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Hidden Greens, Hidden Inequities? Evaluating Accessibility and Spatial Equity of Non-Park Green Spaces in London

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Abstract

Urban green spaces (UGSs) are critical to ecological sustainability and human well-being, but equitable access remains a key challenge, particularly in high-density cities. While existing studies have predominantly focused on parks, the role of non-park green spaces (NPGSs) has received limited attention. This study examines the spatial equity of NPGSs—an overlooked but essential component of urban green infrastructure in Inner London—using a typological classification informed by previous research, along with multi-threshold accessibility assessment and spatial justice evaluation. We apply GIS-based buffer analysis, decomposed Gini coefficients, and Moran's I clustering to quantify distributional disparities. The main findings are as follows: (1) five NPGS types are defined and mapped in Inner London: Natural and Protected, Community and Household, Purpose-Specific, Linear, and Underutilized; (2) significant accessibility inequities exist among NPGS types, with Community and Household demonstrating high equity (Gini coefficient < 0.25), while Underutilized exhibit severe deprivation (Gini coefficient > 0.74); (3) spatial clustering analysis reveals a core–periphery differentiation, characterized by persistent low–low clusters in central boroughs and emerging high–high hot spots in southeastern/northwestern boroughs. This study underscores the critical role of NPGS in complementing park-based greening strategies and provides a transferable framework to assess green equity, thereby contributing to the achievement of the United Nations Sustainable Development Goals (SDGs).

Keywords: non-park green spaces; spatial equity; accessibility; core-periphery differentiation; sustainable development goals

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1. Introduction

UGSs, which play an important role in purifying air, mitigating urban heat island effects, and regulating the microclimate, are recognized for their contribution to human well-being [1–6]. Beyond ecological benefits, UGSs positively influence physical and mental health [7,8], also providing suitable spaces for social interaction [9]. For citizens, UGSs function as areas for stress relief, physical exercise, leisure, and entertainment [10–13]. The association between abundant UGSs and lower crime rates is also well documented [14]. Through direct contact and participation, citizens obtain better physical health and life satisfaction [15,16]. Therefore, the benefits of UGSs are indispensable and fundamental in the process of urbanization [17].

UGSs are often divided into public parks, street greenery, community green spaces, etc. [18]. While numerous studies have primarily focused on large-scale UGSs, such as

parks [19], exploring their contributions to residents' well-being and to urban climate regulation [4,8], some have also examined smaller, formally designed green spaces like pocket parks and urban squares [20,21]. However, these spaces belong to the official park system and are therefore excluded from this study. Instead, we focus on non-park, informally managed green spaces, often referred to as "leftover" places [22], with untapped multi-dimensional potential. These green spaces are defined as NPGSs, including allotment gardens, street greenery, cemeteries, neighborhood green spaces, and private or non-public trees [23]. Empirical studies have shown that NPGSs can mitigate urban heat island effects and support microclimate regulation [24,25]. They also enhance biodiversity and ecological connectivity [26,27], foster community cohesion [28], preserve cultural landscapes [29], and generate economic benefits through agricultural and forestry production [30]. Beyond these ecological and social functions, NPGSs exhibit considerable diversity in form and use. Some, such as community gardens and neighborhood greens, are socially accessible and support daily recreation and interaction [31,32]. Others include street greenery with distinct linear morphology, cemeteries, and ruderal sites that fulfill specific infrastructural or landscape functions [33,34], whereas brownfield areas represent underutilized zones with potential for sustainable redevelopment and restoration [35]. Table 1 summarizes the five NPGS categories frequently identified in the literature. These NPGSs collectively complement park-based UGSs and contribute critically to ecosystem service provision and biodiversity conservation [36,37].

Table 1. Typologies and definitions of NPGSs summarized the literature.

Category	Subcategory	Literature
Natural and Protected	urban forests	forest (remnant woodland, managed forest, mixed forms) [31]
	grasslands	grassland [38]
	protected green areas	nature [39], nature reserve [40]
Community and Household	community-managed green spaces	community gardens [41], allotment gardens [42]
	neighborhood and residential green spaces	neighborhood green spaces [32], residential green spaces [43], tenant gardens [44]
	private household gardens	house gardens [11], private gardens [10]
Purpose-Specific	agricultural and horticultural green spaces	urban agriculture [45], horticulture [46], cultivated lands [30]
	institutional green spaces	school greening [33], hospital gardens [47]
	zoological and botanical green spaces	zoological gardens [48], botanical gardens [49]
	cemeteries	churchyard [29], cemetery [50]
Linear	street greenery	street trees [51], street greenery [34]
	green verges	roadside green verges, railway green verges [52], airport green verges [18]
Underutilized	brownfields	industrial brownfields [35], post-industrial brownfields [53]
	vacant lots	vacant lots [54], vacant land [14]
	abandoned, ruderal, and derelict areas	abandoned [55], ruderal areas [56], derelict sites [57]

Environmental justice emphasizes equitable access to ecological resources regardless of race, gender, socioeconomic status, or residence [58–60]. Despite this principle, inequity in UGS access persists globally, as park expansion in high-density cities fails to address spatial disparities [18]. Unlike parks, NPGSs are typically smaller, more dispersed, and

embedded within residential areas, enabling everyday contact with nature for diverse social groups [31–35]. Recent studies highlight the critical role of NPGSs in advancing environmental justice through diverse pathways. Emerging evidence demonstrates that NPGSs can improve urban thermal comfort by mitigating heat island effects [61], enhance accessibility through strategic distribution [62], and expand service availability through functional diversification [36,37]. These synergistic effects collectively mitigate spatial and social inequalities in green resource allocation, thereby fostering more equitable urban ecosystems [63]. The accumulating empirical findings underscore the necessity of systematic investigations into NPGS distribution and characteristics, particularly regarding their underexplored role in achieving environmental justice objectives [36]. Such research provides critical insights for urban planning strategies that move beyond traditional park-centric paradigms towards inclusive and diversified UGS networks.

Accessibility is a key indicator in spatial equity research which reflects the potential opportunities residents have to benefit from UGSs, and is widely regarded as an effective measure of green availability and distributional equity [17]. While the two-step floating catchment area method is often praised for capturing spatial differences between supply and demand [64], its applicability is limited in NPGSs due to their typical small-scale configurations and functional heterogeneity [52]. To overcome this limitation, buffer analysis offers an effective means for assessing NPGS accessibility at varying pedestrian thresholds, quantifying intra-urban disparities with precision. Given the diversity of NPGSs, several critical questions emerge: How do accessibility patterns vary across different NPGS types? What spatial clustering patterns emerge from these disparities? What implications do these patterns hold for advancing spatial justice? These questions form the core investigative framework of this study.

This study proposes a novel framework to evaluate NPGSs in Inner London through three interconnected components: (1) systematic classification and mapping of NPGS typologies based on functional and structural characteristics; (2) multi-threshold pedestrian accessibility analysis using buffer zones to quantify service coverage disparities; and (3) spatial equity analysis combining Gini coefficient decomposition with spatial autocorrelation to detect statistically significant clusters of accessibility deprivation. The framework advances UGS research by integrating typological diversity, distance-sensitive accessibility metrics, and spatial justice assessment, thereby providing actionable insights for equitable and sustainable UGS planning, in line with SDG 11 on universal access to safe, inclusive, and accessible green spaces [65].

2. Methods

2.1. Study Area

This study focuses on Inner London, which comprises 14 boroughs, covers approximately 320 square kilometers, and has a population of 3,505,912 (2025). The area is characterized by high population density, advanced urbanization, and pronounced socioeconomic diversity. Population density varies widely across Inner London, from less than 6000 persons/km^2 in peripheral residential areas to more than 16,000 persons/km^2 in central boroughs. The area is ethnically diverse, with non-White residents accounting for nearly 47% of the population, and exhibits evident income polarization between affluent and deprived districts.

The region contains approximately 4777 hectares of green spaces, accounting for 15% of London's total, including parks, street greenery, community gardens, and other types of NPGSs. These diverse green spaces provide a robust context for evaluating NPGS accessibility. Inner London is divided into 1895 Lower Super Output Areas (LSOAs), the smallest statistical units defined by the Office for National Statistics (ONS, https://www.ons.gov.uk/ (accessed on 1 June 2025)), each containing approximately 1500 people or 650 households. This provides a foundation for quantifying accessibility disparities across LSOAs and analyzing distributional equity in NPGS allocation (Figure 1).



Figure 1. Location of the study area and overall spatial distribution of park and non-park green spaces in Inner London.

2.2. Research Flow

This study employs the systematic workflow illustrated in Figure 2 to evaluate NPGS accessibility and distributional equity. First, based on a literature review, we define an NPGS and classify existing NPGS types documented using three criteria. Second, we utilize Landsat-8 imagery to calculate NDVI, integrating open access datasets to refine green space boundaries, distinguish parks from NPGSs, and identify five distinct NPGS types. Third, considering NPGSs' limited-service range, we assess pedestrian accessibility through multi-ring buffer analysis to represent spatial proximity, and quantify distribution equity across distances using Lorenz curves and Gini coefficients. Finally, we conduct spatial autocorrelation analysis to reveal geographic disparities, identifying high–high clusters, low–low clusters, and spatial outliers.

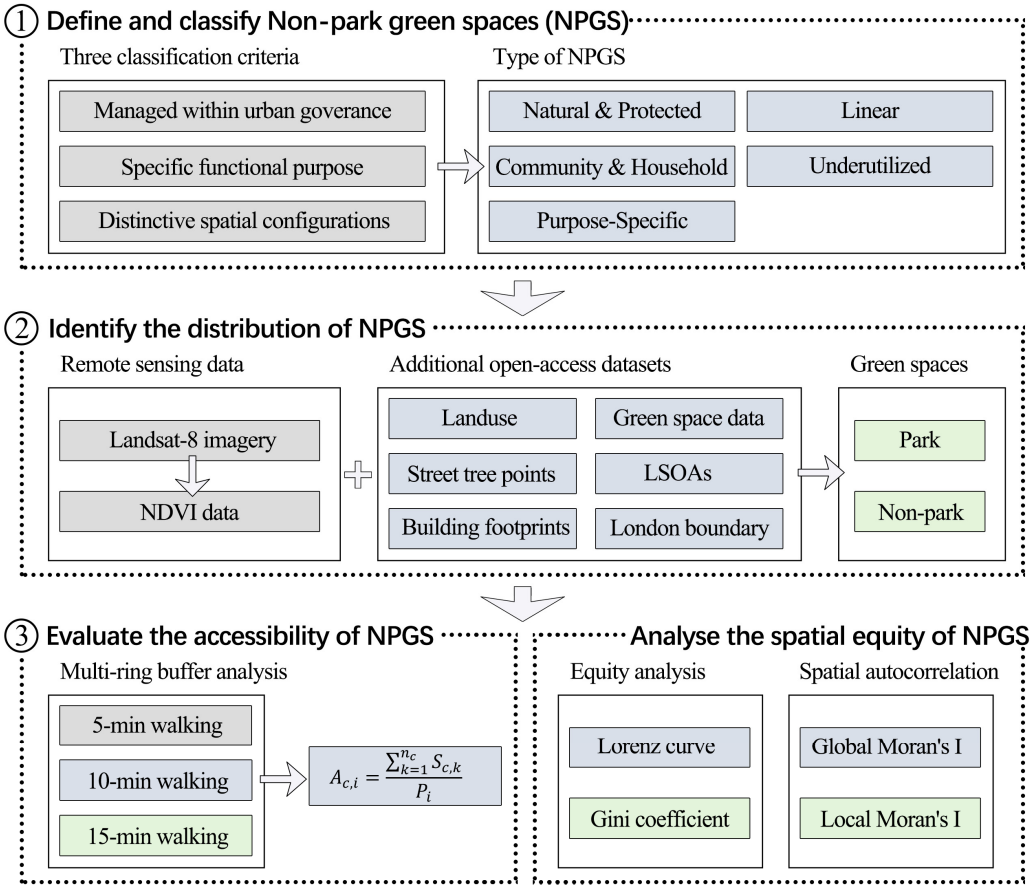


Figure 2. An integrated framework for definition, classification, and accessibility–spatial equity assessment of NPGSs.

2.3. The Types and Distribution of NPGSs

2.3.1. Define and Classify the Five Categories of NPGSs

We define NPGSs as all vegetated urban areas excluding parks [62]. NPGSs include both informal green spaces (IGSs) and certain formal green spaces [63], such as cemeteries [50], allotment gardens [42], and community gardens [41], which differ from parks in terms of user groups and function. IGSs are often classified into managed and unmanaged categories based on governance [23], but this classification inadequately addresses the functional and spatial complexity of urban green systems. To resolve this gap, we propose a novel framework classifying NPGSs through three criteria: (1) whether the green spaces are institutionally managed within urban governance systems, (2) whether they serve specific functional objectives (e.g., productive, educational, or therapeutic purposes), and (3) whether they exhibit distinctive spatial configurations (e.g., linear corridors versus patch formations). Systematic application of these criteria reveals five distinct NPGS typologies (Figure 3).

The defined NPGS typologies exhibit distinct functions across urban systems. Natural and Protected—comprising urban forests [31], nature reserves [40], and protected grasslands [38]—are primarily dedicated to biodiversity conservation through formal regulatory frameworks. Community and Household, such as residential gardens [10] and neighborhood green spaces [32], foster localized socioecological engagement through high residential accessibility. Purpose-Specific integrate specialized functional landscapes, including botanical gardens [49], cemeteries [50], and urban agricultural lands [45,46], which fulfill specific urban service roles. Linear, exemplified by street greenery [34] and green verges [18,52], enhance landscape permeability and ecological connectivity within

fragmented built environments. Underutilized, such as vacant lots [14] and degraded areas [53,57], retain untapped potential for ecological restoration despite current marginalization in urban planning.

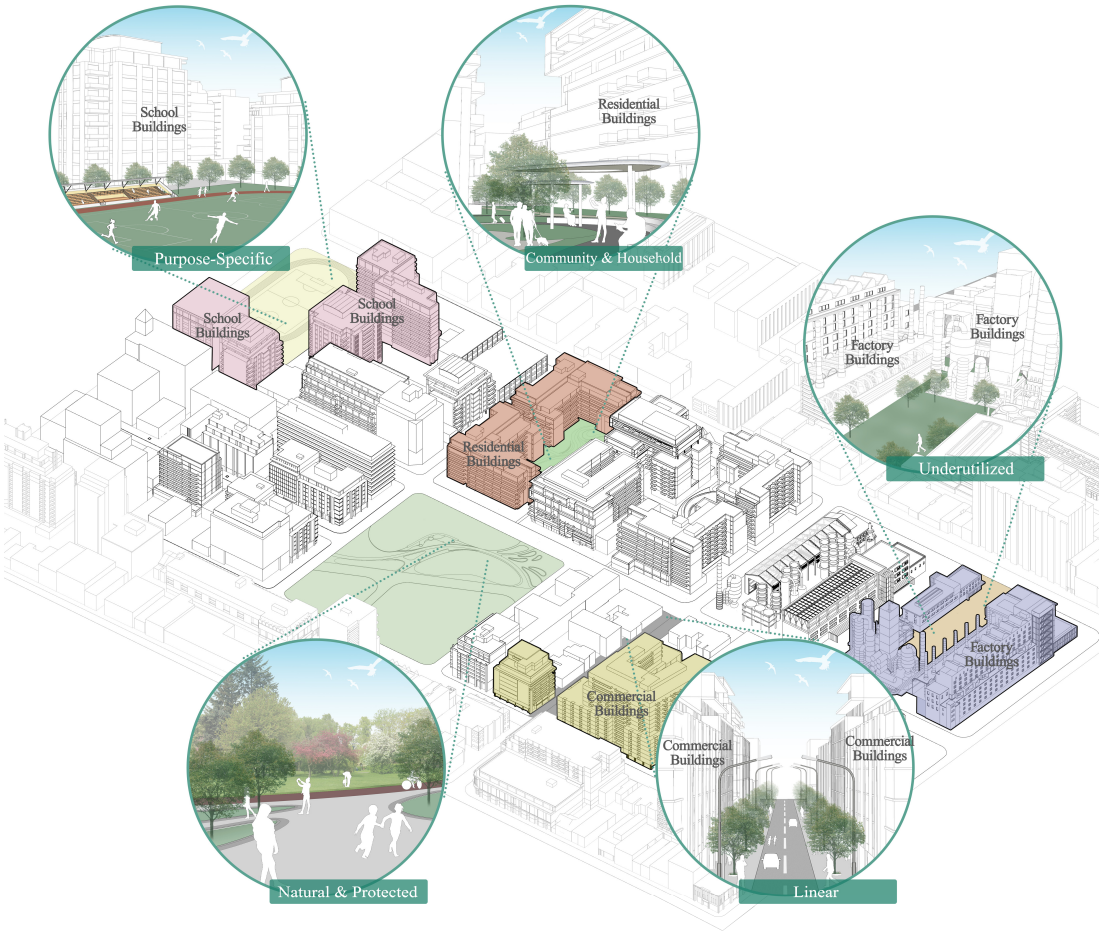


Figure 3. Schematic diagram of five NPGS categories in urban areas based on the proposed classification criteria.

2.3.2. Conduct the Land Use Data and NDVI to Evaluate the Distribution of NPGSs

To analyze the distribution of NPGSs accurately, we integrate remote sensing data, geographic information systems, and open access datasets [66]. Specifically, OpenStreetMap (OSM, https://www.openstreetmap.org/ (accessed on 1 June 2025)), Landsat-8 satellite imagery from the United States Geological Survey (https://earthexplorer.usgs.gov/ (accessed on 2 June 2025)), and data from the London DataStore (https://data.london.gov.uk/ (accessed on 2 June 2025)) are used to obtain NPGS data. We primarily source road, land use, and green space data from OSM, with the Inner London boundary, LSOAs, street tree points, and building footprints acquired from the London DataStore.

Normalized Difference Vegetation Index (NDVI) is a dimensionless indicator widely used to quantify vegetation coverage and condition [67,68]. The resulting NDVI values range from −1 to + 1, where higher values indicate dense, healthy vegetation, and lower values suggest barren land or water bodies [67,69]. To ensure high-quality data, satellite imagery from summer 2024 (June–August) is selected based on two criteria: (1) acquisition during peak vegetation phenology, and (2) cloud coverage below 6% to guarantee optical clarity and minimize atmospheric interference.

The index is mathematically defined as:

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

where *NIR* is the reflectance in the near-infrared band (Band 5) and *RED* is the reflectance in the red band (Band 4).

Of the five categories of NPGSs, Natural and Protected, Community and Household, and Purpose-Specific are primarily derived from land use data. Community and Household are further enhanced with NDVI to identify NPGSs within residential areas, while Purpose-Specific are refined using NDVI combined with medical and educational areas. Linear include both street greenery and green verges. Street greenery is identified by creating 6.5 m buffers around street tree points, according to the average crown width of the trees documented in the London i-Tree Eco Project (https://www.forestresearch.gov.uk/research/i-tree-eco/ (accessed on 1 June 2025)). Three buffers are established to delineate green verges, 15 m for roads, 25 m for railways, and 150 m for airport runways [70–72], and NPGS detection within these buffers is conducted using NDVI. Underutilized are demarcated based on land use classifications, with further identification of NPGSs in these areas carried out using NDVI (Table 2).

Table 2. The sources of NPGS data.

Category	Approach	Data source
Natural and Protected	classification acquisition	OSM
Community and Household	classification acquisition	OSM
	removal of building footprints and roads	OSM
	extracting NDVI within the scope of residential areas	NDVI
Purpose-Specific	classification acquisition	OSM
	extracting NDVI within the scope of medical and educational areas	NDVI
Linear	buffer created by street tree points (6.5 m)	London DataStore
	extracting NDVI within the buffer created by roads (15 m), railways (25 m), and airport runways (150 m)	NDVI
Underutilized	classification acquisition	OSM
	extracting NDVI within the scope of construction	NDVI

2.4. Evaluate the Accessibility of NPGSs

2.4.1. Multi-Ring Buffer Analysis of NPGS Distribution

Considering the functional diversity and limited service range of NPGSs, this study focuses on pedestrian accessibility as an indicator of spatial proximity, reflecting both opportunities for direct use and benefits derived from environmental or visual exposure. Following the Natural England action plan (2024), which calls for equitable access to green infrastructure within a 15 min walking distance for all residents, we quantify NPGS availability using three walking thresholds: 5 min (400 m), 10 min (800 m), and 15 min (1200 m) [73,74].

For each LSOA, buffers corresponding to these distances are generated using GIS tools. Both the total NPGS area and the area of each NPGS category within these buffers are aggregated. The per capita accessible area is then calculated to assess distributional equity, incorporating category-specific and total NPGS metrics. The accessibility of an NPGS category c in LSOA i is defined as:

$$A_{c,i} = \frac{\sum_{k=1}^{n_c} S_{c,k}}{P_i} \quad (2)$$

where $S_{c,k}$ is the area of the k-th NPGS patch within category c, n_c is the total number of NPGS patches of category c, and P_i is the population of LSOA i.

For the total NPGS accessibility, the formula is extended as:

$$A_{total,i} = \frac{\sum_{c=1}^{m} \sum_{k=1}^{n_c} S_{c,k}}{P_i} \quad (3)$$

where m represents the total number of NPGS categories.

2.4.2. Lorenz Curve and Gini Coefficient Analysis

The Lorenz curve and Gini coefficient, originally formalized in economics to measure wealth distribution inequality [75,76], have been widely adopted in environmental justice studies to assess spatial equity of public service facilities and green spaces [77,78]. Given their robustness and interpretability, we adopt these indicators to quantify inequality in spatial resource distribution, enabling direct comparison across NPGS types and distance thresholds. For each NPGS category, we construct Lorenz curves based on per capita accessible area within 1895 LSOAs across three buffer distances (400 m, 800 m, and 1200 m). The Lorenz curve is mathematically expressed as follows:

$$L(p) = \frac{\int_0^p F^{-1}(t)dt}{\mu} \quad (4)$$

where p represents the cumulative population proportion, $F^{-1}(t)$ is the quantile function of resource distribution, and μ is the mean accessible area.

The y = x denotes perfect equality. A closer proximity of the Lorenz curve to this equality line indicates lower inequality [62]. The Gini coefficient quantifies distribution inequality through the ratio of the area between the Lorenz curve and equality line to the total area under the equality line [79,80]. The Gini coefficient is mathematically expressed as follows:

$$G = 1 - 2\int_0^1 L(p)dp \quad (5)$$

The World Bank defines a Gini coefficient of 0.4 as the critical threshold for distributional inequality, with values exceeding this benchmark indicating severe inequity [81]. Empirical urban studies demonstrate that surpassing this threshold in green space distribution reveals significant spatial disparities requiring targeted policy interventions [59,82].

2.4.3. Spatial Autocorrelation and Hot Spot Analysis

Spatial autocorrelation of NPGS distribution is analyzed using Moran's I, a widely adopted method for identifying spatial clustering patterns [83,84]. Moran's I complements the Gini coefficient by revealing how accessibility inequities are spatially distributed, indicating whether they are clustered or dispersed. The analysis encompasses both global and local Moran's I. Global Moran's I quantifies the overall spatial clustering intensity of NPGSs across the study area [85], calculated as follows:

$$I = \frac{n \cdot \sum_{i=1}^{n} \sum_{j=1}^{n} \omega_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\left(\sum_{i=1}^{n} \sum_{j=1}^{n} \omega_{ij}\right) \cdot \sum_{i=1}^{n} (x_i - \overline{x})^2} \quad (6)$$

where n is the number of LSOAs, ω_{ij} represents the spatial weight matrix between units i and j, x_i and x_j denote the per capita accessible NPGS area, and $\overline{x}$ is the mean value.

Global Moran's I ranges from $[-1, 1]$. Values greater than 0 indicate positive spatial autocorrelation characterized by clustering of similar values, values less than 0 suggest

spatial dispersion or negative correlation with dissimilar values distributed adjacently, and a value of 0 corresponds to a random spatial distribution [86,87].

To characterize localized spatial imbalances in NPGS accessibility, local Moran's I identifies statistically significant hot spots representing areas of high–high clustering or cold spots associated with low–low clustering [88,89]. For each spatial unit i, local Moran's I is defined as:

$$I_i = \frac{(x_i - \overline{x}) \cdot \sum_{j=1}^{n} \omega_{ij}(x_j - \overline{x})}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \quad (7)$$

3. Results

3.1. The Category System and Overall Distribution of NPGSs in London

NPGSs in Inner London are classified into five typologies—Natural and Protected, Community and Household, Purpose-Specific, Linear, and Underutilized—based on governance characteristics, functional purpose, and spatial configuration. Table 3 presents the classification of NPGSs in Inner London, accompanied by detailed explanatory descriptions and representative scenes.

Table 3. The types of NPGSs in Inner London.

Category	Details in Inner London	Representative Images
Natural and Protected	nature reserve, conservation, forest, grass	
Community and Household	garden, allotment, community food growing, green space, village green, residential, estate	
Purpose-Specific	golf course, miniature golf, animal enclosure, arboretum, cemetery, churchyard, farmland, flowerbed, greenhouse horticulture, meadow, orchard, plant nursery, planting, medical, educational	
Linear	street greenery (6.5 m for street tree points), green verge (15 m for roads, 25 m for railways, and 150 m for airport runways)	
Underutilized	brownfield (post-industrial brownfield, transport-related brownfield, commercial brownfield, derelict brownfield), dead allotments, underutilized areas	

Geospatial analysis illustrates the distinct spatial distribution patterns of NPGSs in Inner London (Figure 4a). NPGSs in Inner London generally exhibit a balanced spatial distribution, although exceptions are observed in certain areas north of the River Thames. Further variations emerge across NPGS types: Community and Household demonstrate widespread uniformity, whereas Purpose-Specific are characterized by fragmented and patchy patterns. Linear display pronounced regional disparities, while both Natural and Protected and Underutilized show limited presence, with the latter being particularly scarce.

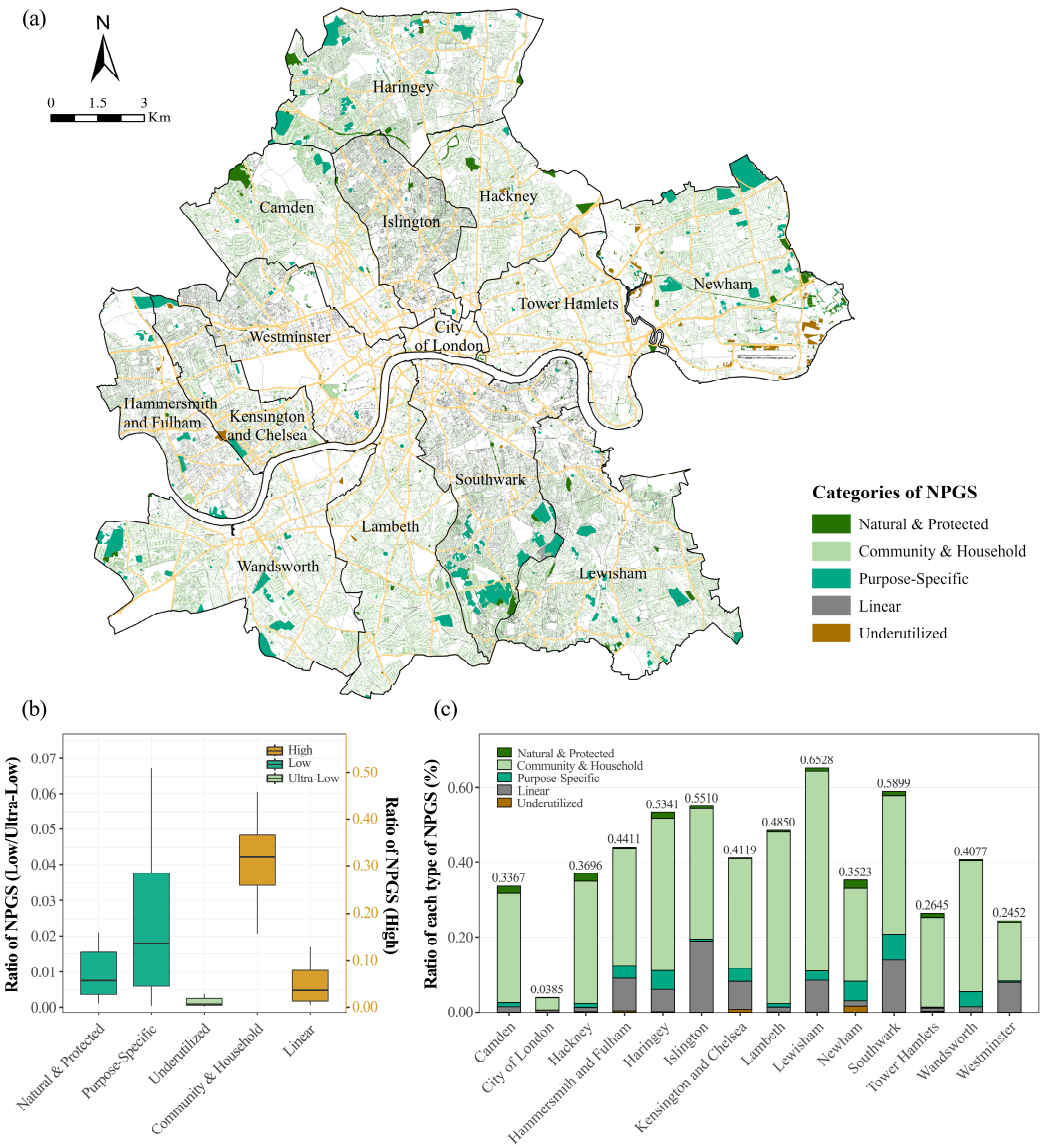


Figure 4. Spatial distribution and coverage patterns of NPGSs in Inner London: (**a**) geospatial allocation, (**b**) category proportion, and (**c**) borough-level variability.

3.2. The Disparities Between the Boroughs and Categories

Boxplot analysis further reveals significant variations in NPGS coverage ratios across typologies (Figure 4b). Community and Household and Linear exhibit higher ratios, with Community and Household showing the highest median (0.3196) and largest interquartile range (IQR = 0.1332), suggesting substantial variability. In contrast, Natural and Protected and Purpose-Specific typologies have lower median ratios. Underutilized typology demonstrates the lowest median (0.0008) and smallest IQR (0.0023), indicating uniform distribution and negligible green coverage.

Stacked bar charts reveal distinct spatial patterns of NPGS distribution across Inner London boroughs and typologies (Figure 4c). Overall, NPGS coverage exceeds 20% in most boroughs, peaking at 65.3% in Lewisham, with the City of London being an exception (3.9%). Among the five NPGS categories, Community and Household consistently dominates all boroughs, followed by Linear and Purpose-Specific. Notably, Purpose-Specific surpasses Linear only in Newham and Wandsworth, attributable to Newham's extensive cemeteries and Wandsworth's large golf courses. Underutilized maintains minimal coverage across all boroughs.

Regional disparities are further evident in detailed spatial patterns. Natural and Protected, comprising nature reserves, protected zones, forests, and grasslands, predominantly cluster along administrative boundaries. Newham and Hackney exhibit the highest vegetation coverage, exceeding 2.0%, in sharp contrast to the City of London, which has a minimal coverage of 0.1%. Community and Household, the most extensive NPGS category, include private gardens, allotments, community food-growing areas, and residential green spaces. At the borough scale, significant inter-borough disparities exist: all boroughs except the City of London (3.1%) and Westminster (15.6%) surpass 20% coverage, peaking at 53.4% in Lewisham. Purpose-Specific encompass recreational facilities such as golf courses and zoos, productive lands like farmlands and greenhouses, cultural heritage sites including cemeteries, and therapeutic-educational green spaces. These areas show localized concentrations in Southwark (6.7%), Newham (5.3%), and Haringey (5.0%), while the City of London shows negligible coverage (0.04%). Linear, primarily consisting of street tree networks and green verges, exhibit spatial polarization, with Islington (19.0%) and Southwark (14.0%) displaying the highest proportions, compared to minimal presence in Tower Hamlets (0.8%) and the City of London (0.5%). Underutilized, characterized by extreme fragmentation and typified by brownfields and abandoned areas, are exceptionally concentrated in Newham (1.6%), whereas 11 of 14 boroughs register coverage below 0.03%.

Aggregate spatial analysis highlights a core–periphery differentiation in NPGS distribution. High-coverage clusters (>50%) are predominantly localized in peripheral boroughs of Inner London, specifically Lewisham (65.3%), Southwark (59.0%), Islington (55.1%), and Haringey (53.4%), in contrast to central boroughs such as Tower Hamlets (26.5%), Westminster (24.5%), and the City of London (3.9%), which exhibit markedly lower coverage.

3.3. NPGS Accessibility

3.3.1. The Comparison of Accessibility Measurements of the Five NPGS Types

Lorenz curves and Gini coefficients reveal improved accessibility across all NPGS categories with increasing buffer distance, as shown in Figure 5. This pattern manifests through Lorenz curves approaching the absolute equity line and progressively declining Gini coefficients. Total NPGS consistently exhibits the lowest Gini coefficients across all distances, closely aligning with the Community and Household category. Among the five typologies, Community and Household demonstrate the most equitable distribution, as Gini values decrease from 0.2523 at 400 m to 0.2216 at 1200 m. In contrast, Underutilized display the least equitable access, with Gini coefficients ranging from 0.8848 to 0.7418. Moderate equity levels are observed in Linear, Natural and Protected, and Purpose-Specific, ordered by ascending Gini coefficients. Notably, Natural and Protected temporarily surpass Linear in equity metrics at larger buffers. At 800 m, this crossover occurs when cumulative NPGS coverage reaches 10.5% for 45.8% of the population, while at 1200 m, it reaches 20.7% coverage for 55.2% of the population before Linear regain dominance.

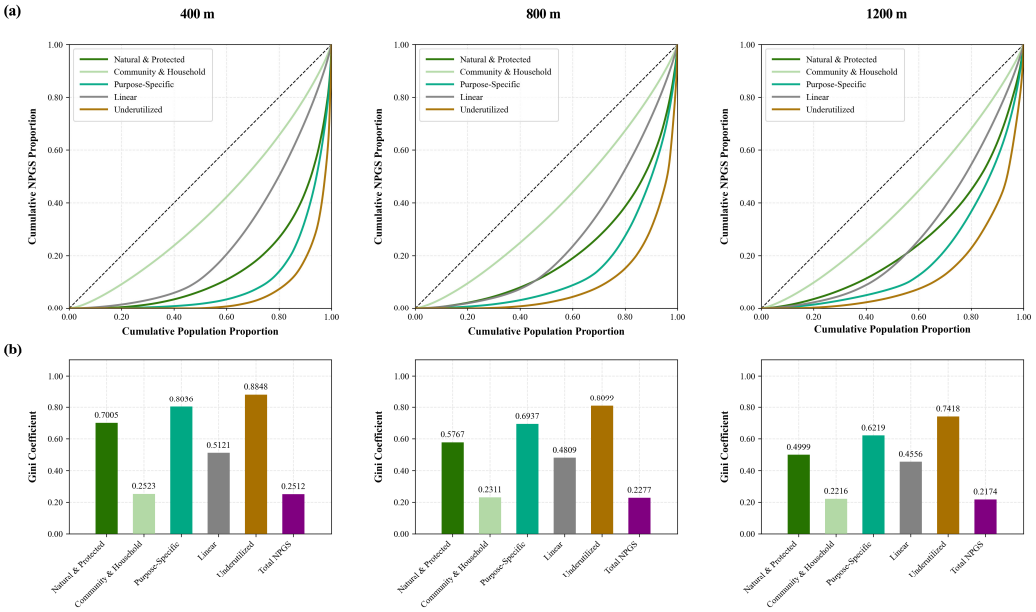


Figure 5. Lorenz curves (**a**) and Gini coefficients (**b**) for accessibility of NPGS categories at different buffer distances. **Note**: Lorenz curves depict the per capita accessibility distribution of five NPGS categories for clarity, while the overall inequality of total NPGS is represented only by its Gini coefficient.

3.3.2. The Global and Local Level Spatial Patterns of the Five NPGS Types

Global Moran's I analysis demonstrates significant spatial clustering across all NPGS categories in Inner London, with statistically robust Z-scores (41.8168–66.3709) and p-values < 0.001 (Figure 6). Moran's I values range from 0.5683 to 0.9162, confirming strong positive spatial autocorrelation.

The Linear consistently exhibit the highest spatial clustering intensity, achieving maximum Moran's I of 0.9162 at 1200 m. Natural and Protected show the weakest clustering at 400 m (Moran's I = 0.5683) but display progressive strengthening to 0.8384 at 1200 m. Community and Household and total NPGS categories maintain moderate clustering levels, with indices ranging from 0.7786 to 0.8183 across buffer distances.

Purpose-Specific exhibit the most pronounced sensitivity to buffer distance expansion, with Moran's I increasing by 36% from 400 m (0.6505) to 1200 m (0.8854). Underutilized follow a similar trend, rising from 0.6546 at 400 m to 0.8265 at 1200 m. All categories show intensified spatial clustering as buffer distances extend, with the strongest clustering observed at 1200 m.

Local Moran's I analysis further reveals spatial clustering patterns (Figure 7). The spatial autocorrelation intensity generally strengthens with increasing buffer distances, a trend most pronounced in Underutilized. For total NPGS accessibility, high–high clusters predominantly concentrate in southeastern boroughs (Lambeth, Southwark, and Lewisham) and northwestern boroughs (Haringey, Camden, and Islington), while low–low clusters dominate central Thames-north boroughs including Westminster, City of London, and Tower Hamlets, surrounded by high–low spatial outliers.

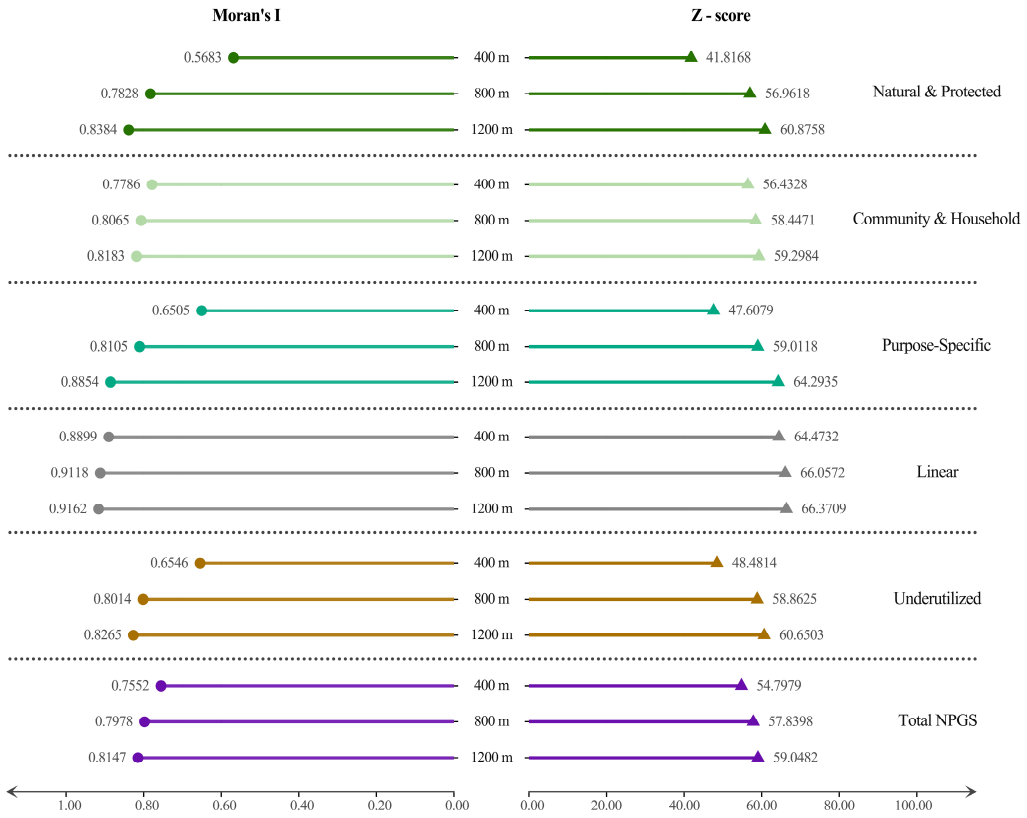


Figure 6. Global Moran's I and Z-score analysis of five NPGS categories.

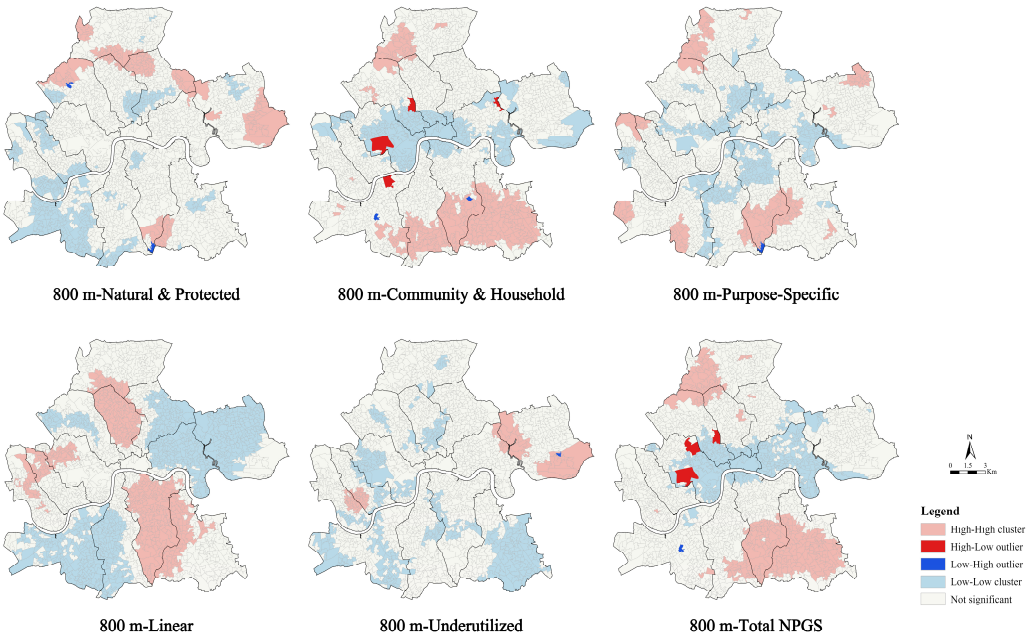


Figure 7. Local Moran's I analysis (800 m) of five NPGS categories and the total NPGS, showing the spatial distribution of cold and hot spots in Inner London. **Note**: Only the 800 m buffer distance is shown in the main text for visual clarity. Detailed results for 400 m and 1200 m buffer distances are provided in the Supplementary Materials (Figures S1–S6).

Natural and Protected exhibit high–high accessibility clusters in the northern borough of Camden and the eastern borough of Newham, in contrast to low–low clusters observed in the southwestern boroughs of Wandsworth and Hammersmith and Fulham. Community and Household mirror the total NPGS distribution pattern, with southeast-

ern/northwestern high–high clusters and central low–low clusters accompanied by peripheral high–low outliers. Purpose-Specific demonstrate distance-sensitive clustering dynamics, transitioning from central high–high clusters to peripheral low–low clusters as buffer distances increase. Linear show concentrated high–high accessibility in the southeastern borough of Southwark and Lewisham, as well as the northwestern borough of Islington. In contrast, low–low clusters are predominantly located in the northeastern boroughs of Tower Hamlets and Newham, and the southwestern borough of Wandsworth. Underutilized initially display limited clustering at 400 m buffers (isolated high–high cluster in Newham), but develop dispersed low–low clusters in Westminster, Wandsworth, and Lewisham as distances increase to 1200 m.

4. Discussion

4.1. Recap of the Main Findings

Our study establishes a typological analytical framework for NPGSs and applies it to Inner London to define and map five distinct typologies. These NPGSs collectively complement parks in forming a more comprehensive urban green infrastructure. Building on this framework, we quantify the accessibility and spatial equity of NPGSs, thereby deepening the understanding of how different forms of non-park greenery contribute to spatial justice within dense urban environments.

While previous research has documented spatial inequities in park provision across London, expanding large-scale parks remains constrained by policy limitations and land costs [90]. In this context, NPGSs demonstrate significant potential due to their dispersed distribution, flexible boundaries, and multi-functional roles in production, ecological protection, infrastructure integration, and habitat restoration [18]. Notably, these spaces play vital roles in microclimate regulation and ecological corridor connectivity [25,27]. Despite their advantages, NPGS management involves diverse stakeholders, with certain sites restricted to specific user groups, thereby limiting universal accessibility [33]. However, NPGSs in Inner London exhibit more equitable spatial distribution and greater proximity to residents compared to parks, which enhances equitable access to their ecosystem services. This inherent advantage underscores the necessity of better integrating these spaces into urban green infrastructure, as they are often overlooked or insufficiently addressed in formal planning and management frameworks.

Accessibility serves as a key index for evaluating green space equity, as walking distance directly reflects spatial proximity, which in turn influences residents' potential exposure to and benefits from nearby NPGSs [17,62]. The fragmented distribution and constrained service radii of NPGSs justify prioritizing pedestrian accessibility as a critical evaluation metric. This study identifies persistent spatial disparities in NPGS accessibility within walking distances across Inner London, though these inequities progressively diminish as walking distance thresholds increase. These findings align with the UK Government's Nature Recovery Plan, which mandates equitable 15 min walking access to green–blue infrastructure for all urban residents [91]. Integrating NPGS into urban greening strategies demonstrates the potential to address deficiencies in park provision, offering practical pathways to achieve inclusive access to nature.

4.2. The Role of the NPGS in the Green Infrastructure System

Our analysis reveals that Community and Household exhibit the highest accessibility and spatial equity among the five NPGS types in Inner London. These spaces are the most widely distributed and proximate to residential areas, reflecting their inherent integration with urban housing systems [32]. This finding affirms established evidence of human preference for proximate greenery in residential environments [43]. The existing literature

further confirms that Community and Household not only provide ecological benefits comparable to conventional green spaces but also serve as critical hubs for daily activities, social interactions, and neighborhood cohesion [28]. Spatial autocorrelation analysis reveals significant low–low clustering north of the River Thames, alongside the presence of high–low outliers. Land use patterns suggest two contributing factors: proximity to large-scale parks and historical urbanization characterized by high-density building and population, but limited residential land allocation. In contrast, Underutilized demonstrate the lowest accessibility and most severe inequality, with pervasive low–low clusters in central boroughs and high–high clusters confined to suburban areas. This spatial disparity suggests their exclusion from urban planning priorities, aligning with documented trends of marginalizing IGSs [55]. Strategic utilization of Underutilized can significantly enhance urban green coverage while avoiding land-acquisition costs [54].

These spatial disparities indicate broader structural differences among NPGS types, which can largely be attributed to planning policies, land-ownership patterns, and socioeconomic context. Community and Household are typically located on residential or privately managed land, ensuring stable maintenance and accessibility [32,43]. In contrast, Underutilized are often constrained by fragmented ownership and complex planning regulations, which hinder their redevelopment into functional green areas, though they retain substantial potential for ecological restoration and community renewal [53–55]. Natural and Protected and Purpose-Specific are mainly distributed along the periphery of Inner London, where planning and conservation regulations restrict redevelopment and limit public access despite their high ecological value [31,45]. Meanwhile, Linear play a crucial role in maintaining ecological connectivity [34], though their uneven distribution across boroughs contributes to accessibility disparities. Similar mechanisms have been observed in other cities such as Chicago and Barcelona, where institutional ownership and planning frameworks strongly shape NPGS equity patterns [54,92]. These insights highlight the importance of considering governance and socioeconomic structures when addressing NPGS equity and integrating diverse green spaces into future planning frameworks [18].

Current policies focus predominantly on parks, overlooking the complementary ecological, climatic, and social contributions of NPGSs, which exhibit great functional diversity and are managed by multiple agencies [36,93]. Integrating NPGSs into statutory planning optimizes the urban green network, enhances access equity, and strengthens the overall resilience of green infrastructure. Improving UGS equity through NPGSs directly contributes to the achievement of the SDGs, specifically Goal 11 on sustainable cities and communities [65]. The attainment of these goals relies on the ecological and social functions of NPGSs and their integration within broader green infrastructure systems. In high-density urban environments, NPGSs serve as a cost-effective lever for meeting interconnected sustainability targets and promoting environmental justice.

4.3. The Provision of NPGSs and Their Implications

Our analysis identifies a significant core–periphery differentiation in NPGS distribution across Inner London. Central boroughs north of the River Thames demonstrate the most severe NPGS supply–demand mismatch [90]. In contrast, peripheral boroughs enhance local well-being through abundant community gardens and private green infrastructures. Central populations primarily depend on fragmented street tree corridors and spatially constrained functional green spaces, worsening limited adaptive capacity against heat stress and air pollution while perpetuating health disparities [61]. These patterns necessitate context-specific management strategies aligned with local resource availability.

However, spatial proximity alone does not guarantee residents' access to the benefits of NPGSs [17]. Actual use depends on quality factors, including maintenance standards,

visual appeal, and biodiversity [88,89]. It also relies on a sense of safety and social inclusion. When green spaces are considered welcoming and secure, they are more likely to be used regularly [94,95]. Conversely, poorly maintained or socially unsafe spaces often remain underused, even if they are within walking distance [7,8]. For example, in Westminster, although street trees increase shade coverage, narrow pavements and traffic noise can limit their restorative function. In contrast, multi-functional green hubs in Newham improve perceived accessibility through participatory governance. Planners should integrate accessibility and quality assessments while incorporating participatory mapping and perception surveys to effectively capture residents' sense of safety and belonging [96–98].

A broader environmental justice framework requires going beyond distributive equity to also address procedural and outcome equity [92,99]. Distributive equity refers to the fair spatial allocation of green resources [100]. Procedural equity ensures that all social groups have a voice in green space design and management [101]. Outcome equity evaluates whether improvements lead to measurable health and social benefits for marginalized populations [102]. Consistent with Schlosberg's tripartite model, NPGS planning should incorporate both procedural and outcome dimensions [103]. For instance, off-peak garden sharing may reduce spatial inequalities, but without secure legal access, it can unintentionally exclude renters. Future frameworks require integration of geospatial data with perceptual indicators to comprehensively identify and resolve justice gaps.

Our study highlights the value of recognizing NPGSs as a separate planning category. Although traditional UGS planning has often emphasized large parks, recent studies have increasingly recognized the value of dispersed, small-scale green spaces, such as roadside vegetation, vacant green lots, and informal community greens [52,63,93]. NPGSs are not just supplementary spaces but form an integral layer of urban green infrastructure that improves accessibility [30,62]. In dense or underserved areas, they can be transformed into micro-parks, community gardens, or green corridors to build urban resilience and advance spatial equity [42,55]. By identifying and categorizing NPGSs, our framework offers a transferable method for cities where adding large parks is no longer feasible. The approach is relevant to cities like New York, Tokyo, and Paris, where land availability is limited but fragmented green assets exist. Adaptive reuse of NPGSs through temporary or modular greening offers an incremental pathway for implementation without major land-acquisition costs [54,57]. The framework is also applicable to rapidly urbanizing Chinese cities such as Xi'an, Shenyang, and Harbin, which face comparable challenges of spatial inequality and compact urban form. Planning for usability—not just availability—is key. Prioritizing how people actually access and engage with NPGSs can support more equitable green space distribution and contribute directly to environmental justice goals [102].

4.4. Limitations and Future Study

This study has several limitations that warrant consideration. First, the accuracy of linear green features, such as street tree corridors, may be affected by incomplete or outdated point data due to dataset limitations. The remote sensing platforms currently in use may also lack the spatial or spectral resolution required to capture fine-scale or vertically structured NPGS types [66], such as green roofs or facade vegetation. Future research should incorporate advanced technologies, including LiDAR and hyperspectral imaging, to improve the detection and quantification of vertical and microscale green infrastructure [104,105]. Second, the evaluation framework focuses primarily on spatial accessibility and does not reflect the esthetic quality or experiential value of NPGSs. This may lead to an overestimation of their functional relevance in practice. A more comprehensive understanding could be achieved by integrating user perception surveys, observational fieldwork, and behavioral data to assess how residents interact with different types of NPGS and what

attributes drive their use [62]. Third, although spatial inequalities in NPGS provision are evident, the socioeconomic mechanisms underlying these patterns remain underexplored. In cities like London, where factors such as ethnicity, income, and education intersect in complex ways, their influence on NPGS equity is not fully understood. Investigating these drivers through spatially explicit models—such as geographically weighted regression combined with machine learning—could reveal context-specific relationships between NPGS access and social disadvantages [106,107]. These approaches would strengthen the evidence base for more equitable and adaptive UGS planning by aligning technical evaluations with social realities and community needs.

5. Conclusions

This study takes Inner London as a case study to analyze NPGSs from the perspectives of classification, accessibility, and spatial equity. First, this study defines NPGSs using multiple open access datasets and classifies them into five categories: Natural and Protected, Community and Household, Purpose-Specific, Linear, and Underutilized. The results reveal a spatially uneven distribution of NPGSs in Inner London, with a clear core–periphery differentiation, where central boroughs experience significant shortages. Second, this study evaluates NPGS accessibility using a multi-ring buffer based on walking distance. It further assesses equity through Lorenz curves and Gini coefficients, and identifies spatial clustering patterns using spatial autocorrelation. The analysis highlights significant spatial and typological disparities: Community and Household tend to be more equitably distributed, whereas Underutilized demonstrate marked inequity. The spatial patterns of hot spots and cold spots underscore localized inequalities in NPGS accessibility across boroughs. Third, this study proposes that underutilized NPGSs, especially those located in central boroughs, could be strategically repurposed into micro-parks, community gardens, or linear green corridors, offering low-cost opportunities to reduce accessibility disparities. Integrating these interventions into existing planning frameworks would directly support SDG 11, which emphasizes universal access to safe, inclusive, and accessible green and public spaces. In conclusion, the analytical framework provides a transferable approach for optimizing NPGS equity in other high-density cities where large-scale park expansion is limited, offering planners practical guidance for developing greener, fairer, and more resilient urban environments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17209284/s1, Figure S1. Local Moran's I analysis of Natural & Protected NPGS at different buffer distances (400 m, 800 m, and 1200 m); Figure S2. Local Moran's I analysis of Community & Household NPGS at different buffer distances (400 m, 800 m, and 1200 m); Figure S3. Local Moran's I analysis of Purpose-Specific NPGS at different buffer distances (400 m, 800 m, and 1200 m); Figure S4. Local Moran's I analysis of Linear NPGS at different buffer distances (400 m, 800 m, and 1200 m); Figure S5. Local Moran's I analysis of Underutilized NPGS at different buffer distances (400 m, 800 m, and 1200 m); Figure S6 Local Moran's I analysis of Total NPGS at different buffer distances (400 m, 800 m, and 1200 m).

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