of rapid urbanization. To examine the characteristics and creation mechanisms of this environmentally fragile region, it is crucial to investigate the interactions among ES. This study attempted to reveal whether there was a significant trade-off and synergy relationship between multiple ES from a spatio-temporal change perspective in order to provide more reliable decision support information for ecological conservation and land-use management. Specifically, the following objectives were addressed in this study: (1) to quantify three ES spatial patterns in Beijing from 2000 to 2020; (2) to identify ES relationships using correlation coefficients and GWR, and to identify the ES trade-off strength of change using

RMSE quantification; and (3) to explore the potential risks in changes in the interactions and mechanisms of ES throughout space and time. Our research findings can contribute to the protection of ecosystems, the establishment of scientific planning decisions, and the achievement of ecological sustainability in Beijing.

2. Materials and Methods

2.1. Study Area

Beijing is the capital of China, with 16 districts covering an area of 16,410 km^2 (Figure 1). The topography slopes from north to south, with an average elevation of 43.5 m. The terrain is mainly mountainous and hilly and is surrounded by mountains on three sides and plains to the east. The four different seasons occur in the typical temperate continental monsoon environment. In the last decade, there has been an average of 644 mm of precipitation and an 11 to 13 °C range in average yearly temperature. Beijing has witnessed rapid social and economic development, with its population expanding from 13.636 million in 2000 to 21.893 million in 2020.

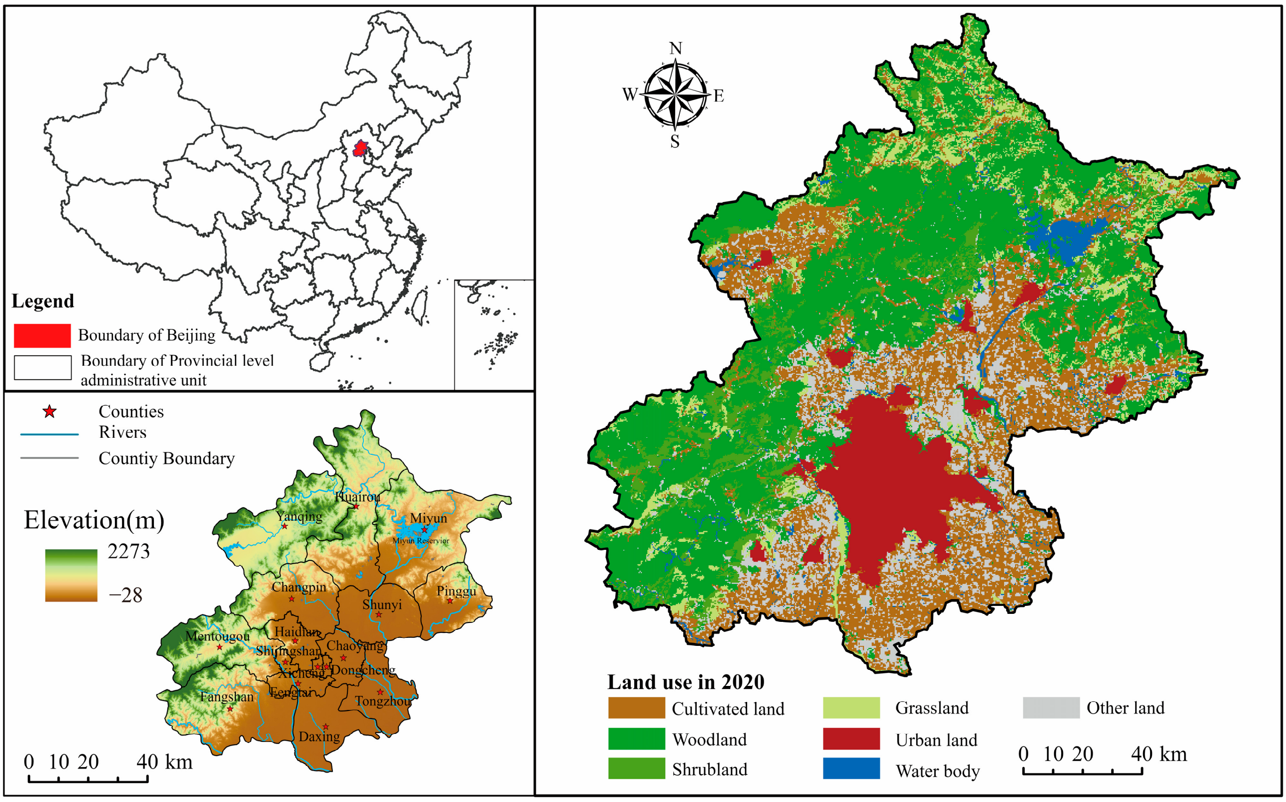

Figure 1. Geographical location of the study area and distribution of the land-use types in 2020.

2.2. Data Sources and Preparation

A multi-source, multi-scale l dataset was used (Table S1). In addition, we categorized the Landsat TM/OLI remote-sensing images into seven groups for land-use classification using ENVI: urban, cultivated land, grassland, forest land, shrubland, other land, and water bodies. The results were then corrected in ArcGIS 10.3 to obtain the 2000, 2005, 2010, 2015, and 2020 Beijing land-use maps. All results were examined using a random sampling method based on data from the Beijing forest resources survey and field survey information. The kappa coefficients of all the classification results were empirically over 0.8, satisfying the research requirements. To facilitate analysis, all grid data were uniformly resampled to 1000 m × 1000 m.

2.3. Quantification of ES

On the one hand, carbon storage (CS), water yield (WY), and habitat quality (HQ) are three key services that ecosystems provide to humans; on the other hand, water scarcity, greenhouse effect, and habitat conservation are concerning issues, and need to be addressed in Beijing and worldwide [12,34,35]. Therefore, considering the actual ecological issues in Beijing and data availability, three key ES (CS, WY, HQ) associated with the research field were selected.

2.3.1. Calculation of the CS Indicator

Carbon storage service was estimated by the InVEST carbon storage and sequestration model in this study. Aboveground biomass, belowground biomass, soil organic matter, and dead organic matter are four primary carbon pools in the ecosystems. In addition to the four basic carbon pools, the fifth type of carbon pool includes the carbon stocks of products such as wood, which represent the carbon of certain products that do not enter the atmosphere; their calculation needs to consider the rotation period of forest trees and the decomposition rate of carbon in wood products. There are large differences in harvesting operation patterns in different countries, and the relevant data are difficult to collect; therefore, this study does not consider the fifth type. The carbon storage and sequestration model is a pool-based alternative approach to monitor the carbon storage dynamics, mainly depending on the status of land-use classification and the carbon storage of four carbon pools to measure the current CS of a certain region. In the InVEST model, total carbon stocks were calculated as follows:

$$C_j = C_{above\_j} + C_{below\_j} + C_{soil\_j} + C_{\mathrm{dead}\_j} \tag{1}$$

$$C_{total} = \sum_{j=1}^{n} C_j \times S_j \tag{2}$$

where C_j, C_{above_j}, C_{below_j}, C_{soil_j}, C_{dead_j} represent carbon density (t·hm^{-2}), aboveground biological carbon density (t·hm^{-2}), belowground biological carbon density (t·hm^{-2}), soil carbon density (t·hm^{-2}), and dead carbon density, respectively; C_{total} and S_j represent total carbon storage (t) and area of seven land-use types (hm^2), respectively; and j represents 1, 2, ..., n, where n = 7.

2.3.2. Calculation of the WY Indicator

As one of the most basic services of ecosystems, water yield service is vital for human life and is controlled by several factors including vegetation type, precipitation, and transpiration. In this study, the WY in Beijing was evaluated using the water yield module in the InVEST model. The model estimates the relative contribution of water by calculating water runoff minus a portion of water evapotranspiration in precipitation for each pixel, and then subtracting water use to obtain the realized water supply. The theory of water balance and the Budyko curve are the foundation of the water yield model [36,37], and climate, land use, and other variables are used to estimate each grid's water yield $Y_{x,j}$ [38]:

$$Y_{x,j} = \left(1 - \frac{AET_{x,j}}{F_x}\right) \times F_x \tag{3}$$

where $AET_{x,j}$ represents the actual evapotranspiration of land-use type j in grid cell x, and F_x is the annual precipitation. As the actual annual evapotranspiration is challenging to obtain, the ratio of $AET_{x,j}$ to F_x can be expressed using the Budyko curve approximation.

2.3.3. Calculation of the HQ Indicator

A habitat or biological habitat is a natural environment that provides a living space for individuals and communities of organisms [39]. Habitat services refer to the capacity of natural ecosystems to offer an appropriate environment conducive to the long-term survival of communities. The effectiveness of biodiversity protection and the sustainability of human development are significantly influenced by habitat services [40]. The InVEST habitat quality module relies on human disturbance, land use, and expert knowledge to obtain dependable indicators of the response of biodiversity to threats [40]. The model was run on raster data, with each grid associated with a land-use type. Different land-use types must first be defined as habitat or non-habitat land, and a numerical value from 0 (non-habitat land) to 1 (highest habitat land) indicates the relative habitat suitability of the various land-use types. This module calculates the habitat condition on grid cell by specifying the threat sensitivity of each land-use category, external factor threat level, threat factor influence distance and influence weight, etc. The equation for calculating $HQ(i)$ is as follows:

$$HQ(i) = S(n) \times \left[1 - \left(\frac{D_i^z}{D_i^z + K^z}\right)\right] \tag{4}$$

where $HQ(i)$ is the grid i's habitat quality; $S(n)$ represents the habitat suitability associated with land-use category n; D_i represents the degree of habitat degradation of grid i; K represents the coefficient of half-saturation.

2.4. Quantification of Synergies and Trade-Offs of ES

Subsequently, to learn more about how ES synergies and trade-offs are distributed geographically, correlation analysis, GWR, and RMSE methods from regional, grid, and the strengths of trade-offs were analyzed.

2.4.1. Pairwise Trade-Offs between ES Using Correlation Analysis

Analysis of the degree to which two or more variables are related is the goal of correlation analysis, which also serves to characterize the relationships between the variables through the use of appropriate statistical indicators. Correlation analysis is a standard tool for investigating correlations between ES, and its value indicates the degree of correlation between ES [23]. When two ES are positively correlated, there is a synergistic relationship between them, whereas when they are negatively correlated, there is a trade-off between them. If the ecosystem service data are normally distributed, the Pearson correlation coefficient approach can be applied for examining correlations; otherwise, the Spearman correlation coefficient method can be used. As not all data from ES are normally distributed, the Spearman coefficient approach was used [41,42]. In this study, the correlation coefficients between ES in Beijing were dynamically analyzed based on the R 4.0 software.

2.4.2. Spatial Synergies and Trade-Offs Based on GWR

We investigated the spatial correlation between ES using a GWR model, which is a spatial relationship model that serves as an extension of correlation analysis. Spatial coordinates were added by GWR to the variables in the regression equation. Not only can this model effectively deal with spatial heterogeneity and spatial correlation, but it also considers the spatial weights of adjacent regions and allows for local parameter estimation instead of global parameter estimation, which is a relatively simple but effective method for detecting spatial non-stationarity. GWR has the following form:

$$y_i = \beta_0(u_i, v_i) + \sum\nolimits_n \beta_n(u_i, v_i)x_{in} + \varepsilon_i \tag{5}$$

where y_i is the dependent variable's value at location i; (u_i, v_i) is point i's spatial location; $\beta_0(u_i, v_i)$ is the intercept at location i; $\beta_n(u_i, v_i)$ represents the regression coefficients; x_{in} is the independent variable's value. Positive regression coefficients, as in the Spearman correlation analysis, signify spatial synergies, whereas negative regression coefficients signify trade-offs. The GWR model was executed on grid scale using the R 4.0 program in this study.

2.4.3. Trade-Off Strength Based on RMSE

In addition to the spatial synergies and trade-offs derived through GWR, the strength of ES spatial trade-offs was also investigated. RMSE is a statistical parameter that characterizes the standard deviation between predicted and true values and is the index that quantifies the trade-off strengths between ES [32]. The RMSE means the distance from the coordinates of the ES pair to the 1:1 line in two dimensions, and the relative position of the data points to the line represents which ES is more beneficial (Figure S1) [32,43]. For example, the trade-off strength is 0 at point A, and the segment BC length means the trade-off strength for point B. This method extends the ES relationship from traditional positive and negative correlations to characterize the uneven rate of change of ES in the same direction, allowing a visual representation of trade-offs. It provides a description of the trade-off strength in terms of the comparative difference between ES [44]. The RMSE is thought to be straightforward and useful to measure the trade-off strength among ES [45].

3. Results

3.1. Analysis of the Spatio-Temporal Dynamics of ES

The three ES were quantified and mapped for the years 2000 and 2020 (Figure S1). Total carbon storage in 2000 was 3.74 million tons (average of 205.93 t/ha), while total carbon storage in 2020 was 3.66 million tons (average of 199.31 t/ha). High-carbon stocks were concentrated in the northeast, with a maximum value 355.68 t/ha, whereas low-carbon stocks are primarily concentrated in central urban area, with a minimum of 0 t/ha. The overall WY is stable, with the total water production slightly increasing from 8.22×10^{10} m^3 in 2000 to 8.23×10^{10} m^3 in 2020. In particular, the high-value areas were primarily in the hilly forest of the northeast, whereas the low-value parts were located in central urban areas. The overall HQ trend is downward, with the mean habitat quality decreasing from 0.72 in 2000 to 0.67 in 2020, mainly due to urban growth caused by the replacement of the original habitat by urban areas.

To facilitate comparison between years, ES were standardized from 0 to 1 (low to high). By comparing the average ES value changes among various land-use categories (Figure 2), CS and HQ of urban, other land, and water all showed a significant decrease, whereas WY did not change significantly. This finding indicated that CS-HQ may have a highly synergistic relationship. Regardless of land-use type, the WY value is always the highest (>0.77). Woodlands had the highest CS and HQ functions, and the average CS and HQ of woodlands increased from 0.77 and 0.89 in 2000 to 0.87 and 0.90 in 2020, respectively. Urban land has the lowest CS and HQ, and the average CS and HQ of urban land have a significant decreasing trend, with CS and HQ decreasing from 0.16 and 0.21 in 2000 to 0.03 and 0.05 in 2020. This result shows that different land uses reflect different natural functions, and it can help create a better understanding of ecological synergies and trade-offs by the examining ES priority for each land use.

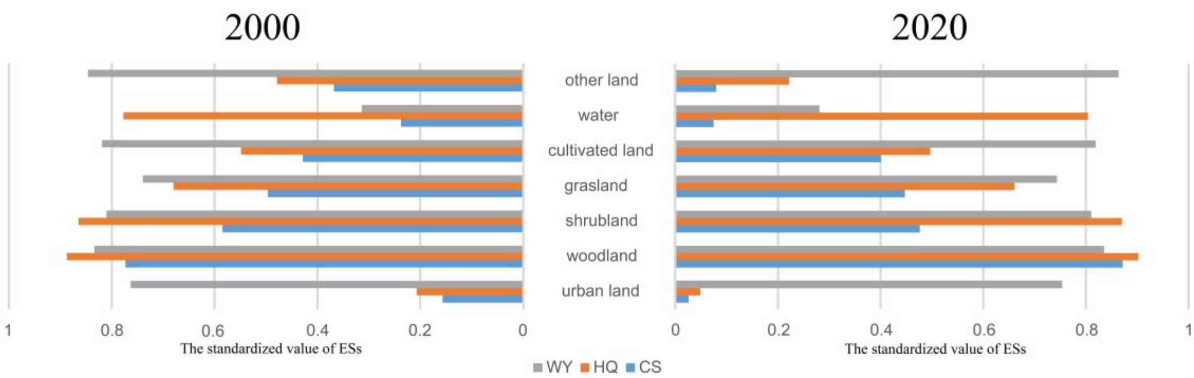

Figure 2. The average value of CS, WY, HQ among different land-use types in 2000 and 2020.

3.2. Synergies and Trade-Offs of ES

Table 1 shows the correlations between three ES pairs from 2000 to 2020, and the results show an overall synergistic relationship in the study area. In the ES literature, a correlation coefficient of 0.2 is often considered as a meaningful correlation [26,46], so the ecosystem services pairs do not have a "no effect" relationship in this study. According to the correlation coefficient results, although fluctuating at intervals, the CS-HQ pair showed a strong synergistic relationship (2000: r = 0.77; 2020: r = 0.78). There was a reduced fluctuation of synergies in CS-WY (2000: r = 0.40; 2020: r = 0.35). The same trend of synergy relationship exists in HQ-WY (2000: r = 0.34; 2020: r = 0.26). Overall, the strongest synergies in Beijing from 2000 to 2020 were found in CS-HQ, with a mean value of 0.78, and HQ-WY was the weakest, with a mean value of 0.32.

Table 1. The correlation coefficients between three ecosystem services from 2000 to 2020.

Year	CS-HQ	CS-WY	HQ-WY
2000	0.77 **[1]	0.40 **	0.34 **
2005	0.80 **	0.39 **	0.33 **
2010	0.75 **	0.34 **	0.30 **
2015	0.81 **	0.43 **	0.37 **
2020	0.78 **	0.35 **	0.26 **

[1] ** indicates significant correlation at the 0.01 level.

The ultimate goal of trade-off studies is to scientifically manage the trade-off relationships between ES. Areas with strong synergistic relationships serve as a spatial guide for areas that exhibit trade-offs or weak synergistic relationships and help promote the development relationships among ES. The GWR results revealed the spatial distribution of ES relationships in Beijing from 2000 to 2020 (Figure S3). The proportion of the ES synergies and trade-offs areas was then calculated (Figure 3). The CS-HQ pair showed synergistic relationships in most areas of Beijing from 2000 to 2020, with synergies accounting for 98.99% in 2000 and 99.13% in 2020. Strong synergistic areas gradually spread from Huairou District to the entire city, and most areas in Pinggu District, Yanqing County, and Fangshan District developed strong synergistic relationships by 2020. In contrast, a trade-off relationship occurred around the Miyun Reservoir, which is also a manifestation of the carbon sequestration capacity of water bodies, with 1.01% ES trade-offs areas in 2000 and 0.87% in 2020. There was a smaller CS-HQ trade-off in 2010 in the central urban and western regions, and the proportion of ES trade-offs areas was 1.13% more than that in 2020. The overall change in the CS-WY trade-offs and synergistic relationships in Beijing from 2000 to 2020 were not significant, and most ES correlations were concentrated in the low trade-off (12.07% in 2000 and 12.33% in 2020) and low synergy regions (73.42% in 2000 and 76.80% in 2020). This trade-off is mostly found on urban land in central Beijing. The region with a strong synergistic relationship in the surrounding area of Pinggu and Yanqing is decreasing, but the area with a strong trade-off relationship in Fangshan District is increasing. Most regions of the Beijing HQ-WY showed a trade-off relationship, with 62.55% in 2000 and 62.12% in 2020. The HQ-WY trade-off in Beijing is located roughly in the northwest, and a synergistic relationship is distributed in the southeast. Both strong synergistic and strong trade-off areas in the HQ-WY pairs declined between 2000 and 2020, decreasing from 2.87% to 0.53% in 2020, and from 2.44% to 0.18% in 2020 for strong trade-off and strong synergistic areas, respectively.

To further quantify the trade-offs strength among ES, locate high-value areas of trade-offs, and enable more target-oriented management, we conducted a trade-off degree analysis of the RMSE based on the above relationships (Figure S4), and counted the area proportion of each division (Figure 4). In 2000, the area with a higher RMSE (>0.4) for the CS-HQ pair continued to spread from Beijing's major urban region, making up 16.38% of the entire area. The area with the highest RMSE (>0.6) around the main urban area tended to constantly grow and significantly decrease, with the percentage of areas with an RMSE greater than 0.6, ranging from 10.80% in 2000 to 0% in 2020. The RMSE of the CS-WY pair did not vary significantly in the study period, and locations with a high RMSE (>0.6) were primarily spread in Beijing's central urban area and surrounding the Miyun Reservoir, accounting for 7.51% of the total area in 2000 and 7.33% in 2020. Moreover, the spatial patterns of RMSE for CS-HQ and HQ-WY perform identically. The RMSE of the HQ-WY pair showed no substantial spatial variance, and the RMSE stayed low (<0.3) in most areas, with a percentage of 54.92% in 2000 and 58.36% in 2020, except for the main urban area, which had high values (>0.5), accounting for 34.88% in 2000 and 26.94% in 2020.

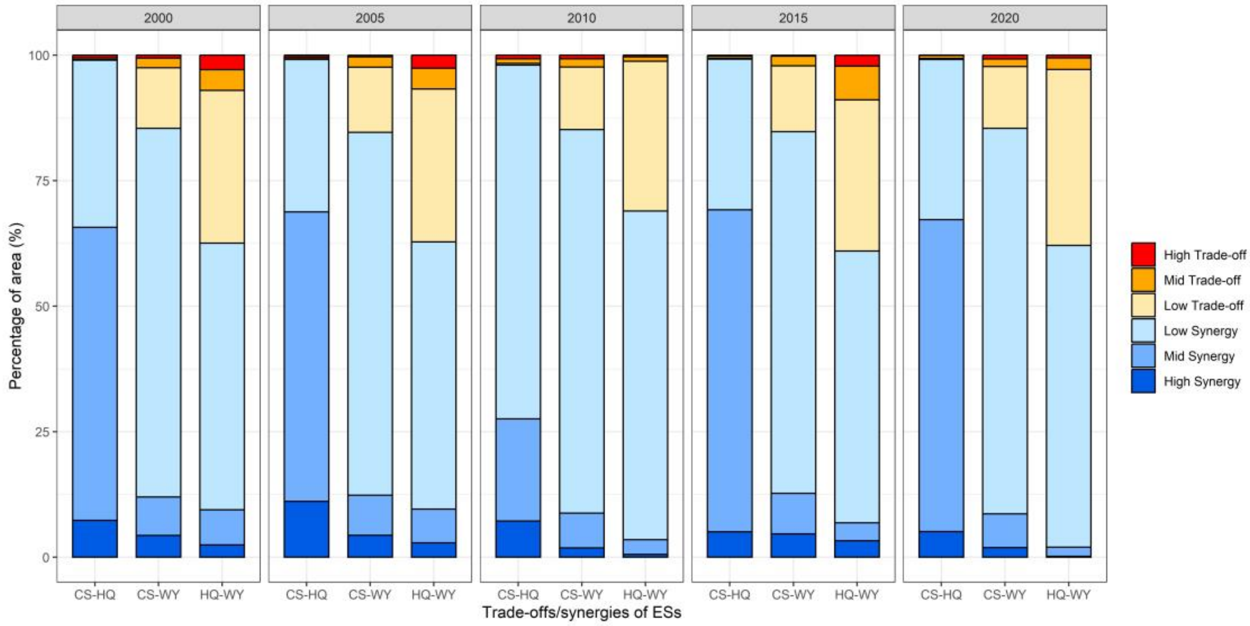

Figure 3. The proportion of the spatial synergies and trade-offs between ES in Beijing in 2000, 2005, 2010, 2015 and 2020.

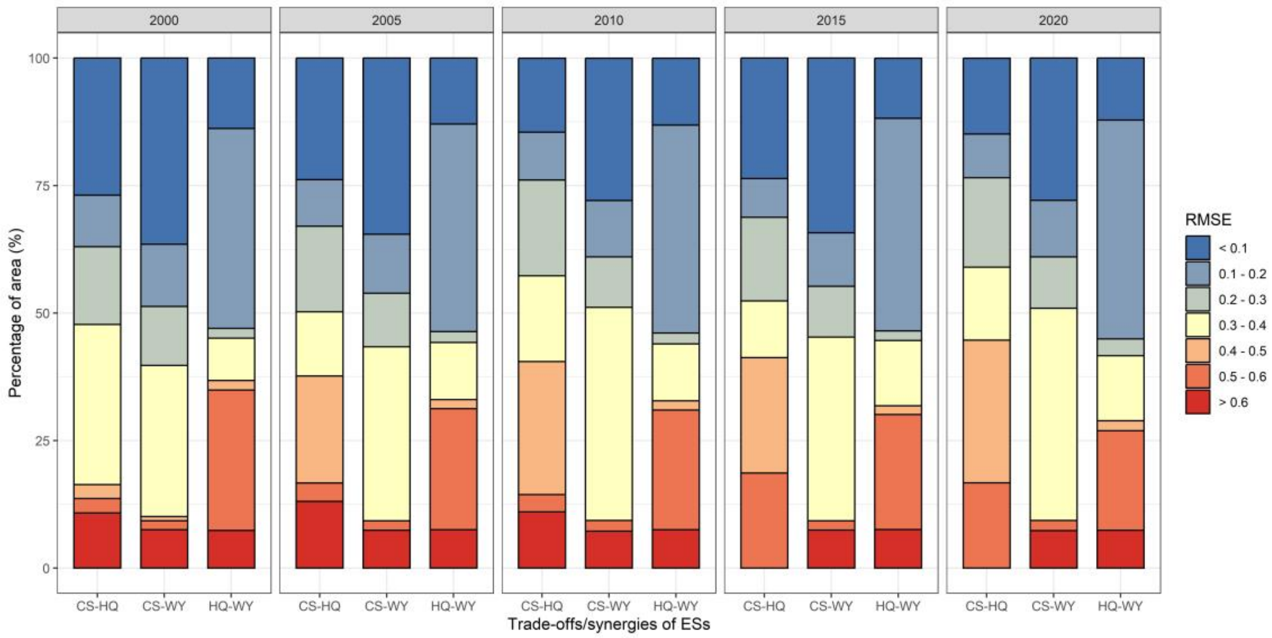

Figure 4. The percentage of the total are under different RMSE for ES pairs of Beijing in 2000, 2005, 2010, 2015 and 2020.

4. Discussion

4.1. Complex ES Synergies and Trade-Offs and Management Suggestions

Understanding the complex interrelationships between ES is key to effectively planning and managing ecosystems. Regarding the spatial distribution of ES in Beijing from 2000 to 2020, all three ES exhibited similar patterns, with high ES values concentrated mostly in mountainous and hilly areas. Carbon sinks and intact habitats are provided by continuous and extensive forest landscapes [47]. Changes in regional ES tradeoffs vary with land use, climate, vegetation type, and other factors. The same ecosystem service is expressed in different ways for different land-use types. Increasing concerns about the effects of declining ES and human welfare can be seen in reactions to land-use changes [48]. Forests had higher CS and HQ values than other land types (Figure 2) [49,50]. Areas with high CS and HQ were often primarily forested, indicating that the most essential land use for carbon stocks and habitat quality is forest. Likewise, since the land-use type in most areas in Pinggu District, Yanqing County, and Fangshan District is dominated by forest, CS-HQ primarily exhibits a strong synergistic relationship in these areas. It can be seen that Beijing has been influenced by the Grain for Green program, and has paid more attention to protecting forest land over the past two decades. Shrubland increased in patches, with large shrublands appearing at the junction of the Mentougou and Fengtai districts, likely due to the influence of large-scale afforestation policies and the Grain for Green program. Grasslands have decreased and are mainly used to replenish croplands or convert to forest land in the form of ecological compensation [51,52]. Although policies such as reforestation improve services such as carbon storage and habitat quality, the increased forest has led to a higher consumption of water, thus reducing surface runoff and ultimately leading to water shortages [25]; this, to some extent, results in WY-related ES trade-off. Figure S4 indicates that the RMSE values in the cultivated areas (concentrated in the urban periphery) are lower, suggesting that cultivated land can better support ES synergies, which is the same as previous studies [32]. Therefore, soil moisture and precipitation need to be studied in future research to select appropriate plant species and density, and in-depth assessments of the long-term impacts of eco-engineering on specific trade-offs are necessary. In addition, climate change leads to trade-offs; for instance, we found more trade-off relationships in the ES pairs associated with WY. This is possibly related to the variance of climatic variables such as precipitation, which is consistent with previous findings [21], and an increasing number of studies have shown that ES are sensitive to climate change [53,54]. Owing to specific geographical conditions, there are also complex variations in precipitation and temperature differences that can have a significant impact on multiple ES [55], ultimately leading to changes in ES synergies and trade-offs. Against the background of a warming climate, increasingly dramatic fluctuations in global precipitation [56], and the scarcity of water resources in Beijing, the important part to scientifically address are the changes in precipitation resources in the region in order to regulate changes in water conservation and minimize trade-offs with other ES. In addition, the area with a strong trade-off relationship in CS-WY in Fangshan District increased from 2000 to 2020. This change in the trade-off in CS-WY may be attributed to an urbanization-induced reduction in cultivated areas, making vegetation significantly less able to sequester carbon and retain water. Furthermore, it should be noted that the trade-offs in CS-WY and WY-HQ are stabilizing, mainly because of the transition of a large area of vegetation to building land, and the effect of land use on water production has diminished. Increased urbanization has exacerbated this problem, making metropolitan areas more susceptible to floods and droughts [57,58]. Hence, actions (e.g., urban greenspace development and Grain for Green) are required to minimize the possible detrimental effects of urbanization on these critical ES. Finally, it was observed that various synergies and trade-offs vary at different scales [18,59]. For example, in this study, although the three ES showed synergistic relationships in the study area, they had different degrees of trade-offs at the grid scale. Therefore, the grid was used for identifying areas of synergies and trade-offs among ES and achieving spatial and quantitative displays to avoid ignoring the spatial heterogeneity among ES relationships.

4.2. The Strength of Trade-Offs and the Potential Ecological Risk Areas

This study further quantifies the trade-off strengths among ES, and locates the high- and low-value areas of trade-offs based on RMSE, which allows for more targeted management. The central region and southern plain of Beijing are flat and widespread with urban areas, arable land, and villages, and are the main human settlements. The HQ and CS have declined due to dramatic changes from cultivated and forest land to urban regions [60]. It is noteworthy that the trade-offs among three ES are significant in most urban-rural regions. This may have had a significant impact due to the ecoregion's heterogeneous ES (edge effect). The rural-urban rim is a type of ecoregion that combine the features of two neighboring ecosystems with greater species richness and/or landscape diversity [61]. Understandably, the largest proportions of synergies and trade-offs occur in urban and rural-urban peripheries; that is, all paired ES exhibit substantial proportions of trade-offs at rural-urban fringes. Furthermore, these regions have the strongest relationships between ES. For instance, the strength of the trade-off in CS-HQ remains high near urban areas with values above 0.6. In addition, the RMSE in CS-HQ, CS-WY, and WY-HQ in rural-urban areas always had high values (>0.5), accounting for 16.72%, 9.33%, and 26.94% of the total area, respectively.

The trade-off strengths spatial distribution provides a corresponding foundation for the partition management of ES [32]. The strong trade-off areas among the three ES are relatively similar, mostly concentrated in rural-urban fringe areas, which will be the focus areas for future ES regulation as potential ecological risk areas. Based on these results, we suggest that at most one service can be developed in areas with a high trade-off strength, and ES can be developed synergistically in areas with a low trade-off strength. The study provides an in-depth understanding of the trade-offs among ES and informs research on the drivers and mechanisms related to ES trade-offs.

4.3. Limitations and Perspectives

The characteristics of the three ES in space and time were explored, and the spatial distribution of their interrelationships and strengths were clarified in the study, offering appropriate theoretical supplies for the conservation and improvement of ES. There are, however, still shortcomings in the research process that need to be addressed and improved in the future.

ES depend on dynamic and interactive spatial processes; however, our understanding of these processes is limited. Therefore, a comprehensive study of ES should further strengthen the study of the evolutionary mechanism of ecosystem structure, processes, functions, and services from multi-temporal, multi-scale, multi-level and multi-factor systems. Future research will identify, assess, and explain multi-scale ES trade-off interactions to promote spatially explicit ecosystem management.

5. Conclusions

This study quantified CS, WY, and HQ in Beijing from 2000 to 2020 based on multi-source data, analyzes their spatial and temporal trends, and evaluates the synergies and trade-offs among ES at city and grid levels. The findings were as follows: (1) From 2000 to 2020, the three ES distributions show spatial heterogeneity, among which both CS and HQ show a continuously decreasing trend and a significant variation in the spatial pattern and the water yield fluctuates, but its variation is not significant during this period. (2) Quantitatively, there was an overall synergistic effect between the three essential ES at the city-level. Different ES pairs have different synergies and trade-offs at the grid level, and it was revealed that ES synergies and trade-offs were significantly heterogeneous. Moreover, the synergistic relationship in CS-HQ was stronger than the other pairs in the research area, and WY exhibited trade-offs with other ES at the grid level. (3) The trade-off strengths among ES tends to be larger in urban-rural areas than in other places. Since transition zones can be complex, urban-rural fringe areas are potential ecological risk areas for action and behavior substitution in sustainable ecosystems. By observing the dynamics of ES over a long time series and analyzing the synergies and trade-offs relationships as a whole and spatially, we can create a foundation for the development of science-based ecological conservation policies in the region.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12051000/s1, Figure S1: illustration of the trade-offs strength between two ecosystem services. Figure S2: spatio-temporal distributions of three ecosystem services in Beijing from 2000 to 2020. Figure S3: the spatial distribution of ES synergies and trade-offs of Beijing in 2000 (a), 2005 (b), 2010 (c), 2015 (d), and 2020 (e). Figure S4: variation of RMSE across three ecosystem services of Beijing in 2000 (a), 2005 (b), 2010 (c), 2015 (d), and 2020 (e). Table S1: model input and data sources [38,62,63].

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