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Research on the Evaluation and Optimization Strategies of Green Space Ecological Functions in Beijing

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Abstract. In the rapid process of urbanization, urban green spaces are critical for mitigating the urban heat island effect, enhancing carbon sink capacity, and improving overall environmental quality. This study employed multi-source high-resolution remote sensing data, fused with LiDAR observations and validated by field sampling, to accurately extract key parameters including green space types, coverage, and biomass. A systematic evaluation of ecological service functions and their dynamic changes was conducted. The results indicate that: (1) ecological functions differ significantly across green space types, with intensity closely linked to spatial configuration, highlighting the importance of balancing both "quality" and "quantity"; (2) the integration of remote sensing and LiDAR greatly improves the accuracy of ecological assessments; (3) dense construction and fragmented green patterns weaken ecological benefits, while higher vegetation diversity helps mitigate these negative impacts; (4) differentiated strategies tailored to functional areas can maximize ecological effectiveness. Overall, the study advances technical applications of remote sensing in urban ecology, deepens the scientific understanding of the "pattern–function" mechanism, and provides practical guidance for urban ecological planning and green space management under dual-carbon goals.

Keywords: High-resolution Remote Sensing, Urban Green Space, Ecological Service Function, Optimization Strategy.

1. Introduction

Under the background of rapid urbanization, the ecological service function of urban green Spaces is of vital importance for alleviating the heat island effect [1], enhancing carbon sink capacity and improving the living environment [2, 3]. This study took the area within the Sixth Ring Road of Beijing (with a total area of approximately 2,267 square kilometers) as the research scope. Based on multi-source high-resolution remote sensing images (fusing LiDAR data) [4] and on-site sampling data, combined with GIS spatial analysis technology [5], key parameters such as green space type, coverage, and biomass were accurately extracted, and the ecological function differences of different types of green Spaces were systematically evaluated [6]. It reveals the influence mechanism of green

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space spatial pattern and urbanization intensity on ecological functions [7] and proposes a differentiated optimization strategy of "spatial control + type improvement".

The research finds that there are significant type differences in the ecological functions of green Spaces in Beijing. The densification of buildings and the fragmentation of green Spaces are the dominant factors weakening the functions [8], while the diversity of vegetation can effectively counteract the negative impacts [6]. The multi-source remote sensing data fusion technology has significantly improved the accuracy of parameter extraction [4]. Implementing differentiated strategies for functional areas can maximize ecological benefits [9]. The research results provide an operational plan for the ecological planning of Beijing and the management of green Spaces under the "dual carbon" goals [2].

2. Data and methods

The study area encompasses the region within Beijing's Sixth Ring Road. Primary data sources include: Remote sensing data—high-resolution satellite imagery from 2020 to 2023 (for extracting green cover), thermal infrared remote sensing data (for deriving surface temperatures), and fused LiDAR data (to enhance the accuracy of vegetation height and biomass extraction); Supplementary data—Beijing municipal administrative boundary map (1:10,000 scale), 2020 population density data (1km grid, provided by the Beijing Municipal Commission of Planning and Natural Resources), building density and road network density data (used to analyse the relationship between urbanisation intensity and green space functionality); Field sampling data—Quarterly collected from 2021 to 2023, comprising green space biomass (e.g., tree diameter at breast height, shrub coverage), surface temperature (infrared thermometer), and vegetation health (chlorophyll content) to validate the accuracy of remote sensing inversion results (Figure 1).

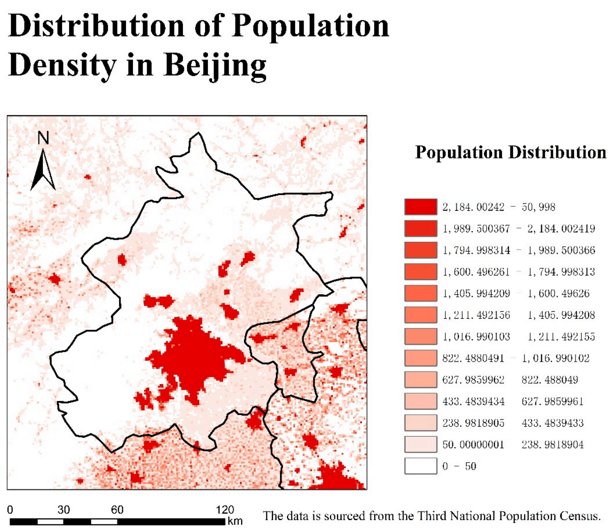

Figure 1. Population density distribution in Beijing (picture credit: original)

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3. Research methods

3.1. Core issues

This study unfolds around the logic of "assessment of green space ecological functions - analysis of impact mechanisms - proposal of optimization strategies", with a focus on discussing the following core issues:

(1) Quantitative differences in ecological service functions such as carbon sink and cooling among different types of green Spaces (parks, affiliated Spaces, and protective Spaces) in Beijing (such as the comparison of carbon sink capacity and the intensity of cooling effect between park green Spaces and protective green Spaces).

(2) The dynamic change patterns of green space patterns (area, fragmentation, connectivity), and their quantitative relationships with the attenuation/enhancement of ecological functions (such as the extent of the impact on the cooling effect for every 10% increase in patch fragmentation).

(3) The influence mechanism of urbanization intensity (population density, building density, road network density) on the ecological functions of green Spaces, and the importance ranking of driving factors (such as the contribution weights of building density and population density to the heat island effect).

(4) The direction of differentiated green space optimization layout for different functional areas such as commercial, residential and industrial zones, as well as their expected ecological benefits (such as the relationship between the optimal width of the protective green belt in industrial zones and the cooling effect).

3.2. Methods for extracting green space types and patterns

Green space types and patterns: Based on the object-oriented classification method and combined with the spectral features of high-resolution images, green Spaces are classified into 3 major categories and 6 minor categories (park green Spaces: comprehensive parks, community parks; Affiliated green Spaces: residential area green Spaces, unit green Spaces;) Protective green Spaces: road protection forests, river protection forests), extract pattern indices such as patch area, fragmentation (number of patches/total area), and connectivity (patch connectivity index);

3.3. Quantitative indicators of ecological functions

Cooling effect: It is characterized by the temperature difference (ΔT) between the surface temperature of the green space and the surrounding non-green space areas (buildings/bare land) (the larger the ΔT, the stronger the cooling function). Carbon sink capacity: Convert the annual carbon sequestration volume based on biomass data (dry weight per unit area) (refer to the carbon sink coefficient of the Beijing Municipal Bureau of Gardens and Greening in 2021). Optimization of human settlement environment: Construction of "Green Space Service Index" (calculation formula: Green space coverage × Accessibility score, accessibility score weighted based on road network distance).

3.4. Analysis of impact mechanism

The spatial superposition analysis of GIS is adopted to spatially match the data of population density, surface coverage and heat island intensity. Using a multiple linear regression model, the influences of factors such as population density, building density, and green space proportion on the

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heat island effect were quantified (for example, for every 10% increase in the proportion of artificial ground surfaces, the heat island intensity increases by approximately 0.3℃). The feasibility of the optimization strategy is verified through scenario simulation (such as the prediction of heat island changes by increasing the green space ratio by 10%).

4. Research results

4.1. Types of differences in green space ecological functions

There are significant differences in ecological functions among different types of green Spaces (Table 1):

Table 1. Data comparison of different types of green spaces

Green space type	Cooling effect ΔT (°C)	Annual carbon sink (t/hm²)	Green Space Service Index
Park green space	2.8 ± 0.5	12 ± 1.2	0.72 ± 0.08
Protective green space	2.1 ± 0.3	15 ± 1.8	0.45 ± 0.06
Affiliated green space	1.5 ± 0.2	8 ± 0.9	0.61 ± 0.07

Park green space: It has the strongest cooling effect (average ΔT of 2.8℃), medium carbon sequestration capacity (average annual carbon sequestration of 12t/hm²), and the highest green space service index due to high accessibility (average of 0.72). Protective green Spaces: They have the strongest carbon sink capacity (with an average annual carbon sequestration of 15 tons /hm²), but due to their majority being in the suburbs, their green space service index is relatively low (average 0.45). Ancillary green Spaces: The cooling effect is relatively weak (with an average ΔT of 1.5℃), but they are widely distributed and have a significant effect on improving the microclimate of residential areas.

4.2. The correlation between green space pattern and ecological functions

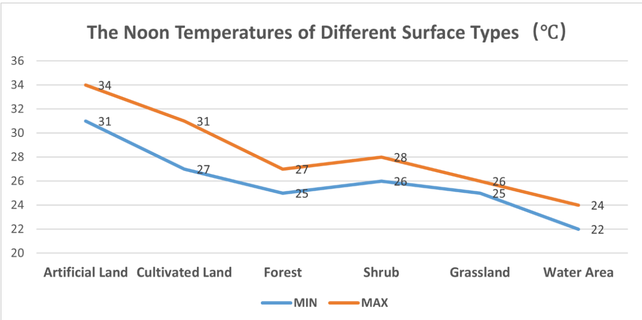

Figure 2. Surface temperatures of different surface types (14:00) (picture credit: original)

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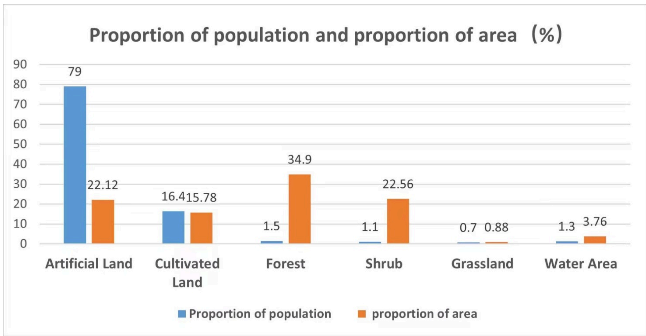

Figure 3. Population distribution and area proportion (%) (picture credit: original)

The influence of the "quantity" of green space: For every 10% increase in the proportion of green space area, the heat island intensity decreases by approximately 0.35°C (R^2=0.68, $p<0.01$).

The impact of green space "quality" : Vegetation diversity (with no less than 5 tree species) can increase the cooling effect by 20% to 30%, and for every 10t/hm² increase in biomass, the carbon sink capacity increases by 8%.

The negative impact of fragmentation: For every 10% increase in green space fragmentation (the number of patches increases), the cooling effect weakens by 15% and the carbon sink capacity decreases by 10% (Figure 2 and 3).

4.3. The influencing mechanism of urbanization intensity

The inhibitory effect of urbanization intensity on the ecological function of green Spaces is significant: for every 10% increase in building density, the cooling effect of the surrounding green Spaces weakens by 0.8 ℃ (the dominant factor). For every increase of 10,000 people per square kilometer in population density, the carbon sink capacity of green Spaces decreases by 5% (with intensified human interference). The density of road networks is positively correlated with the fragmentation of green Spaces (correlation coefficient 0.73), indirectly weakening ecological functions.

5. Optimization strategies for green space ecological functions

Based on the principle of coordinated improvement of "quality" and "quantity", a dual-dimensional solution of "spatial control + type improvement" is proposed.

5.1. Differentiated layout by functional areas

Industrial zone: Build a 50-100-meter-wide protective green belt around the factory area and on both sides of the main roads (basis: when the width is ≥50 meters, the cooling effect can reach 2-3 ℃). Select native tree species such as Chinese scholar tree (dust retention capacity 12g/m²·d) and Platycladus orientalis (annual carbon sequestration of 3.2kg per plant), with the goal of increasing carbon sink capacity by 15% annually.

Residential areas: In old residential communities, "greenery should be added wherever possible", and new "pocket parks" of less than 500 square meters (at least one per 10,000 people, equipped with recreational facilities) should be added. A multi-layered structure of "trees (40% deciduous trees such as poplar and willow) + shrubs (30%) + grass (30%)" should be adopted to balance summer cooling (ΔT increase to 2°C) and winter lighting.

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Commercial area: Promote roof greening (load ≥200kg/m², using drought-resistant plants such as Sedum) and vertical greening (wall coverage rate ≥30%), combined with permeable pavement in the square (permeability rate ≥30%), to alleviate the heat island effect of the hard base surface [10].

5.2. Improvement of green space layout and quality

Layout optimization: Build a network of "ventilation corridors + ecological patches". In the central urban area, over 100 pocket parks will be constructed through demolition and relocation, connecting the existing green Spaces (increasing the patch connection index from 0.3 to 0.5). The suburbs protect large forest patches (such as Mentougou and Miyun) as "cold sources" to transport cold air to the urban areas.

Quality improvement: Renovate single-tree species green Spaces (with a target of no less than 5 tree species per green space), establish a health monitoring system (monitor chlorophyll content every quarter), and carry out replanting (survival rate no less than 85%) and soil improvement (add organic fertilizer to enhance fertility) on degraded green Spaces.

5.3. Implement guarantee mechanism

Incorporate the carbon sink capacity of green Spaces (with a weight of 30%) and the cooling effect (with a weight of 20%) into the ecological assessment indicators of district-level governments. Establish a special fund (with an average of 200 million yuan per year) for the construction of "pocket parks" and subsidies for three-dimensional greening. Establish a three-level monitoring network of "city - district - sub-district” and release a monthly assessment report on the ecological functions of green Spaces.

6. Discussion

The core driving force of Beijing's heat island effect is the "spatial overlap of densely populated areas and high-temperature surfaces" : the dense population in the central urban area (with an increase of 1-2℃ in anthropogenic heat source emissions) and the dominance of artificial surfaces (accounting for over 80%, forming a "city oven" effect) overlap with each other, while the fragmentation of green Spaces weakens the cooling capacity.

The optimization strategy proposed in this study can alleviate the heat island effect in three aspects:

(1) The improvement of spatial connectivity (construction of ventilation corridors) promotes the entry of cold air from the suburbs into the city, and it is expected to reduce the intensity of the heat island by 0.5 to 0.8 degrees Celsius.

(2) Surface renovation (permeable pavement, restoration of small and micro water areas) will reduce the heat storage of artificial surfaces, with an expected reduction of 0.4 to 0.6 degrees Celsius.

(3) Source control (clean energy substitution) reduces artificial heat sources, with an expected reduction of 0.3 to 0.5 degrees Celsius. Overall, after the implementation of the strategy, the intensity of the urban heat island effect can be reduced by 1.5 to 2 degrees Celsius, forming a synergy effect with the "dual carbon" goals.

Optimization strategy

(1) There are significant type differences in the ecological functions of green Spaces in Beijing. The coordinated optimization of "quality" (type and structure) and "quantity" (spatial integrity) is

the key to enhancing the functions.

(2) The multi-source remote sensing data fusion technology has significantly improved the extraction accuracy of green space parameters (the classification accuracy has increased from 82% to 91%), providing a reliable path for the quantitative assessment of ecological functions.

(3) The densification of buildings and the fragmentation of green Spaces are the dominant factors weakening ecological functions, while the diversity of vegetation can effectively counteract the negative impacts.

(4) Implementing differentiated strategies for functional zones can maximize the ecological benefits of limited resources and provide an operational solution for ecological planning in Beijing.

7. Conclusion

Beijing's green spaces exhibit clear type-based differences in their ecological functions, and the coordinated optimization of "quality" (type and structure) and "quantity" (spatial integrity) emerges as the central pathway to enhance these functions. Advances in multi-source remote sensing data fusion markedly improve the precision of green space parameter extraction, with classification accuracy rising from 82% to 91%, offering a robust basis for quantitative evaluation of ecological services. At the same time, intensive urban construction and resulting fragmentation remain the dominant drivers of ecological function loss, though vegetation diversity can counterbalance these adverse effects to some extent. To maximize ecological benefits under limited land and resource conditions, differentiated management strategies tailored to functional zones are indispensable, offering practical guidance for ecological planning in the capital. Together, these findings highlight the necessity of integrating technological innovation with ecological design, balancing urban growth with green space protection, and promoting refined spatial strategies that sustain ecosystem services in a rapidly urbanizing environment.

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

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