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Area Threshold Interval of Urban Forest Patches Required to Maintain the Synergy between Biodiversity Conservation and Recreational Services: Case Study in Beijing, China

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Abstract: Promoting sustainable urban development is crucial in light of upcoming environmental change and population expansion. Urban forests play a key role in transporting ecosystem services to urban areas. They not only offer a crucial biological setting for preserving urban biodiversity, but they also give recreation dwellers access to a variety of urban opportunities and ensure their spiritual and cultural needs are met. Maintaining urban biodiversity and offering recreation services have trade-offs and synergies, and both were highly connected with the size of an urban forest patch. Six districts in Beijing's central urban area were chosen for this study to serve as the research objective. First, the MSPA model was employed to conduct a thorough scientific analysis of the pattern and distribution characteristics of urban forests in Beijing's central urban area. Second, the recreation services were quantified by merging many sources of big data, the urban forest biodiversity preservation services were assessed using the InVEST model, and the spatial heterogeneity of the two services was examined. In conclusion, the coupling coordination degree model was utilized to calculate the crucial threshold interval between urban biodiversity service and recreation service for urban forest patch area. The findings indicated that the ideal urban forest patch scale for achieving the synergy of the two types of services was an area between 0.5 and 1 hectare. The outcomes can serve as a scientific foundation for urban forest planning and management in the future, assist in realizing the synergistic growth of the two services, as well as support the improvement of ecosystem services and the ecological welfare of people.

Keywords: urban forest; biodiversity conservation services; recreational services; synergy; threshold interval

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1. Introduction

Global urbanization has continually advanced since the Industrial Revolution, and the human settlements space is undergoing global alterations [1]. Currently, 55% of the world's population resides in urban areas; by 2050, this proportion is expected to rise to 68%, and urban areas are developing rapidly to meet this growth [2]. Urbanization has taken the lead in transforming the global landscape as the hub of economic, social, and cultural development [3]. Due to decades of intensive, high-density, and high-speed urbanization growth in China, the nature of urban land use has undergone tremendous changes and structural adjustments. Several environmental issues, including climate change, urban flooding, and biodiversity loss, have also posed a major threat to the health of the local population. Meanwhile, environmental deterioration has also increased urban dwellers' demands for green recreational space. Therefore, people pay more and more attention to the direct interaction between people and the environment, as well as various problems caused by environmental degradation [4–8]. Urban green space plays an important role in preserving the equilibrium of the urban ecosystem and improving the living environment of residents. It is also the key to alleviate various environmental problems [9,10]. As the conflict between human existence and the environment grew more serious, relevant experts started to think about the way of coexistence between human and nature. The idea of "urban forest" was born. Introducing forests into urban interior and suburbs is an important measure to readjust the relationship between human, society, and nature and promote the coordinated development of cities and ecosystems [11].

The term "urban forest" is used to describe a network or system composed of all woodlands or tree groupings, including individual trees located in urban and suburban areas, street trees, trees in parks, and trees and gardens in abandoned corners. It is an important component of a city [12]. Urban forests not only provide essential ecological spaces, but also have a positive impact on the well-being of urban residents [13,14]. Within the city, urban forests provide a variety of ecological services and socio-economic benefits for human beings, such as improving climate, regulating hydrological cycles, offering habitats for animals and plants, and providing space for recreation and spiritual enjoyment [15–17]. Consequently, urban forest is an important space for maintaining the health of urban residents, ensuring the sustainability of economic and social growth, and preserving urban biodiversity, which can provide an important ecosystem service [18]. The urban forest is not only the most important carrier of urban biodiversity but also the most important recreational space for urban residents. Therefore, the two primary types of ecosystem services offered by urban forests are biodiversity preservation and recreation functions for urban residents [19,20].

Urban biodiversity plays a vital role of maintaining the stability and function of urban ecosystems and is a key objective for the scientific planning of urban forests [21,22]. Numerous urban construction practices seriously harm the habitats of animals and plants throughout the development process, which results in biodiversity loss, habitat degradation, and other urban problems [23]. According to several ecological studies, urban biodiversity is impacted by various land use types, urban architectural styles, and socioeconomic conditions [24–27]. Among these, forest types, urban forest characteristics, and urbanization have considerable effects on urban biodiversity [28]. Nonetheless, few studies have explored the relationship between the patch size of urban forest and biodiversity. In addition to requiring expensive fieldwork, the existing functional evaluation approaches for biodiversity conservation in urban forests are primarily transformed to ecosystem service value assessment [29]. Studies have confirmed that habitat quality assessment, as an indicator of a space's capacity to offer resources and support the survival and reproduction of species, can accurately evaluate biodiversity. The higher the habitat quality is, the higher the biodiversity level is [30,31]. The fundamental strategy for protecting biodiversity is to improve habitat quality [32–34]. Habitat quality typically declines as human land use increases [35,36]. The research and application of ecological models like SolVES (Social Values for Ecosystem Services) [37], ARIES (Artificial Intelligence for Ecosystem Services) [38], and InVEST (Artificial Intelligence for Ecosystem Services) has emerged as the most important technique for determining the quality of a habitat as a result of the advancement of remote sensing technology [39]. It is possible to examine habitat quality more logically and scientifically. The InVEST model jointly developed by Stanford University, the Nature Conservancy (TNC), and the World Wide Fund for Nature (WWF), is the most widely used [40,41]. Related studies have also confirmed that the InVEST model can effectively assess habitat quality, and it can be used as a tool to scientifically measure the function of biodiversity conservation in urban forests [42–45].

Urban forests are desirable locations for recreation due to their topographical advantages and rich natural surroundings. Compared with parks, urban forests have distinctive aesthetic value and relatively good accessibility. Therefore, urban residents increasingly engage in leisure activities in urban forests. Urban forests can offer important recreational services to urban residents while also highlighting the contribution of forest recreation to urban economic development [46–49]. Human activity has an important impact on the development of urban forest characteristics since it is a significant component of urban landscape [50]. From the perspective of users, residents' recreation needs for forests vary greatly according to their different residences. The larger the city, the greater the demand for forests adapted to recreational purposes. The needs of the urban population in relation to the recreational function of forests are also important for the construction of urban forests. At the same time, the scale of urban forest will also affect the recreation willingness of tourists to a certain extent [51]. Some studies have also deeply analyzed the impact of different forests' features on the quality of forest landscapes. Terrain slope, forest site humidity, and age of tree stands are the three main factors which have a strong relationship with the aesthetic quality of forest landscape. The four supporting impacts are stand density, presence of undergrowth and underbrush, soil cover, and species composition of the stand [52,53]. At the same time, the recreational carrying capacity of forests is not unlimited. Scientific management of the recreational behavior of urban forests is also crucial for balancing the protection of urban forests and improving the recreational potential of urban forests [54]. Additionally, the scale of urban forest will also affect the recreation willingness of tourists to a certain extent [55]. As a result, urban forest development must strike a balance between promoting social, economic, and environmental sustainability while completely accommodating inhabitants' requirements. It is crucial to scientifically evaluate the recreational services of urban forests [56]. The existing evaluation of urban forest recreational service function mostly evaluates the recreation value of large-scale urban forest from the perspective of market value and alternative function [57], or uses the Scenic Beauty Estimation Method (SBE) model to study the recreational attraction of urban forests for different users with the object of individual urban forest plots [58]. Nonetheless, there are few studies that quantitatively assess the function of urban forest recreational services at the pattern scale. Related research shows that the location conditions of tourists for urban forest, the accessibility of tourists, and the development potential of an urban forest area are of great significance to promote the optimal development of urban forests [8,59].

Maintaining biodiversity and providing recreational services are the main ecosystem services that urban forests can provide in highly urbanized metropolises. There is a certain trade-off and synergistic relationship between the two services [60,61]. Decision-makers can be assisted in planning and designing urban forests logically via scientific examination of the two types of services. Among these, the size of the urban forest patch is an important factor for determining the pattern of the urban forest. An essential component of urban forest structure that directly influences the ecosystem services provided by urban forests is the patch area [62]. Related studies have revealed that the functions of various patch sizes for ecosystem services vary significantly in less stable ecosystems. The patch size is also the primary factor affecting various ecosystem services [63–65]. However, the majority of recent studies on the size threshold of urban forest patches examine it as one of the parts of the general characteristics of the urban forest distribution pattern [66–68]. Studies on the impact of urban forest patch size on ecosystem services mostly concentrate on the impact of patch size on carbon sink benefits, PM2.5 and PM10 distribution, soil respiration, benefits of cold islands, and other ecosystem regulating services [69–71]. There are limited studies on the relationship between cultural services represented by recreational services and support services for biodiversity conservation. In addition, prior studies on the relationship between urban forest patch area threshold and ecosystem services tended to concentrate on a single service [72]. The complex relationship between the synergistic promotion of two types of services and urban forest patch area threshold has not been investigated.

Six districts in Beijing's central urban area are the subject of this study. With the fastest development and expansion, Beijing is one of the core cities in Asia [73]. The rapid socioeconomic development and the lack of urban construction land have posed a severe threat to the sustainable development of Beijing [74]. Urban forest is an important component of urban ecological environment construction. Taking Beijing as an example, we have scientifically investigated the scale of urban forest construction and provided the maximum biodiversity conservation and recreational services possible. The specific aims of the study were as follows: (1) scientifically analyze the distribution characteristics of urban forests in the central city of Beijing; (2) quantify the biodiversity conservation and recreational services and evaluate the spatial heterogeneity of the two services; (3) determine the key area threshold interval of urban forest patches required to maintain the synergy between biodiversity conservation and recreational services; (4) propose a research framework to study the urban forest patch area threshold for the optimal co-benefit of two ecosystem services (Figure 1).

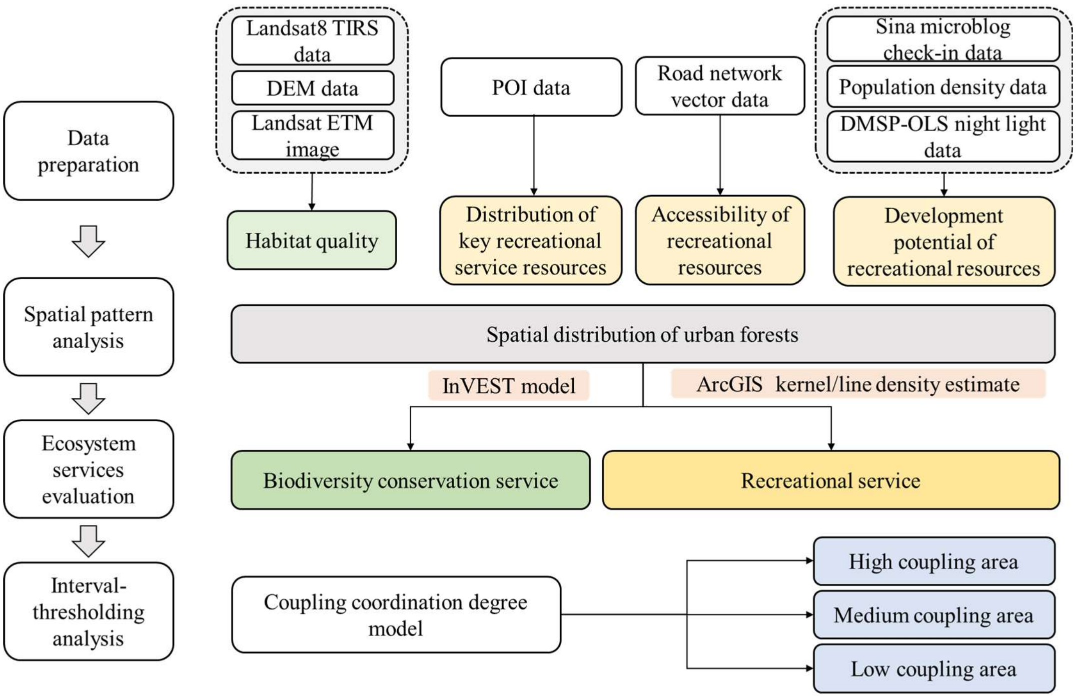
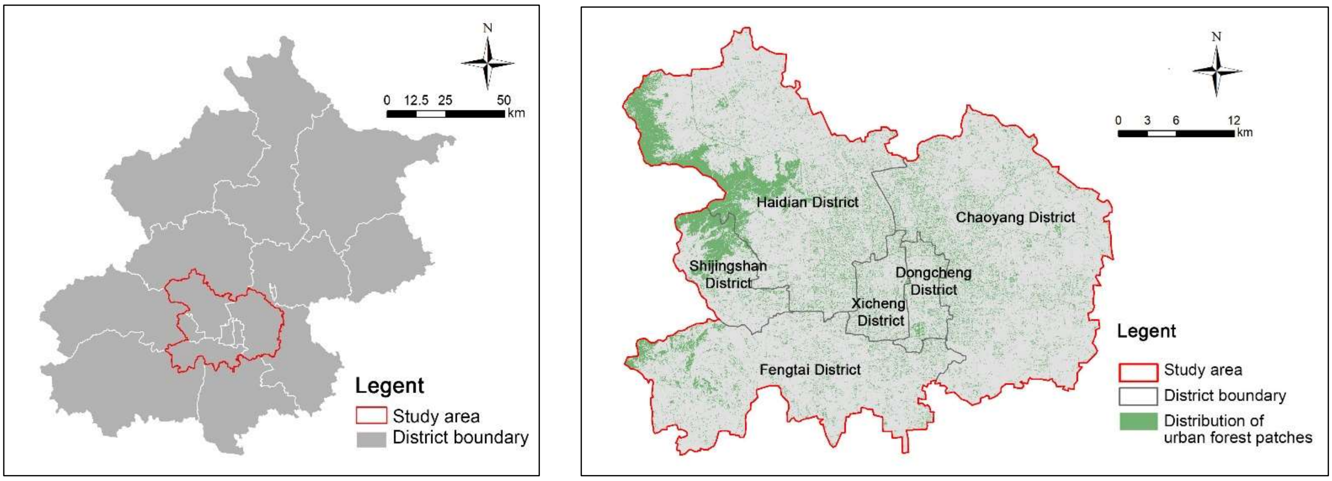


Figure 1. Conceptual framework of the study.

2. Materials and Methods

2.1. Study Area

Beijing (39°28′ N–41°05′ N, 115°22′ E–117°30′ E) is located at the northern end of the North China Plain. With a total area of 16,410.54 square kilometers, Beijing is the capital of China and the largest city in northern China. After decades of rapid urbanization, Beijing had 21.886 million permanent residents by the end of 2021, of which 19.161 million lived in cities, with an urbanization rate of 87.55% [75]. The increasing urbanization process in Beijing places higher demands on the ecological function of the city's green space [76]. Beijing's forest area is currently 7182 square kilometers, and 49% of the city is covered with green space. A number of strategies, including "forest city construction" and "leave blank space and increase green space", have been released by pertinent government agencies to improve the ecological advantages of urban green space [77,78]. Six districts in the central city of Beijing, Dongcheng, Xicheng, Chaoyang, Haidian, Fengtai, and Shijingshan, with a combined area of 1365 square kilometers, were chosen as the research objects in order to study the urban forest construction there and improve the biodiversity conservation and recreational services. According to the results of remote sensing image interpretation, the study area's urban forest area is 22,378.91 hectares (Figure 2).



(a) (b)

Figure 2. (**a**) The location of the study area; (**b**) the distribution of urban forest patches.

2.2. Data Sources

The study used Landsat ETM remote sensing images extracted from the Geospatial Data Cloud (http://www.gscloud.cn/, accessed on 17 July 2021) as the basic data. Specifically, on 21 July 2018, we acquired a clear-sky and good quality image with 123 strips and 32 lines and a spatial resolution of 30 m. ENVI 5.3 (The Environment for Visualizing Images) software was used to complete the preprocessing, fusion, mosaic, clipping, supervision, and classification of remote sensing images and precision verification. The precision after fusion is 15 m. Arable land, forestland, grassland, wetland and water area, construction land, and other land were the six types of land distribution that served as the study's foundation. The Point of Interest (POI) data of urban facilities used in the study were obtained from Amap API system (https://lbs.amap.com/, accessed on 20 January 2022). From the Open Street Map website (https://www.openstreetmap.org/, accessed on 1 February 2022), road network vector data was obtained. Sina Weibo is the most popular microblogging social networking site in China, and it also serves as an example of crowdsourced geo-graphic data. It is possible to record all the check-in information, including the user's text entry as well as the time and geographic data. Microblog check-in data have the qualities of a huge quantity of data, good current situation, and rich analysis, which can more accurately depict the use of urban forests and the distribution area of aggregation degree of users [79–81]. In this study, the POI data of Sina Weibo check-ins from 1 October to 7 October 2017 were analyzed to determine the crowd activity trend in the second lane green area [82]. To a certain extent, night light data can reflect the trend of urban expansion and the service of economic development, and collaborative population density data can be used as an indicator to gauge locations with greater potential for the development of recreational services [83,84]. Data about evening lighting for 2018 were obtained from NOAA (https://www.ngdc.noaa.gov/, accessed on 3 February 2022). Data on population density were obtained from the U.S. Department of Energy Oak Ridge National Laboratory (ORNL)'s LandScan Population dataset (https://landscan.ornl.gov/, accessed on 15 February 2022).

2.3. Methods

2.3.1. Analysis of Urban Forest Pattern

An important tool for examining the spatial characteristics of regional landscape patterns is Morphological Spatial Pattern Analysis (MSPA) [85]. The principle is based on mathematical morphological classification. Based on land use data, the binary image pixels are divided into seven types of mutually exclusive landscape elements through mathematical morphological principles such as erosion, dilation, opening operation, and closing operation, and the regions that play an important role in landscape connectivity in the study area are identified from the pixel level [86–89]. In order to investigate the characteristics of urban forest patterns, forestland was used as "foreground" and other land types as "background" in order to create a basis map for binary analysis of foreground and background. The binary raster pictures were translated into seven different landscape types (core, islet, perforation, edge, bridge, loop, and branch) using the MSPA analysis module of the Guidos Toolbox 3.0 platform (Table 1). The analysis of the characteristics of the urban forest pattern were then obtained.

Table 1. MSPA landscape types and their implications.

Landscape Type	Ecological Significance [90]
Core	Larger habitat patches can provide larger habitats for species, which is of great significance for biodiversity conservation and can be used as a source in the habitat network.
Islet	Isolated and fragmented patches that are not connected to each other, with low connectivity between patches, and less possibility of internal material and energy exchange and transmission.
Perforation	The transition area between the core area and the non-green landscape patch, namely, the inner patch edge.
Edge	A transitional area between the core area and the predominantly non-green landscape area.
Bridge	The narrow area connecting the core area represents the corridor connecting patches in the ecological network, which is of great significance for biological migration and landscape connectivity.
Loop	Corridors connecting the same core area are shortcuts to species migration within the same core area.
Branch	An area where only one end is connected to an edge zone, a bridge zone, a loop, or a pore.

2.3.2. Biodiversity Conservation Service Evaluation

Urban forest's biodiversity conservation services can be measured as an assessment of habitat quality to study its function as a biological habitat and to control habitat risk. The "Habitat Quality" module of the InVEST model was utilized in this study to measure habitat quality. The "Habitat Quality" module reflects the quality of habitat provided by the ecosystem by assessing the habitat types, the range of vegetation types, and the degree of vegetation degradation, which can reflect the biodiversity of the study area to a certain extent [39,91]. The habitat quality and scarcity indices used in this module serve to illustrate the study area's habitat quality. According to the model guidance manual, the specific calculation formula of habitat quality index is as follows:

$$Q(x)_i = H_i\left[1-\left(\frac{D(x)_j^z}{D(x)_j^z+k^z}\right)\right] \quad (1)$$

Among them, $Q(x)_i$ represents the habitat quality index of raster x in land use type j, H_i represents the habitat adaptability of land use type j, $D(x)_j$ is the threatened level of raster x in land cover type j, and k is a constant of half-saturation sum, which is a scaling factor, and its value is usually equal to D. In this study, the value of k is half of the maximum value of $D(x)_j$. Z is another scaling factor, usually a constant of 2.5. The threat level index is calculated using the following formula:

$$D(x)_j = \sum_{r=1}^{R}\sum_{y=1}^{Y_r}\left(\frac{w_r}{\sum_{r=1}^{R} w_r}\right) \times r_y \times i(xy)_r \times \beta(x) \times S_{jr} \quad (2)$$

Among them, j represents the land use type, r represents the threat factor, y represents the total number of grids of the r-threat factor graph, and Y_r is one of the groups of threat factor grids. Due to the variation in the raster resolution, each threat factor graph has a set of grids. w_r is the circle of threat factors, and the value ranges from 0 to 1. r_y represents whether the y grid is a threat grid. A value of 0 indicates a non-threat grid, and a value of 1 indicates a threat grid. S_{jr} is the sensitivity of land use type j to the threat factor r, and the value ranges from 0 to 1. $\beta(x)$ represents the level of accessibility of grid x, ranging from 0 to 1. $i(xy)_r$ is the threat level of the threat factor value of threat grid y to grid x.

The specific calculation formula includes a linear distance decay function and exponential distance decay function, and the formula is as follows:

$$i(xy)_r = 1 - \left(\frac{d(xy)}{d_{rmax}}\right) if\ linear \quad (3)$$

$$i(xy)_r = exp\left[-\left(\frac{2.99}{d_{rmax}}\right)d(xy)\right] if\ exponential \quad (4)$$

$d(xy)$ is the linear distance between grid x and threat grid y, d_{rmax} represents the maximum action distance of r threat factor.

The input data required for running this module include land use type raster data, future land use type raster data (optional), basic land use type raster data (optional), threat factor data, threat source data, habitat type, and habitat type's sensitivity to threat, half-saturation, parameters, etc. The habitat quality index calculated by the model takes a grid as the unit and ranges from 0 to 1. Grid precision is consistent with land use data. The research refers to the recommended values in the InVEST model guidance manual and sets the model parameters in combination with the situation of the area, relevant research, and expert consultation results (Tables 2 and 3) [92–95]. The necessary data were included in the model in this study in order to evaluate the functional indicators of Beijing's urban forest biodiversity conservation.

Table 2. Threat factors and their maximum impact distance, weight, and attenuation types.

Threat Factors	Maximum Impact Distance/Km	Weight	Attenuation Types
Arable Land	12	0.2	exponential
Grassland	8	0.4	linear
Construction Land	10	1	linear
Other Land	7	0.5	exponential

Table 3. Sensitivity of different land use types to threat factors.

Land Use Type	Habitat Suitability	Threat Factors			
		Arable Land	Grassland	Construction Land	Other Land
Arable Land	0.4	0.3	0.7	1	0.6
Forestland	1	0.8	0.7	1	0.8
Grassland	0.65	0.5	0.7	0.75	0.8
Wetland And Water Area	1	0.7	0.5	0.8	0.5

2.3.3. Recreational Service Evaluation

The premise of evaluating urban forest recreational services scientifically is to establish a reasonable evaluation index system. We consulted 30 planners and designers from China Academy of Urban Planning & Design, Beijing Municipal Institute of City Planning, Beijing BLDJ Landscape Architecture Institute Co., LTD., Beijing Tsinghua Tongheng Urban Planning and Design Institute, and Beijing Park Ancient Construction Design Research Institute, who had participated in projects related to urban forest planning and construction in Beijing. According to the inquiry results, in the process of urban forest recreational service evaluation at the municipal scale, the key influencing factors are the recreation value of the current urban forests, whether it is easy to reach, population density distribution, regional economic development, and the recreation willingness of the users.

Therefore, the five indicators that affect the evaluation of recreational services were divided into three categories. The distribution of key recreational service resources was used to characterize the recreation value of the current urban forests. The accessibility of recreational resources was used to measure whether urban forests were accessible.

The recreation demand potential of urban forests was represented by the distribution of population density, regional economic development status, and the recreation willingness of the users. They provide distribution information for important recreational resources that is obtained from POI data. A Kernel Density Estimation (KDE) model was used to extract the spatial distribution of POI data of national and municipal intangible cultural heritage and cultural relic protection units, Chinese historical and cultural villages, and scenic spots in order to analyze the distribution characteristics of key recreational resources in Beijing's urban forests. The vector data of the local road network and the line density analysis tool were used to examine the accessibility of recreational resources. For a thorough evaluation of the recreation demand potential of urban forests, the population density, night light data, and Sina Weibo check-in data were included. The spatial distribution properties of Sina Weibo check-in data were evaluated via the KDE model.

The KDE model is based on the location of each sampling point as the center, and the density contribution value of each grid cell in the specified range of each sampling point is calculated and superimposed using the kernel density function in order to obtain the distribution density of elements throughout the entire study area. The specific formula is:

$$\mathrm{f}(x) = \frac{1}{nh^d}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) \tag{5}$$

In the formula, n is the number of sampling points, h is the distance decay threshold of the path, d is the spatial dimension of the data, K is a kernel function, and $x - x_i$ is the estimated dot distance.

To calculate the density of each output grid pixel line element, line density analysis tools were used. The principle is to take the center of each grid pixel as the center of the circle, use the search radius to make a circle, calculate the sum of each line's length and weight (the population field) when it falls inside the circle, and to apply this calculation to the area of a circle to determine the density value of the grid. The specific formula is:

$$D_r = \sum_{k=1}^{n} \frac{L_k - V_k}{A} \tag{6}$$

D_r is the density value, n is the number of inner lines of a circle, L is the line length, V is the weight of the line, and A is the area of the circle.

2.3.4. Estimation of the Area Threshold Interval of Urban Forest Patches Required to Maintain the Synergy between Biodiversity Conservation and Recreational Services

The coupling coordination degree model can be used to analyze the interaction and influence between two or more systems. The model not only reflects the degree of interdependence and mutual restriction between systems, but also realizes the dynamic correlation relationship of synergistic development among different systems [96]. The model involves the calculation of the C value of the synergy degree, the T value of the coordination index, and the D value of the coupling coordination degree. The degree of interaction between systems increases with the value of synergy degree C. The calculation formula is as follows:

$$C = \left[\frac{U_1 \times U_2}{(U_1 + U_2)^2}\right]^{\frac{1}{2}} \tag{7}$$

where C is the value of synergy degree C, between 0 and 1. U_1 is the evaluation result of the synergy index biodiversity conservation service. U_2 is the evaluation result of recreational service with synergy index.

The coordination index T value is the comprehensive evaluation index of the level of coupled coordination development, respectively the weight of each system. The index weight for both types of services was set at 0.5 in this study since it was determined that biodiversity conservation and recreational services are equally important. The calculation formula of coordination index T is:

$$T = \beta_1 U_1 + \beta_2 U_2 \quad (8)$$

where T is the coordination index between 0 and 1. β_1 is the weight of the synergy index biodiversity conservation service, which was set as 0.5 in this study. β_2 is the weight of the synergy index recreational service, which was set as 0.5 in this study.

The coupling coordination degree D value is an index to judge the synergy coordination degree, and its value is also between 0 and 1 [97]. Its calculation formula is as follows:

$$D = \sqrt{C \times T} \quad (9)$$

Based on the analysis of the coupling coordination degree of two types of services, this study used the ArcGIS10.6 platform to perform threshold classification on the existing urban forest area. It counted the synergy coordination degree of various areas of urban forest, weeded out areas with a high coupling degree, and calculated the proportion of urban forest patch area in high coupling areas. Thus, the patch threshold of urban forest area for the combination of biodiversity conservation and recreational services was calculated.

3. Results

3.1. Analysis of Urban Forest Pattern in Beijing

The ArcGIS platform was used to count the area proportion of various landscape types in accordance with the operation results of the Guido Toolbox 3.0 program. The islet area represented the highest percentage of the foreground elements in the primary spatial pattern of urban forest distribution in 2018 with 45.61% of the foreground factors and 7.48% of the study area's total area. This showed that the urban forest patches in the majority of areas were generally separated. The overall urban forest pattern in Beijing was scattered. The core area, which made up 30.58% of the foreground factor area and 5.01% of the research area, was the second most significant factor area. A tiny portion of the core area was scattered across Fengtai District, but it was primarily concentrated in the western Haidian and Shijingshan districts. The distribution pattern was generally more to the west and less to the east, as well as more to the north and less to the south. With a total area of 1367.09 hectares, the largest core patch among them was situated in Haidian District's Xishan forest, making up 19.98% of the core region's overall size. The distribution of the core area was strongly tied to Beijing's recent intention to afforest millions of acres and build an urban park ring. Only 7.69% of the elements were found in bridge areas that had a significant impact on biological migration, which was a low proportion. Together with the quantitative features of islet patches, it showed that the study area's biological migration capacity is low. Perforation, loop, and branch lines accounted for 1.37%, 1.63%, and 3.47 prospect elements, respectively. This showed that, despite the existence of large-scale core patches like Xishan forest in Haidian District, the overall distribution pattern of urban forests in Beijing was relatively dispersed, making it difficult to carry out functions related to biodiversity conservation. (Figure 3 and Table 4).

Table 4. The area and proportion of landscape types based on MSPA.

Indicator Statistics	Core	Islet	Perforation	Edge	Loop	Bridge	Branch
Area (ha)	6843.98	10,206.50	307.60	2159.19	363.80	1721.68	776.16
The proportion of urban forest area (%)	30.58%	45.61%	1.37%	9.65%	1.63%	7.69%	3.47%
Area portion of study area (%)	5.01%	7.48%	0.23%	1.58%	0.27%	1.26%	0.57%

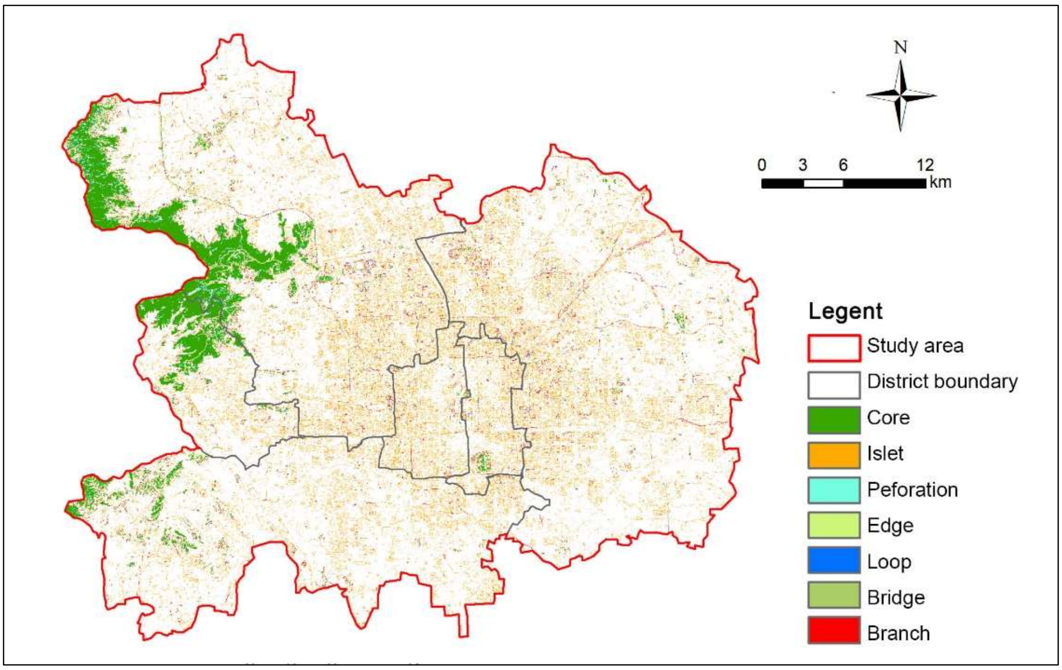


Figure 3. The analysis results of MSPA landscape types.

3.2. Evaluation of Biodiversity Conservation Services

The "Habitat Quality" module of the InVEST model was used to determine the habitat quality index in order to assess the ecosystem biodiversity conservation services provided in the study area. The model's outcomes showed that the study area's total habitat quality index ranged from 0 to 0.99. Based on the reference of related studies, the study area was divided into low biodiversity conservation service area (0~0.40), medium biodiversity conservation service area (0.41~0.70), and high biodiversity conservation service area (0.71~0.99) according to the habitat quality result [43].

The coverage area of the low biodiversity conservation service area was 115,138.77 hectares and accounted for 84.39% of the study area's total area. It was the largest in the entire study area, according to statistics on the area and proportion of habitats with varying quality. While the distribution of urban edge areas was scattered, the spatial distribution of inadequate biodiversity conservation service areas was obviously concentrated in the city's area.

Additionally, the distribution pattern was more to the south and less to the north, as well as more to the west and less to the east. This outcome might be a result of the recent conversion of agriculture to forest and grassland in core urban areas, as well as the encroachment of construction land there. The medium biodiversity protection service area was 7428.83 hectares in size, making up the smallest percentage of the entire area—5.44%. It was mainly distributed in the urban park ring area and the implementation area of Beijing's one million hectares afforestation strategy, indicating that the implementation of a series of policies related to urban forest construction has achieved certain results. The total area of high biodiversity conservation service area was 13,875.11 hectares or 10.17% of the entire study area. The Xishan area in the western section of the study area, which had a sound ecological foundation, was where the spatial distribution of high biodiversity conservation service areas was primarily concentrated. Other high biodiversity conservation service areas were mostly distributed along the edge of the central urban area. They were clustered along the main river systems such as Yongding River in Fengtai District and large urban parks such as Olympic Forest Park in the northwest of Chaoyang District, while the distribution was scattered in other areas.

According to research on the distribution of urban forest services for biodiversity conservation, the area of Beijing's urban forest with inadequate biodiversity conservation service coverage was 1528.00 hectares or 6.83% of the total area covered by urban forests. Its spatial distribution was mostly concentrated in the city's center and showed a trend of expanding to the city's edge. This was directly tied to the high-density construction in the city center and the city's ongoing outward expansion trend. The medium biodiversity conservation service area covered 7031.81 hectares or 31.42% of the total service area. Most of its spatial distribution was along the main ring roads of the city. The high biodiversity conservation service area accounted for 61.75% of the total urban forest area; 13,819.10 hectares of urban forest belonged to this type of area, accounting for the largest proportion. This indicated that urban forest was the key area to provide biodiversity conservation in cities. Its primary spatial distribution was consistent with the general spatial distribution trend of high biodiversity conservation services in the study area (Figure 4 and Table 5).

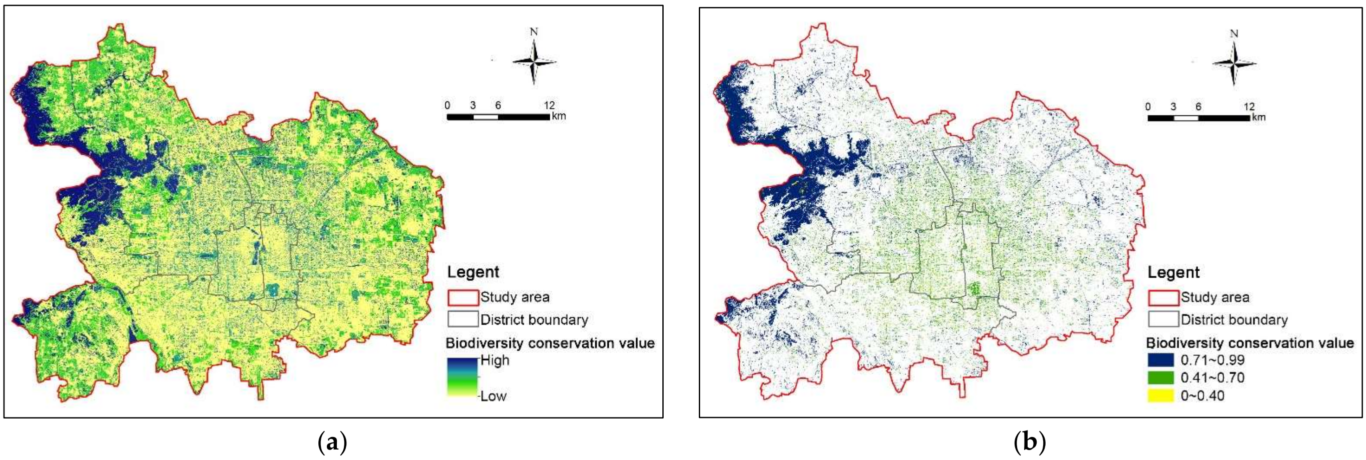


Figure 4. (**a**) Spatial distribution of overall biodiversity conservation services in the study area; (**b**) spatial distribution of urban forest biodiversity conservation services.

Table 5. The distribution of the levels of biodiversity conservation services.

Statistical Type	Low Biodiversity Conservation Service Area (0.00~0.40)	Medium Biodiversity Conservation Service Area (0.41~0.70)	High Biodiversity Conservation Service Area (0.71~0.99)	Total
Urban forest area (ha)	1528.00	7031.81	13,819.10	22,378.91
Proportion of total urban forest area (%)	6.83%	31.42%	61.75%	100.00%
Area of all land use types (ha)	115,138.77	7428.83	13,875.11	136,442.71
Proportion of the total study area (%)	84.39%	5.44%	10.17%	100.00%

3.3. Evaluation of Recreational Services

Figure 5 depicted the geographic distribution, the accessibility, and the recreation demand potential of urban forests in the study area. Among them, the areas with a high distribution level of key recreation resources were mainly concentrated in the central area of the city. The areas with high accessibility of recreation resources were mainly distributed along the main roads of the city, showing an obvious concentric circle pattern. The most concentrated distribution was in the south of Haidian District and the west of Chaoyang District. The degree of population aggregation in the area was shown by the population density data in the recreation demand potential of urban forests index, which exhibited a clear concentric circle distribution characteristic that gradually decreased from the city center to the outside. Night light data could represent the economic development potential of a region [77]. The areas with better evaluation scores also displayed the concentric circle distribution's properties. The area with the most concentrated distribution of population usage data represented by Sina Weibo check-in data was also concentrated in the central urban area [81]. Among these, the areas with a high tendency for users were primarily distributed in the southeast of Haidian District, the west of Dongcheng District, and the west of Chaoyang District (Figure 5).

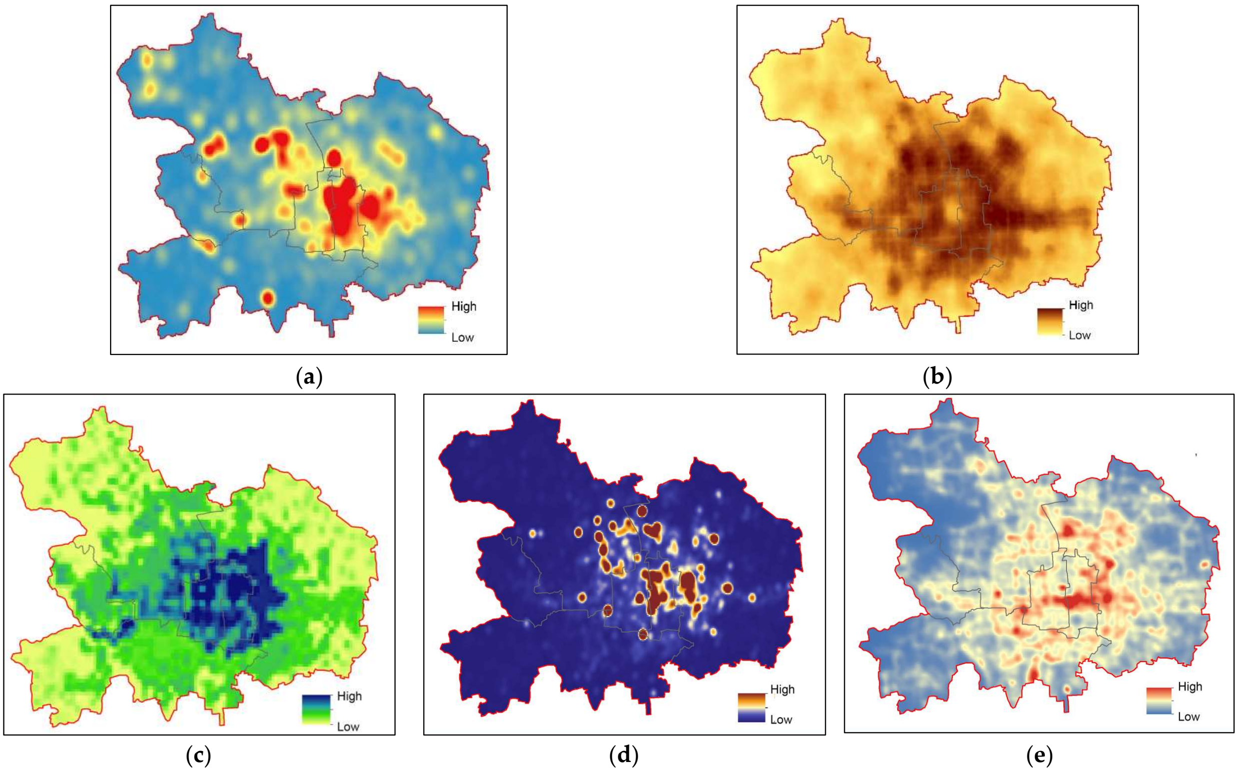


Figure 5. Evaluation results of various recreational services factors in the study area: (**a**) assessment of distribution of key recreation resources; (**b**) assessment of accessibility to recreational resources; (**c**) assessment of the recreation demand potential—population aggregation; (**d**) assessment of the recreation demand potential—economic development potential; (**e**) assessment of the recreation demand potential—user's tendency.

Thirty experts in related fields were consulted for the study to rate the weighting of each evaluation factor for recreational services. The statistical results showed that the distribution factor of key recreational service resources accounted for 0.4, the distribution factor of recreation resources accessibility accounted for 0.5, and the recreation demand potential factor of recreation resources accounted for 0.3. Among these, population density, night light data, and Sina Weibo check-in data each reflected area vitality, potential for future economic development, and the public's actual travel behavior. The three factors each accounted for 0.1. The "Grid Calculator Tool" was utilized on the ArcGIS 10.6 platform for weighted superposition based on the normalization of each factor and the proportion of each factor. The comprehensive evaluation result of the recreational services was obtained.

Statistics showed that there were three categories for the entire recreational services: low recreational service area (0.00~0.15), medium recreational service area (0.16~0.30), and high recreational service area (0.31~0.66). The comprehensive recreational service of the study area presented a circular distribution pattern with low in the peripheral and high in the middle. The high recreational service area covered 4008.22 hectares, accounting for 2.94% of the total area of the study area. Among this, 17.66% of the urban forest was in the high recreational service area and was predominantly concentrated in the city's center. In terms of spatial distribution, it was mainly concentrated in Dongcheng District, the west of Chaoyang District, and the southeast of Haidian District, which was closely related to large urban parks such as Olympic Forest Park, Chaoyang Park, Longtan West Lake Park and Dongba Country Park. This suggested that these larger urban forest patches provided substantial recreational services. The area with the highest percentage, making up

87.07% of the entire area, was the medium recreational service area. The middle recreational service area covered 5418.88 hectares, or 24.21%, of the urban forest patches. The study area had 13,640.18 hectares of low recreational service area or 10% of the total study area. However, in the urban forest patch, the area of low recreational service accounted for 58.13% of the total area of urban forest, accounting for the highest proportion. This suggested that Beijing's urban forests' potential for recreation had not yet been completely realized. Furthermore, the low recreational service areas were predominantly concentrated in the west, northwest, and southwest directions. Although these areas had large forest patches, their accessibility was not high because they were mainly located on mountains in the west. The road system is not perfect, which ultimately leads to relatively weak recreational services (Figure 6 and Table 6).

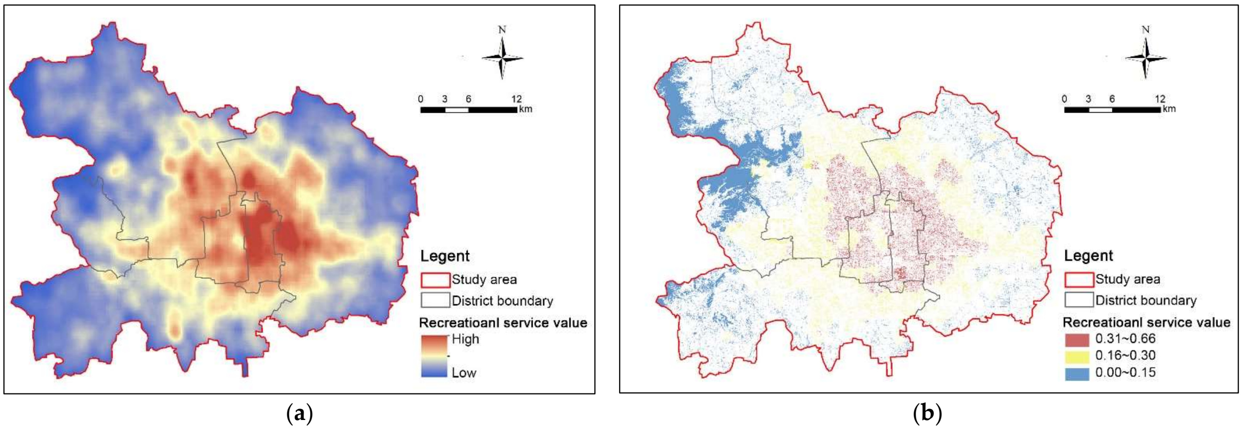


Figure 6. (**a**) Spatial distribution of overall recreational services in the study area; (**b**) spatial distribution of urban forest recreational services.

Table 6. The distribution of the levels of recreational services.

Statistical Type	Low Recreational Service Area (0.00~0.15)	Medium Recreational Service Area (0.16~0.30)	High Recreational Service Area (0.31~0.66)	Total
Urban forest area (ha)	13,007.88	5418.88	3952.15	22,378.91
Proportion of total urban forest area (%)	58.13%	24.21%	17.66%	100%
Area of all land use types (ha)	13,640.18	118,794.31	4008.22	136,442.71
Proportion of the total study area (%)	10.00%	87.07%	2.94%	100%

3.4. Threshold of Urban Forest Patch Area Based on Biodiversity Conservation and Recreational Services Synergy

To maximize the two kinds of ecosystem services, it is helpful to understand the mathematical relationship between the urban forest patch area and ecosystem services. First, the Pearson correlation coefficient between the area of 184,582 urban forest patches and the evaluation outcomes of biodiversity conservation service, as well as comprehensive recreational service, was calculated. The findings revealed a weak association between urban forest area and recreational service, but a considerable correlation between urban forest area and biodiversity conservation service. However, there was a strong link between services for biodiversity conservation and recreation. To actualize the synergy of the two types of services, it was still crucial to study the threshold of the urban forest patch area. Second, the coupling coordination degree model was utilized to calculate the synergy relationship between biodiversity conservation and recreational services offered by all urban forest patches. The evaluation results were divided into three groups based on the natural breakpoint method: low coupling area (0.00~0.48), medium coupling area (0.49~0.60), and high coupling area (0.61~0.82). Then, using the ArcGIS 10.6 platform, the area threshold of urban forest patches in the study area was divided into 8 categories. They were 0.00~0.50 hectares, 0.51~1.00 hectares, 1.01~5.00 hectares, 5.01~10.00 hectares, 10.01~20.00 hectares, 20.00~40.00 hectares, 40.00~80.00 hectares, and more than 80.00 hectares, respectively. Finally, the proportion of urban forest area as well as the quantity of patches in low, medium, and high coupling areas of urban forests with various area thresholds were counted (Table 7).

Table 7. Results of Pearson correlation coefficient analysis.

Correlation Analysis Indicators		Urban Forest Area	Biodiversity Conservation Service Evaluation	Recreational Service Evaluation
Urban forest area	Pearson correlation	-	−0.014 **	−0.001
	Significance (double-tail)	-	0.000	0.530
Biodiversity conservation service evaluation	Pearson correlation	−0.014 **	-	−0.471 **
	Significance (double-tail)	0.000	-	0.000
Recreational service evaluation	Pearson correlation	−0.001	−0.471 **	-
	Significance (double-tail)	0.530	0.000	-

** $p < 0.01$.

The findings indicated that most of the low coupling areas were mainly distributed in the Xishan forest of the study area. This region was also home to an enormous urban forest patch with an area greater than 80 hectares. This showed that there was a need to increase the coupling coordination degree between the two services in big urban forest patches. The medium coupling area distribution presented a certain linear aggregation feature in the west, which was mainly distributed along the foothills of the Xishan urban forest patch. Most of the medium coupling areas were large urban forest patches. The number of medium coupling urban forests with area thresholds of 5.00~10.00 hectares, 10.01~20.00 hectares, and 40.00~80.00 hectares all accounted for more than 60%. High coupling areas were mainly distributed within the inner urban forest in the city area. According to the statistics, the proportion of high coupling areas was largest in the total area and the number of urban forest patches with an area threshold of 0.51~1.00 hectares.

The number of patches located in the high coupling area was 1172, with a total area of 770.86 hectares. It accounted for 48.55% of the total number of urban forest patches and 47.92% of the total area in this interval. This showed that in high-density urbanized areas, small-scale urban forests are crucial for achieving synergy for biodiversity conservation and recreational services (Figure 7 and Table 8).

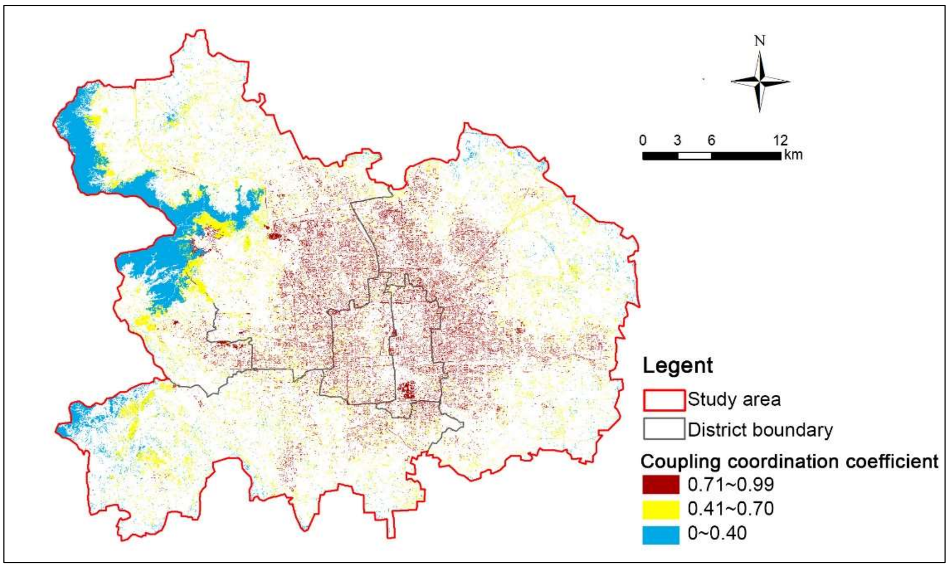


Figure 7. Spatial distribution of coupling coordination degree between urban forest biodiversity conservation and recreational services.

Table 8. Statistics of different urban forest patch area thresholds for the synergy of biodiversity conservation and recreational services.

Urban Forest Patch Area Threshold (ha)	Statistical Type	Proportion of Low Coupling Area (0.00~0.48)	Proportion of Medium Coupling Area (0.49~0.60)	Proportion of High Coupling Area (0.61~0.82)
0.00~0.50	Area (hectare)	2319.49	5759.3	5571.67
	Proportion of urban forest (%)	246.60%	42.19%	40.82%
	Number of urban forest patches	33,662	78,095	64,643
	Proportion of the number of patches in this category (%)	19.08%	44.27%	36.65%
0.51~1.00	Area (hectare)	278.24	559.59	770.86
	Proportion of urban forest (%)	17.30%	34.79%	47.92%
	Number of urban forest patches	403	839	1172
	Proportion of the number of patches in this category (%)	16.69%	34.76%	48.55%
1.01~5.00	Area (hectare)	288.44	435.73	278.34
	Proportion of urban forest (%)	28.77%	43.46%	27.76%
	Number of urban forest patches	169	255	198
	Proportion of the number of patches in this category (%)	27.17%	41.00%	31.83%
5.01~10.00	Area (hectare)	29.59	65.81	35.87
	Proportion of urban forest (%)	22.54%	50.13%	27.33%
	Number of urban forest patches	5	9	5
	Proportion of the number of patches in this category (%)	26.32%	47.37%	26.32%
10.01~20.00	Area (hectare)	65.07	137	15.82
	Proportion of urban forest (%)	29.86%	62.88%	7.26%
	Number of urban forest patches	5	10	1
	Proportion of the number of patches in this category (%)	31.25%	62.50%	6.25%
20.01~40.00	Area (hectare)	140.94	136.51	0
	Proportion of urban forest (%)	50.80%	49.20%	0.00%
	Number of urban forest patches	4	5	0
	Proportion of the number of patches in this category (%)	44.44%	55.56%	0.00%
40.01~80.00	Area (hectare)	120.02	242.78	0
	Proportion of urban forest (%)	33.08%	66.92%	0.00%
	Number of urban forest patches	2	4	0
	Proportion of the number of patches in this category (%)	33.33%	66.67%	0.00%
>80.00	Area (hectare)	4931.86	195.98	0
	Proportion of urban forest (%)	96.18%	3.82%	0.00%
	Number of urban forest patches	6	1	0
	Proportion of the number of patches in this category (%)	85.71%	14.29%	0.00%

4. Discussion

4.1. The Relationship between Biodiversity Conservation and Recreational Services

Human desire for recreation and a healthy ecological environment is increasing along with the growth of the urban population. To meet the growing demand, urban forests can offer crucial services for biodiversity conservation and recreational services [18]. Although there have been numerous studies on the ecosystem services offered by urban forests, few have gone in depth on the interaction between the two different types of services. Our study demonstrates a significant negative correlation between biodiversity conservation and recreational services in Beijing urban forests. However, this correlation is not a straightforward linear correlation and exhibits clear spatial heterogeneity. Both antagonistic and synergistic effects coexist. Residents' recreational activities may degrade habitat quality to some extent, which leads to the reduction of the services provided for biodiversity conservation. Nevertheless, areas with poor habitat quality often lack a recreational environment that attracts tourists, which also lead to the reduction of residents' recreation willingness and the weakening of recreational services provided by urban forests, which is consistent with previous studies [98–101].

The habitat quality of urban forest patches does not totally influence how recreation residents engage in urban activities. Our study quantifies the synergy relationship between biodiversity conservation and recreation services and the specific urban forest patch space and explores the spatial heterogeneity of the synergy of the two types of ecosystem services. The study discovered that the habitats of living things might be significantly impacted by human activity. However, people do not have a higher willingness to enjoy recreation in areas with better biodiversity protection. People are more likely to carry out recreational activities in areas with excellent infrastructure and convenient transportation. The highly coupled space of biodiversity conservation and recreational services is mainly distributed in the central area of the city. This is also consistent with the strong positive correlation between recreational behavior and the level of socio-economic development [63]. As a result, for urban forests of the same size, being located in the central area of the city has higher service synergy benefits than being located at the urban edge. This area emphasizes how vital it is to safeguard biodiversity conservation services in urban central areas and how vital it is to strengthen the construction of urban forest recreation infrastructure in marginal areas.

4.2. Enlightenment of Optimization of Urban Forest Pattern

According to the study's findings, Beijing's urban forest pattern is not excellent. It is showing a generally dispersed state and an unequal distribution of ecological sources. The weak movement capabilities of local creatures and the high proportion of islets do not support the development of biodiversity conservation services. The spatial heterogeneity of recreational services is also impacted by urban forest pattern to a certain extent. When we investigated the relationship of synergy between the two services, we found that in high-density built-up urban areas such as Beijing, the vast majority of urban forest patches are less than 5 hectares in size. Only a few urban forests have large patches. The urban forest patches in the central city have been cut off by development land as a result of Beijing's rapid urban expansion as a metropolis and the country's capital.

Trade-offs between various ecosystem service requirements have measurable scale impacts, according to earlier research [102]. This study found that urban forest patches with an area between 0.5 and 1 hectare had the highest proportion of patches with a high synergistic relationship between biodiversity conservation and recreational services. Therefore, with changes in the landscape's structure, the protection of sporadic tiny and microurban forest patches can also provide quantitative comprehensive services of ecosystems [103].

Not only will the loss of landscape connectedness, species transmission, and biodiversity conservation result from the fragmentation of urban forest pattern [104], it will also diminish the humidity of these forests [105] and may lead to the threat of invasive species [106]. However, our study also revealed that more attention should be paid to the planning, construction, and spatial layout of the small urban forests in the overall pattern construction of urban forests in the central area of mega cities. This type of urban forest has high accessibility, which is more convenient for daily use of urban residents and is of great significance for achieving the coordinated improvement of different ecosystem services.

However, while having higher biodiversity conservation functions, large-scale urban forest patches are frequently located in urban peripheral areas due to the restricted amount of available construction space. Owing to its distance from the city center and lack of basic recreational amenities, large-scale urban forest patches could offer limited recreatioanl services. The "U-shaped" relationship between user satisfaction and the amount of green space, as well as between user satisfaction and the proximity to green space, has been demonstrated in relevant studies [107]. Our study confirms that people tend to spend more time in suburban urban forest areas [108]. Therefore, for such large urban forest patches, on the basis of protection, it is necessary to increase the recreational infrastructure construction of large urban forest patches located far from the urban center. By cooperating with the surrounding infrastructure construction, this is a good way to enhance their recreational attraction.

In addition, quantifying the interactions among multiple ecosystem services is very important for improving human understanding of ecosystems and improving human well-being [100]. It is more conducive to strengthening the management of urban forest ecosystems [99]. Our need for ecosystem services is evolving as human society advances. As a result, the forestry management department should strengthen their monitoring of the many ecosystem services that urban forests provide while also better controlling and understanding the pattern of the urban forest as a whole. The development of a scientific urban forest monitoring and management system, as well as the collecting of demand information from users of urban forests, should receive more focus.

4.3. Research Limitations and Future Research Directions

The relationship between urban forest biodiversity conservation and recreational services was thoroughly investigated in this study. A set of research techniques was developed to determine the patch area threshold for the synergy of two different types of urban forest ecosystem services. This study has a certain guiding significance for the optimization of urban forest patterns in Beijing and can provide an important reference for urban forest planning and construction. This study does have certain restrictions, though. First, we narrowed our attention to only two relatively important ecosystem services—conservation of biodiversity and recreation. However, the development of urban forests is significantly influenced by the interconnections of carbon sinks, microclimate regulation, soil conservation, and other ecosystem services. The interaction mechanisms between various ecosystem services have not been fully investigated in this study. More research is still needed to fully understand the associations between various types of ecosystem services. Second, the study area uses Beijing as an illustration, which has particular meteorological and regional characteristics. Furthermore, Beijing's central city has very few urban forest patches for a mega-city with a high percentage of built-up urban space. Accordingly, future research on the connection between the threshold of urban forest patch areas and the synergy of the two ecosystem services should be carried out in collaboration with other cities. There has to be further research done to see whether the findings of this study are applicable to the construction of urban forests in other cities. Third, the study's data collection is constrained, particularly in data of the accuracy of the information needed for recreational services. Sina Weibo check-in data are mainly applicable to youthful and middle-aged people. Children and the elderly have less consumption data. In addition, the three main criteria of the recreational potential of forests—habitat moisture, age of tree stands, and inclination of the terrain—as well as four supporting criteria—stand density, presence of undergrowth and underbrush, soil cover, and species composition of the stand—have not been taken into account because of the limitation of data. In the future, we will supplement a large number of relevant in-depth fieldwork data to improve the assessment of the development potential of recreation resources of urban forests. Future research can explore more scientific recreational service evaluation techniques by combining other types of data, such as mobile phone signaling data, fieldwork, and so on.

5. Conclusions

Urban forest plays an important role in improving the living environment of residents and maintaining the balance of urban ecosystems. It is also the key to alleviate various environmental problems. There are complex interactions between ecosystem services provided by urban forests. Among them, biodiversity conservation and providing recreational services are the main ecosystem services that urban forests can offer in highly urbanized metropolises. This study quantified these two important services of Beijing's urban forests by dividing them into seven types based on an investigation of the city's urban forest pattern. The research quantitatively evaluated the biodiversity conservation and recreational services of urban forests in Beijing and analyzed the area threshold interval of urban forest patches based on the synergy of the two services. Although the patch size of urban forest is not the decisive factor to determine the level of ecosystem services provided, it is very important to achieve the synergy of the two services. The research conclusions are as follows:

1. Beijing's urban forest has a generally scattered pattern. Among all landscape types, island patches accounted for the highest proportion; 45.61% of urban forests were isolated. The core area made up 30.58% of the foreground factor area. The distribution pattern was generally more to the west and less to the east, as well as more to the north and less to the south. The largest core patch among them was situated in Haidian District's Xishan forest. The distribution of its core area was influenced by the construction of the urban park ring and the implementation of programs like the city's recent one million hectares afforestation strategy. However, generally speaking, there were fewer bridge areas than island patches, which makes it difficult to provide services for the protection of biodiversity.
2. The evaluation results of biodiversity conservation services in Beijing showed that a low biodiversity conservation service area covered the largest area and was obviously concentrated in the urban center. Large scale urban construction activities are unfavorable to biodiversity conservation. High biodiversity conservation service areas mainly relied on the original sound ecological foundation and were mostly distributed at the edge of the study area. This proved that urban forests are the key areas for biodiversity conservation in cities.
3. The evaluation results of recreational services showed that the overall comprehensive recreation function presents a circular distribution trend of low in the periphery and high in the middle. In the central area of the city, larger urban forest patches had stronger recreational services. However, 58.13% of the areas still had a low recreational service. Most of these areas were concentrated in the centre of the city. Although there were large forest patches in these areas, the recreational services provided by these forests were relatively weak due to the poor infrastructure construction in the surrounding area.
4. There is a correlation between the biodiversity conservation and recreational services of urban forests. We should concentrate on enhancing the recreational services provided by large urban forest patches larger than 80 hectares by improving the infrastructure construction in surrounding areas. The biodiversity conservation services in these areas were high, while the recreational services were low. In urban central areas, we should pay more attention to the role that small urban forest patches play in protecting biodiversity. For urban forests in these areas, biodiversity conservation services were low, while recreational services were relatively high.
5. The maximum effect of urban biodiversity conservation and recreational services synergy can be obtained at the threshold of urban forest areas between 0.5 and 1 hectares. Therefore, for mega cities with high urbanization, more attention should be paid to the construction quality of small urban forests with this area threshold interval. For upcoming urban forest design and management, the study's findings could offer quantifiable indications. It could assist in efficiently realizing the synergistic development of the two services, promoting the effective enhancement of ecosystem service functions and residents' ecological welfare, as well as addressing the expanding spiritual and cultural demands of urban residents.

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