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Green Transport Accessibility and Carbon Emission Coupling of Urban Public Recreational Spaces: The Case of New York

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Abstract. The short-distance accessibility of urban public recreational spaces directly determines their actual utilization efficiency. As the mainstream modes of short-distance travel, green transport options such as walking and cycling serve as the key link connecting residents with recreational spaces. Their accessibility levels are closely associated with carbon emissions from recreational travel, emerging as a crucial dimension of urban low-carbon development. Current relevant studies mostly focus on green space itself, with insufficient attention paid to green transport-oriented accessibility, and there remains room for expansion in the coupled analysis of accessibility and carbon emissions. Taking New York City, USA as the research object, this study integrates diverse recreational spaces including urban parks, sports facilities, and cultural or educational sites. Employing the Gaussian Two-Step Floating Catchment Area method, it systematically explores the accessibility levels and distribution patterns of recreational spaces under the context of green transport, while conducting coupled carbon emission accounting for recreational travel. The results reveal significant regional disparities in the accessibility of recreational spaces in New York City in accessibility indices, presenting a circular gradient characteristic of "core agglomeration-transitional median-peripheral dispersion". Recreational travel carbon emissions show a significant strong negative correlation with green transport accessibility. Low-accessibility areas form a high-carbon emission structure due to the high proportion of motor vehicle travel, and the spatial differentiation patterns of the two are highly consistent. Based on the above findings, this study presents targeted optimization suggestions from two dimensions: spatial layout and green transport network, as an exploration for the planning practice of low-carbon recreational spaces.

Keywords: Green transport, Recreational space, Accessibility, Gaussian Two-Step Floating Catchment Area, New York City, Carbon emission

1. Introduction

Recreational spaces refer to accessible open spaces and facilities located in urban areas or suburban peripheries, serving functions such as rest, social interaction, exercise, entertainment, sightseeing, and tourism. *The UN-Habitat Strategic Plan2026–2029* explicitly advocates a shift in global urban development from unregulated expansion to intensive growth characterized by compactness and functional integration. This policy orientation signifies that cities worldwide have entered a phase of

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in-depth transformation, transitioning from incremental expansion to inventory renewal and functional restructuring. Against this backdrop, the urban functional system has become increasingly complex. With the improvement of residents' quality of life, the role and status of leisure and recreational functions in urban space have continued to gain prominence. In practice, constrained by factors such as time costs, road network density, and public transportation accessibility, people's trips to recreational spaces tend to rely on short-distance travel—especially low-carbon modes like walking and cycling. Consequently, the ease of access has emerged as a pivotal determinant of the utilization efficiency of recreational spaces.

Accessibility to recreational spaces is widely adopted by academia as a metric to measure the level of ease of access. In recent years, studies on the accessibility of recreational spaces have primarily taken economically developed large and medium-sized cities as core research objects, such as Philadelphia [1]. Research methodologies have integrated a variety of geospatial analysis approaches, including statistical analysis [2], buffer analysis, Space Syntax [3], nearest neighbor analysis, cost-weighted distance analysis, gravity model, and the Two-Step Floating Catchment Area method [4]. Among these, the Gaussian Two-Step Floating Catchment Area method, as an optimized version of the traditional 2SFCA method, has been extensively applied to accessibility analyses of green spaces, public facilities and other scenarios [5] due to its ability to accurately fit the distance decay effect, and is particularly suitable for accessibility assessment scenarios dominated by short-distance green transport. From a research perspective, existing studies mostly focus on the research framework of "spatial layout – supply-demand matching – equity evaluation – ecological effect". For instance, scholars have explored the layout optimization and supply-demand matching efficiency of recreational spaces from dimensions such as "classification and grading" and "supply and demand" [6, 7]. Some studies have even extended to in-depth topics including the equity evaluation of accessibility [8-10] and ecological environmental impacts [11]. Despite the abundant research achievements, against the backdrop of the advocacy for green low-carbon development and urban stock-based development, three prominent research gaps remain: first, insufficient attention has been paid to accessibility under the guidance of green transport; second, research objects are mostly limited to park green spaces, neglecting the value of composite recreational resources such as cultural venues and sports facilities; third, the coupling relationship between accessibility and carbon emissions from recreational travel has not been quantified, which makes it difficult to provide empirical support for the planning and construction of low-carbon recreational spaces.

To address the aforementioned research gaps, this study takes New York City as the research subject, integrates diverse types of recreational spaces, and adopts the Gaussian Two-Step Floating Catchment Area method to focus on analyzing the level of residents' accessibility to recreational spaces via green transport. Combined with authoritative official data, it conducts carbon emission accounting for short-distance recreational trips of 1.5 km at the borough scale. This research aims to explore recreational spaces, emphasize the core role of green transport in accessibility evaluation, and conduct an integrated analysis of recreational travel accessibility and carbon emissions. This study is an exploration for the optimization of low-carbon recreational space layout in New York City and other similar high-density megacities.

2. Data preparation and preprocessing

2.1. Study area and definition

New York City is located in the southeastern part of New York State, the United States, and consists of five administrative boroughs: Manhattan, Brooklyn, Queens, the Bronx, and Staten Island, with a total area of 789 square kilometers. The study area and its location are illustrated in Fig.1. Its overall terrain is characterized by a south-high and north-low trend, as well as an east-low and west-high distribution. As the most populous city in the United States, New York City has a permanent population of over 8 million. The Greater Greenways: NYC Greenway Plan, a special planning document released by the New York City Department of Transportation (NYCDOT) in 2025, systematically sorts out and plans the construction of the city-wide greenway network, and promotes the in-depth integration of recreational spaces with green transport networks such as walking and cycling paths. This plan demonstrates the city's practical exploration in the integration of recreational spaces and green transport, as well as the development of low-carbon cities. Therefore, conducting a study on the current accessibility and carbon emissions of recreational spaces in New York City holds great practical significance.

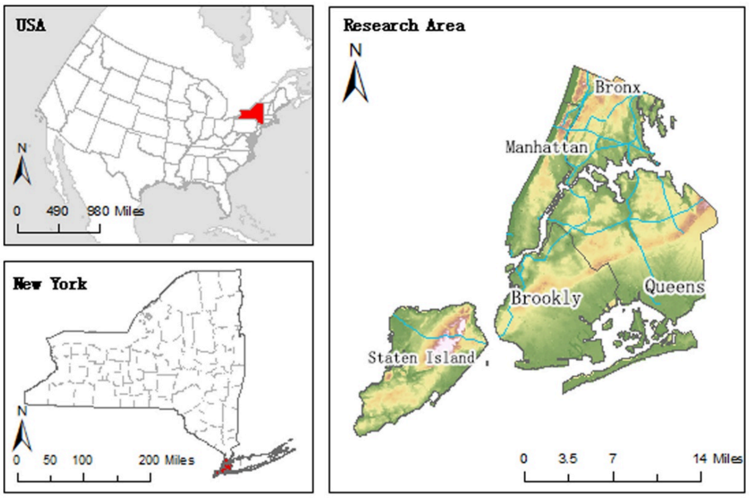

Figure 1. Administrative division of New York City

2.2. Data sources and processing

The identification of recreational spaces was based on multi-source data [12]. First, functional screening was conducted using Point of Interest data from OpenStreetMap to extract relevant locations including leisure venues, green spaces, parks, squares, and cultural, museum and educational sites, thus initially constructing a candidate set of potential recreational spaces. Second, the Normalized Difference Vegetation Index (NDVI) was retrieved from remote sensing images to accurately capture areas with prominent greening characteristics, which were then used to supplement and verify the candidate set. This further improved the accuracy and comprehensiveness of identifying spaces that actually possess ecological and recreational functions.

Population data adopted raster data with a 1000 m resolution from 2020 to characterize the heterogeneous spatial distribution of the population. A 2 km × 2 km fishnet was constructed as the basic analysis unit, and the Zonal Statistics tool in ArcGIS was used to aggregate the total population in each grid (D_k), forming a discretized demand unit layer.

2.3. Research method: Gaussian Two-Step Floating Catchment Area

In this study, the Gaussian Two-Step Floating Catchment Area (G2SFCA) method was adopted to calculate the accessibility of recreational spaces, with the specific process as follows. The overall

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research workflow and key steps are illustrated in Fig.2.

(1). Calculate the supply-demand ratio of recreational spaces: Taking each recreational space j as the center, a maximum service radius of d_0 = 1000 meters was set. All population grids k within its influence scope were identified, and the population was weighted by distance attenuation. The calculation formula for the supply-demand ratio R_j of recreational space j is as follows:

$$R_j = \frac{S_j}{\sum_{k \in \left\{d_{kj} < d_0\right\}} G\left(d_{kj}\right) D_k} \tag{1}$$

where $G(d_{kj})$ denotes the Gaussian decay function, defined as follows:

$$G\left(kj\right) = \frac{e^{-\frac{1}{2} \times \left(\frac{d_{kj}}{d_0}\right)^2} - e^{-\frac{1}{2}}}{1 - e^{-\frac{1}{2}}} \left(d_{kj} < d_0\right) \tag{2}$$

(2). Calculate the comprehensive accessibility of population units: Taking each population grid i as the center, a search scope with d_0 = 1000 m was set again. All recreational spaces j within its accessible range were identified, and the supply-demand ratios $R_j$of these spaces were superimposed after distance attenuation to obtain the overall accessibility index A_i^D of the grid:

$$A_i^D = \sum_{j \in \{d_{ij} \le d_0\}} G\left(d_{ij}\right) R_j \tag{3}$$

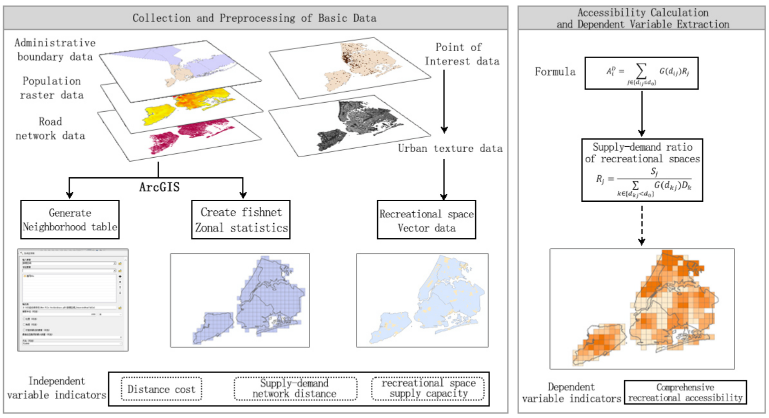

Figure 2. Research technical roadmap

3. Research results

3.1. Descriptive statistical analysis and overall spatial pattern

The comprehensive accessibility index (A_i^D) of recreational spaces in New York City was calculated using the Gaussian two-step floating catchment area method. Descriptive statistical analysis was first carried out to show the overall accessibility characteristics. The results are displayed in Table 1. The accessibility values range from 0.032 to 41.66, with a range of 41.628, indicating an extremely large spatial difference across the city. The mean value is 12.8 and the median is 10.967; the mean is higher than the median, suggesting that high-accessibility areas drive

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up the overall level. The standard deviation is 10.5 and the coefficient of variation is 0.82, falling into the medium–high dispersion interval, which confirms that the spatial distribution of accessibility is significantly uneven.

Table 1. Overall statistical characteristics of NYC recreational accessibility

Statistical standards	Min	Max	Mean	Median	SD	CV
value	0.032	41.66	12.8	10.967	10.5	0.82

Spatially, recreational space accessibility in New York City presents a distinct core-periphery differentiation pattern, with significant spatial imbalance across the city. The distribution of recreational spaces in New York City is shown in Fig.3. High-accessibility areas are concentrated in the central urban core, including Midtown Manhattan and the northern core of the Bronx, where dense recreational facilities and a well-developed slow traffic system enable continuous, balanced service coverage. In contrast, low-accessibility areas are primarily located in the southern, eastern, and peripheral zones of the city. Among these, the southern industrial zone of Brooklyn, the eastern suburbs of Queens, and the western edge of Staten Island stand out as the most underserved areas, with overall accessibility remaining at a persistently low level. This disparity stems from a severe mismatch between population agglomeration and recreational supply: high-density residential areas in these zones lack sufficient park and green space support, coupled with low green transport network density that restricts walking and cycling conditions, a pattern fully consistent with the general law of recreational space accessibility in high-density cities [13]. Transitional zones, including central Brooklyn, the western adjacent areas of Queens, and the eastern coast of Staten Island, exhibit obvious internal differentiation: while some neighborhoods achieve basic service coverage through community green spaces, widespread local service shortages leave overall accessibility at a moderate level.

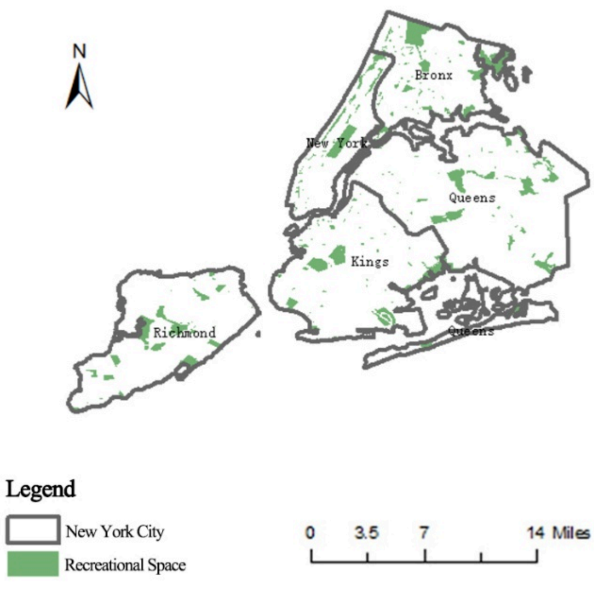

Figure 3. Recreational space distribution of New York City

3.2. Zonal division of recreational space accessibility

Based on the spatial agglomeration and gradient attenuation characteristics of accessibility, this study further identifies the key influencing factors and divides the study area into three concentric zones: core zone, transitional zone, and peripheral zone.

Spatial disparities in accessibility are largely associated with the density of recreational spaces, completeness of the green transport network, population concentration, and land development intensity. High-accessibility areas are mostly concentrated in the urban center, where recreational facilities are dense and green transport systems are mature. Low-accessibility areas are mainly located in the urban periphery, with insufficient recreational resources and limited coverage of green transport.

According to the natural breaks method and actual spatial morphology, the study area is divided into three zones, namely the core zone, the transitional zone, and the peripheral zone. The grouped statistics of recreational space accessibility by zone are presented in Table 2. The core zone features high overall accessibility, continuous distribution of recreational spaces, and nearly full green transport coverage. The transitional zone is characterized by moderate accessibility, patchy distribution of recreational spaces, and partial gaps in green transport services. The peripheral zone presents relatively low accessibility, scattered recreational facilities, and obvious service blind spots in green transport. The spatial zoning result is illustrated in Fig.4.

Table 2. Grouped statistics of recreational space accessibility by concentric zones in NYC

Zone Type	Number of Units	Percentage (%)	Mean	Median
Core Zone	65	25.11	26.67	26.39
Transitional Zone	177	45.17	9.79	10.36
Peripheral Zone	77	29.72	1.79	1.92

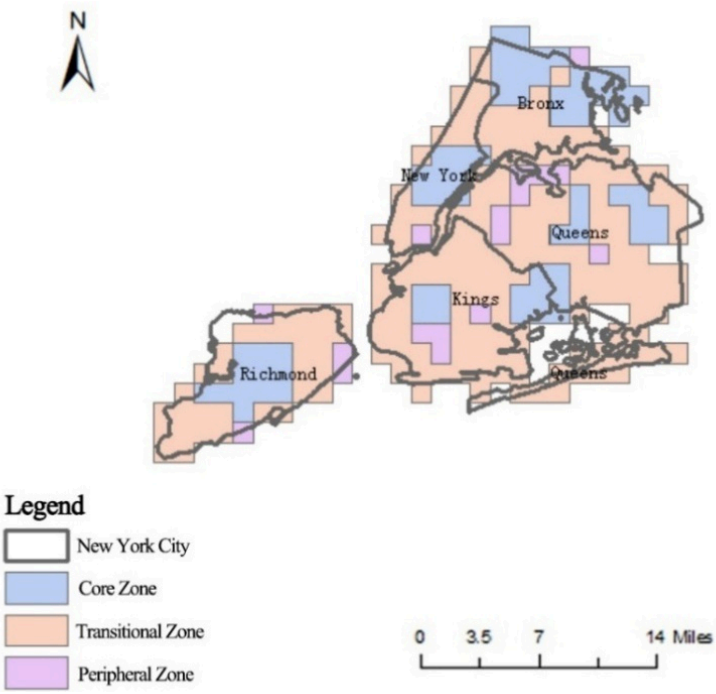

Figure 4. Recreational space Zoning in NYC

Overall, the accessibility of recreational spaces in New York City presents a distinct pattern of "high in the center and low at the periphery", which is consistent with the common resource agglomeration effect in high-density cities. The core area forms efficient service coverage by virtue of its dense park network and well-developed non-motorized transport system; in contrast, the peripheral areas are constrained by lagging infrastructure and spatial fragmentation, making it difficult for residents to reach suitable recreational venues even if they are willing to walk.

The concentric zone analysis reveals a distinct gradient-decreasing characteristic of recreational space accessibility in New York City. Although the core zone contains only 65 units, it demonstrates a significant advantage with a mean accessibility of 26.67, presenting a "core agglomeration" pattern. This zone is characterized by a high-density distribution of recreational spaces and full coverage within the 1000-meter green transport service radius. Additionally, the core area is supported by a high-density green transport network formed by the renovation of pedestrian and bicycle spaces along Broadway, Ninth Avenue, and other corridors [14] making it a high-quality area for recreational services. The transitional zone includes 177 units with a mean accessibility of 9.79, where recreational spaces are mostly small and medium-sized community green spaces with incomplete 1000-meter walking coverage, representing an intermediate level of recreational services. The peripheral zone consists of 77 units with a mean accessibility of only 1.79, featuring scarce and scattered recreational space supply, severely restricted green transport accessibility, and an almost "service vacuum" status.

3.3. Carbon emission accounting

This study calculates traffic carbon emissions for recreational trips in New York City, focusing on 1.5 km short-distance green travel, which represents the dominant recreational travel distance. Travel modes are classified into motor vehicle, public transport, and green transport (walking and cycling). A weighted carbon emission accounting method is applied based on mode share: single-mode emissions are computed by multiplying the carbon emission factor by the 1.5 km benchmark distance, and total emissions are aggregated using mode share weights [15]. Carbon emission factors and mode share are derived from official U.S. and New York City government data and the 2022 NYCDOT Citywide Mobility Survey.

The carbon emission factor is 0.27 kg·CO_2/km for gasoline passenger vehicles (EPA), 0.046 kg·CO_2/km for public transport (DOE and MTA), and 0.0046 kg·CO_2/km for green transport (life-cycle assessment). According to the survey, the citywide mode shares are 21% motor vehicle, 14% public transport, and 63% green transport, indicating green transport as the primary recreational travel mode. Single-mode emissions for 1.5 km trips are weighted by mode share to obtain the contribution of each mode and total recreational travel carbon emissions, as shown in Table 3.

Table 3. Carbon emission accounting results for 1.5km recreational trips in NYC

Travel Mode	Carbon Emission Factor (kg·CO_2/km)	Mode Share	Carbon Emission Contribution (kg·CO_2)	Total Carbon Emission (kg·CO_2)
Motor Vehicle Trips	0.27	21%	0.08505	
Public Transport Trips	0.046	14%	0.00966	0.099
Green Transport Trips	0.0046	63%	0.004347	

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As shown in the accounting results, there are significant differences in carbon emission contribution among different travel modes. Although motor vehicle trips account for only 21% of recreational trips in New York City, their carbon emission contribution reaches 0.08505 kg·CO_2, accounting for 85.86% of the city's total carbon emissions, making them the main source of carbon emissions from recreational travel in New York City. The carbon emission contribution of public transport trips is 0.00966 kg·CO_2, and that of green transport trips is only 0.004347 kg·CO_2. Together, these two modes contribute less than 15% of total carbon emissions, with green transport trips accounting for only 4.39% of the total. This highlights the core value of green transport in the low-carbon development of recreational travel and confirms the significance of improving green transport accessibility for promoting low-carbon urban recreational development.

To explore the spatial differentiation characteristics of carbon emissions and their relationship with accessibility, the comprehensive carbon emissions of recreational trips in each borough were calculated based on the differentiated travel mode share of each district and the single-mode carbon emissions for a 1.5km trip. By linking these results with the accessibility statistics, the statistical carbon emission accounting results at the borough scale in New York City were obtained, as shown in Table 4.

Table 4. Statistical carbon emission results for 1.5km recreational trips in NYC

Borough	Motor Vehicle Share (%)	Public Transport Share (%)	Green Transport Share (%)	Carbon Emission (kg·CO_2)
Manhattan	12	16	69	0.06850
Brooklyn	45	12	43	0.19350
Queens	38	13	49	0.16625
The Bronx	15	16	69	0.07655
Staten Island	30	14	56	0.135024

There is a significant strong negative correlation between recreational travel carbon emissions and green transport accessibility in New York City. The mean accessibility of the five boroughs from high to low is the Bronx, Manhattan, Staten Island, Queens, and Brooklyn, while total carbon emissions show a strict stepwise increase. The Bronx and Manhattan, with the highest accessibility, have carbon emissions below 0.08 kg·CO_2, forming the city's core low-carbon areas. Manhattan, with nearly 70% green transport share, records the lowest carbon emissions. Brooklyn, with the lowest accessibility, has carbon emissions of 0.1935 kg·CO_2, 2.94 times that of Manhattan, representing the high-carbon area. Travel mode structure is the dominant cause of carbon emission differentiation. The Bronx and Manhattan both have a green transport share exceeding 69%, supporting low-carbon recreational travel. By contrast, Brooklyn and Queens have high motor vehicle shares 45% and 38%, with motor vehicles contributing over 90% of carbon emissions. This indicates that insufficient recreational space supply in low-accessibility areas forces residents to rely on motor vehicles, resulting in a high-carbon travel structure.

Overall, the spatial pattern of recreational travel carbon emissions is highly consistent with that of accessibility. High-accessibility areas realize low-carbon travel supported by dense recreational resources, whereas low-accessibility areas form a motor vehicle-dominated high-carbon structure.

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3.4. Optimization of recreational space accessibility

Based on the concentric gradient pattern of recreational space accessibility and its strong negative correlation with carbon emissions in New York City, this study addresses key problems: over-concentrated resources in the core area, insufficient green transport services in the periphery, and high-carbon travel structures in low-accessibility regions due to limited recreational supply and high motor vehicle dependency. Targeted strategies are proposed from spatial layout optimization and green transport network improvement to promote the coordinated development of recreational accessibility and low-carbon urban recreation.

For spatial layout optimization, differentiated policies are formulated according to the "high-core, low-periphery" pattern to remedy supply shortages and balance resource distribution. The core zone focuses on functional integration and quality improvement by combining parks, cultural, and educational facilities to enhance resource efficiency and avoid redundancy. The transitional zone prioritizes the supplementation and densification of recreational spaces, especially small and medium-sized community green spaces and pocket parks in areas uncovered by the 1000-meter green transport service radius. The peripheral zone takes Brooklyn, Queens, and Staten Island as key areas, and prioritizes user-friendly recreational facilities in high-density residential zones to solve the scarcity and fragmentation of recreational resources.

For green transport network improvement, a well-matched green transport system will be constructed to strengthen connections between transport networks and recreational spaces. The core zone will optimize pedestrian and bicycle lane connectivity to achieve seamless green travel links and consolidate its low-carbon characteristics. The transitional and peripheral zones will accelerate the construction of green paths and extend the greenway network to communities and recreational sites, realizing full coverage of green transport and ensuring accessibility within the 1000-meter service radius. Meanwhile, green connections between public transit stations and recreational spaces will be optimized to integrate greenways with the public transport system, reduce motor vehicle dependency, and promote low-carbon travel transformation in low-accessibility areas, in line with New York's low-carbon development goals.

4. Conclusions and discussion

Taking New York City as the study area, this paper applies the Gaussian two-step floating catchment area method to explore the accessibility characteristics of multi-type recreational spaces under green transport orientation, and calculates carbon emissions of 1.5 km short-distance recreational trips to reveal their spatial coupling relationship. Results show that green transport accessibility presents a significant concentric gradient pattern of "core agglomeration, transitional median, peripheral dispersion". Recreational travel carbon emissions are significantly and negatively correlated with accessibility, showing an opposite stepwise distribution. Low-accessibility areas tend to form high-carbon emission structures dominated by motor vehicles.

This study breaks through the limitation of traditional research that focuses on a single type of park green space, emphasizes the core role of green transport in accessibility evaluation, and realizes the integrated analysis of recreational travel accessibility and carbon emissions. It provides an empirical reference for the optimization of low-carbon recreational space layout in New York City and other similar high-density megacities.

Limitations of this study lie in that carbon emission accounting only covers 1.5 km short-distance trips without considering long-distance travel, vehicle types or peak-hour differences. Future research can carry out more refined accounting to support targeted low-carbon planning.

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