Article

Assessment of Urban Green Space Equity in Beijing's Central Urban Villages: A Remote Sensing Perspective on Environmental Justice

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Abstract: Urban Green space (GS) equity is crucial to achieving environmental justice. From the environmental justice perspective, this study focuses on the equity of GS in residential areas of urban disadvantaged groups, quantitatively assessing and comparing the fairness of GS usage between Urban Villages (UVs) and formal Residential Quarters (RQs). Using data on green space area, NDVI, and FVC, this study analyzes GS conditions across different buffer distances within the central urban area of Beijing. Statistical methods, including the Theil index, were employed to evaluate the equity of per capita green space, vegetation coverage, and vegetation conditions. Our findings reveal distinct spatial distribution patterns of internal and external GS characteristics between UVs and RQs. Additionally, while the internal GS equity in UVs is generally lower than in RQs, FVC equity demonstrates an opposite trend. Finally, intra-group inequity in both UVs and RQs is the dominant factor contributing to overall GS disparities in residential areas. This study establishes a comprehensive evaluation framework for analyzing GS avail- ability, NDVI, and FVC equity in two types of residential communities. It provides a valuable reference for subsequent GS equity assessments and offers actionable recommendations for policymakers to prioritize improving GS equity in certain residential areas. By addressing gaps in environmental justice theory regarding urban GS, this study proposes a pragmatic and effective approach to enhancing GS equity in large, rapidly developing cities.

Keywords: Inequity, Urban geography, Disadvantaged groups, Environmental justice, Urban Village

1. Introduction

Urban green spaces (UGS) are widely acknowledged as essential contributors to the social, ecological, and economic well-being of urban environments. Their role in enhancing quality of life, supporting biodiversity, and fostering sustainable development underscores their significance in contemporary city planning and management.They serve as essential contact points between people and nature (Venter et al., 2020), offering opportunities for physical activity (BedimoRung et al., 2005), which contributes to mental and physical well-being (Grilli et al., 2020; Hartig et al., 1996; Mitchell, 2013; Astell-Burt et al., 2013). In addition, green spaces foster community cohesion (Basu et al., 2020; Francis et al., 2012) and social growth, making them a critical resource for human well-being (Larson et al., 2016; Flocks et al., 2011). Ecologically, UGS improves wildlife habitats (Garizabal-Carmona and Javier Mancera-Rodriguez, 2021), and provides ecosystem services (Song et al., 2020) such as air quality improvement (Gallo et al., 2017), temperature regulation (Skoulika et al., 2014; Norton et al., 2015), water flooding management (Kazmierczak and Cavan, 2011), carbon sequestration (Speak et al., 2015), and biodiversity enhancement (Munoz-Pacheco and Villasenor, 2022). These contributions significantly improve urban sustainability (Jennings et al., 2016; Chiesura, 2004) and resilience (Wolch et al., 2014). In addition, UGS provides economic value by increasing property values and attracting investment (Crompton, 2008; Harnik and Crompton, 2014).

Despite their benefits, numerous studies in recent years have revealed that inequitable access to green spaces adversely affects various socioeconomic (Pham et al., 2012), racial (Nesbitt et al., 2018), and age groups (Rigolon, 2017). For this reason Green space inequity can also be treated as an Environ- mental Justice (EJ) issue, that manifests itself in disparities in the quantity, quality, and safety of these spaces (Wolch et al., 2014). This inequality is apparent in countries of varying development levels, where wealthier neighborhoods often feature higher diversity, abundance, and vegetation coverage (Hope et al., 2003; Leong et al., 2018). Conversely, marginalized groups, including ethnic minorities, individuals of certain age groups, residents of specific urban spaces, and economically disadvantaged populations, generally face inferior green space characteristics (Macedo and Haddad, 2016; Rigolon, 2017; Tan and Samsudin, 2017; Nesbitt et al., 2019; Zhou and Kim, 2013). To address these disparities, the United Nations has incorporated a goal into its Sustainable Development Goals (Osborn et al., 2015), advocating for "universal access to safe, inclusive, and accessible green and public spaces, particularly for women, children, older persons, and persons with disabilities".

Environmental Justice is founded on the principle (Lopez, 2012) that everyone has the right to a healthy environment. Substantial progress has been made in green space equity research, primarily focusing on urban parks, green coverage, and vegetation conditions (Rigolon et al., 2018; Uribe and Villasen˜or, 2024; Zhang and Park, 2023; Williams et al., 2020; Kiani et al., 2023; Chuang et al., 2017; Guan et al., 2023). Studies examining population demographics, park quantity, and park quality consistently highlight the significant role of parks as a critical environmental justice issue, particularly for low-income populations. Disparities in access to green spaces disproportionately affect marginalized groups, including racial and ethnic minorities, youth, the elderly, and women—populations that often derive greater benefits from these resources due to their heightened need for recreational, health, and social amenities. (Macedo and Haddad, 2016; Rigolon, 2016; Tan and Samsudin, 2017; Rigolon, 2017; Chawla, 2015; Krenichyn, 2006). Research further shows that economically stable and affluent communities enjoy more consistent tree canopy coverage, whereas impoverished areas have fewer and less abundant street trees (Nesbitt et al., 2019; Pinault et al., 2021; Quinton et al., 2022). Economic factors also influence the equitable availability of vegetation (Hunter et al., 2019; Lin and Wang, 2021). However, these studies typically examine single aspects of green spaces, such as area or vegetation conditions, without comprehensively evaluating their combined impact on environmental justice.

This study addresses this gap by integrating three characteristics of green spaces—per capita green space area, NDVI (Normalized Difference Vegetation Index), and FVC (Fractional Vegetation Cover)—to quantify equity. Previous studies on green space equity primarily emphasized socioeconomically disadvantaged groups, such as low-income populations, minorities, and vulnerable age groups, including children, youth, women, and the elderly (Nesbitt et al., 2019; Rigolon and Flohr, 2014; Zhou and Kim, 2013; Roman et al., 2021; Locke et al., 2023; Pinault et al., 2021). However, there has been limited research on green space equity in specific urban spaces, such as peri-urban areas and low-income communities (Xu et al., 2024). To bridge this gap, our study focuses on urban villages, a type of marginalized urban space. Unlike prior studies examining green space availability, this research adopts a holistic approach by incorporating vegetation quality and coverage. Green space accessibility is typically assessed through proximity to amenities, reflecting notions of availability, acceptability, affordability, sufficiency, and awareness. Equity assessments, which are intrinsically linked to enviromental justice (EJ), can advance through three dimensions: distributive justice, procedural justice, and interactional justice (Low and Boettcher, 2020;

Kabisch and Haase, 2014; Nesbitt et al., 2018). Distributive justice, the focus of this study, concerns the geographic distribution of resources and bur- dens. It is closely associated with proximity, availability, affordability, and adequacy of green space. Some studies have also explored social equity concerning changes in green spaces (Roman et al., 2021). For example, research based on 2001 and 2011 census data and NDVI in the United States revealed that neighborhoods with higher proportions of racial ethnic minorities and lower proportions of white residents experienced lower levels of greenness in 2001 and greater declines in greenness between 2001 and 2011(Casey et al., 2017). By supplementing NDVI and FVC data, this study employs remote sensing methods to comprehensively quantify green space characteristics and assess their equity.

The primary objective of this study is to quantitatively evaluate the equity in green space between urban villages and residential neighborhoods, highlighting issues of distributional justice within urban spaces occupied by disadvantaged groups. By establishing a novel evaluation framework grounded in remote sensing data, Gini coefficients, and Theil indices, this research analyzes green space equity from the perspectives of area, vegetation quality, and coverage. The findings not only address gaps in the environmental justice literature but also contribute to the development of a remote sensing-based framework for the evaluation of urban green space equity. Furthermore, the results provide actionable insights for optimizing resource allocation in urban planning, supporting the advancement of urban environmental justice.

2. Materials and Methods

2.1. Subsection

This study acknowledges certain limitations in the existing research, such as time- and cost-intensive data collection methods, lack of timeliness, and a narrow scope of evaluation metrics. To address these challenges, we propose a comprehensive research framework leveraging multiple critical data sources to advance the analysis of equity in urban green space distribution.

The research framework consists of three main components. Green Space Data Extraction

Using Landsat remote sensing data, urban green space information was extracted through ENVI processing. The results are presented in Figure 1A in Section 2.2. Additionally, urban land use classification data was utilized to extract information on residential communities and urban villages, including their area and geographic locations, as shown in Figure 1 of Section 2.2. Population estimates for residential communities were derived using data on building area, geographic location, building height, and the average residential floor area per capita in Beijing.

Comprehensive Evaluation Metrics

To enable a more robust evaluation of green space equity, Normalized Difference Vegetation Index (NDVI) and Fractional Vegetation Cover (FVC) metrics were derived through analysis conducted in ENVI.

Equity Assessment

Equity in access to green space was evaluated using Theil and Gini indices. These indices were utilized to assess the spatial distribution of per capita green space area, NDVI, and FVC across multiple buffer zones of varying scales. The methods for calculating equity metrics are detailed in Section 2.3.3, and the results are discussed in Section 3.3.

2.2. Study Area and Data Sources

As of 2021, Beijing's core urban area encompasses approximately 47,385.56 hectares of green space and houses 1.815 million residents (Dong et al., 2022). This area serves as the capital's core and is one of China's most densely populated regions. Additionally, Beijing faces significant challenges related to urban villages (UVs) (Zheng et al., 2009), and its central urban scale offers valuable references for other cities. Consequently, the central urban area of Beijing was selected as the study region, encompassing seven administrative districts: Dongcheng, Xicheng, Chaoyang, Haidian, Fengtai, and Shijingshan. The total area spans approximately 1,378 square kilometers (Dong et al., 2022) (Fig. 1). Within this region, we included 166 urban villages and 3,347 residential quarters (RQs), both of which are the fundamental research units of this study.

Three data sources were utilized in this research. The first dataset includes 2021 architectural data for UVs and RQs, encompassing building area, geographic location, and the number of floors. The dataset, acquired from the Resource and Environmental Science Data Platform (https://www.gscloud.cn/), was employed to estimate population distribution within each residential unit by integrating the total building area with Beijing's per capita housing area (Fig. 1).

The second dataset consists of 2021 remote sensing imagery for Beijing, utilized to calculate and extract green space (GS), Normalized Difference Vegetation Index (NDVI), and Fractional Vegetation Cover (FVC). Sourced from the Geospatial Data Cloud (https://www.gscloud.cn/), the dataset offers surface temperature data at a 30-meter spatial resolution. Images with minimal cloud cover and land interference were selected and pre-processed through radiometric calibration and the MODTRAN atmospheric correction model to reduce the influence of clouds, atmospheric scattering, and aerosols. To address edge effects, where GS outside the study area influences accessibility, the study included green spaces within a 2,000-meter buffer be-yond the urban boundary of the core (Fig. 1). The second dataset also includes 2021 land use classification data for Beijing, identifying UVs and RQs. While UVs offer affordable housing and typically have low-rise, high- density buildings, many unnamed UVs exist beyond those identified in official classifications. These were identified using satellite images from the 2021 Global Mapper (https://www.bluemarblegeo.com/global-mapper/), resulting in a comprehensive dataset of UVs in Beijing's core urban area (Fig.1).

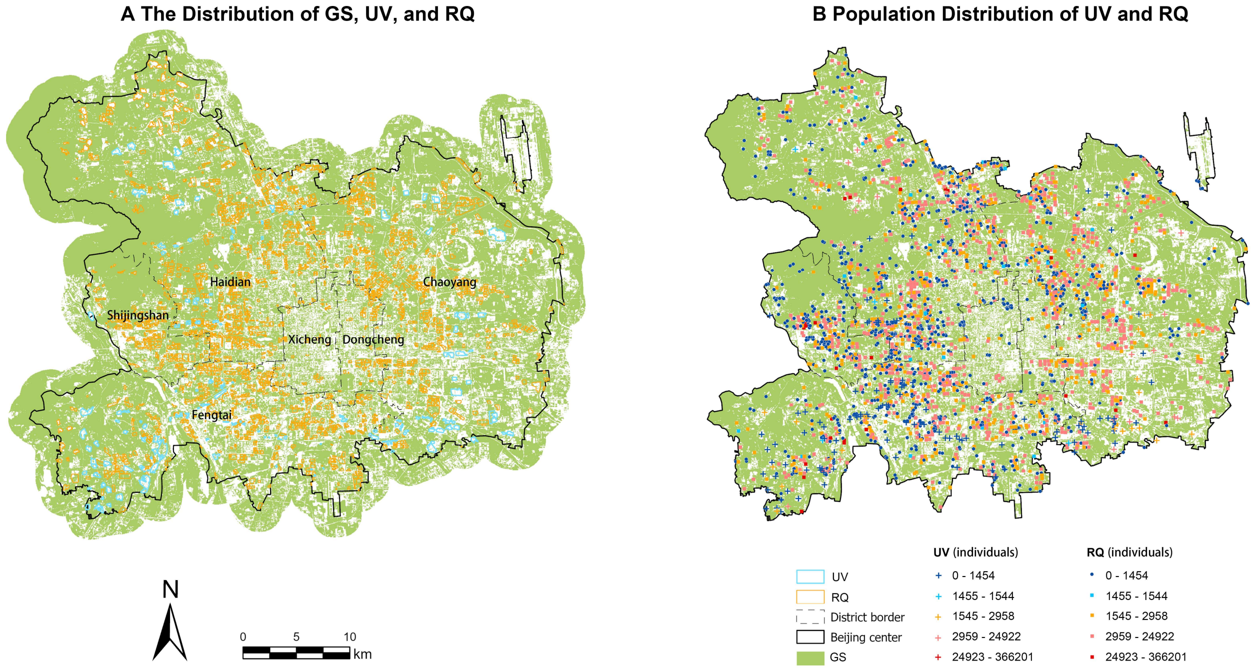

Figure 1: A) Spatial distribution of green spaces, urban villages, and residential quarters within Beijing's core urban area in 2021. B) Population distribution across urban villages and residential quarters.

2.3. Methods

2.3.1. Per Capita Green Space Calculation

Previous studies have shown that GS benefits human well-being more when it is closer to residential areas (Dony et al., 2015; Sharifi et al., 2021a).

Therefore, accessibility within multiple buffer zones was the primary evaluation criterion for GS availability, NDVI, and FVC. Following Browning and Lee's approach (Browning and Lee, 2017), the buffer radii were set at increments of 200 meters, ranging from 0 to 2,000 meters. A radius of 0 represents inner-GS (green spaces within residential areas). For each radius r, buffer zones were created around residential areas, and the green space area within each zone (Si) was calculated using overlay analysis. The per capita green space was then derived using Equation (Yang et al., 2020) (1):

$$S_r = \sum_{i=0}^{r} S_i, i = 0,200,\dots,r; r \leq 2000 \qquad (1)$$

2.3.2. NDVI and FVC Calculations

The Normalized Difference Vegetation Index (*NDVI*), calculated using satellite-derived infrared (*IR*) and near-infrared (*NIR*) spectral bands (Abdullah & Barua, 2022), is expressed in Equation (2). *NDVI* quantifies vegetation coverage on a scale from -1 to 1, where higher values correspond to denser vegetation. (Zhang et al., 2023).

$$NDVI = \frac{NIR - IR}{NIR + IR} \qquad (2)$$

Where NIR represents near-infrared reflectance, and IR represents infrared reflectance. Fractional Vegetation Cover (*FVC*) measures the proportion of vegetation's vertical projection relative to the total study area, providing insights into vegetation distribution. It is derived from NDVI values corresponding to areas with complete vegetation cover ($NDVI_{veg}$) and bare soil ($NDVI_{soil}$). as shown in Equation (Zhang et al., 2023) (3).

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}} \quad (3)$$

$NDVI_{soil}$ and $NDVI_{veg}$ correspond to the 5th and 95th percentile values of *NDV*I within the study area, respectively. For this study, *NDVI* and *FVC* data were calculated for each residential unit and its surrounding buffer zones to analyze and compare the equity of GS accessibility, *NDVI*, and *FVC* between UVs and RQs. The data were processed in ArcGIS.

2.3.3. Equity Evaluation

his study employs the Theil Index (Silver, 1967) to assess the equity of GS availability, NDVI, and FVC, and compares the results with the Gini coefficient (Xu, 2020) to ensure robustness. The Theil Index is particularly suitable for decomposing inequality into between-group and within-group components, offering a detailed evaluation of disparities between UVs and RQs. The Theil Index is calculated using Equation (4):

$$T(g,p)_r = \sum_{i=1}^{n} g_{i,r} \ln\left(\frac{g_{i,r}}{p_i}\right) \quad (4)$$

Here, n represents the total number of residential units, *g(i,r)* denotes the per capita green space (GS), NDVI, or FVC for residential unit i, and pi signifies the population proportion of unit ii. Higher values of the Theil Index reflect greater inequality in GS distribution across residential areas. The index can be further decomposed into within-group (*Tw*) and between-group (*Tb*) components. (Cowell, 1980; Silver, 1967) (Equation 5):

$$T(g,p)_r = T_w + T_b = \sum_{t=1}^{m} g_{t,r} T(g,p)_{t,r} + \sum_{t=1}^{m} g_{t,r} \ln\left(\frac{g_{t,r}}{p_t}\right) \quad (5)$$

Where *m* is the number of groups (UVs and RQs), and *gt,r*, *p*t, and *T (g, p) t,r* represent group-specific values. The Gini coefficient was also calculated for comparison, as shown in Equation (6):

$$Gini = 1 + \left(\frac{1}{l}\right) - \left(\frac{2}{\bar{G} \times l^2}\right) \sum_{i=1}^{l} [(l - i + 1) \times G_i] \quad (6)$$

Where *Gi* represents GS availability for residential unit *i*, and *G* is the mean GS availability. Finally, to investigate disparities between UVs and RQs, the ratio of GS availability, NDVI, and FVC was calculated using Equation (7):

$$R = \frac{G_{RQ}}{G_{UV}} \quad (7)$$

Here, R represents the ratio of green space (GS) availability, NDVI, or FVC between residential quarters (RQs) and urban villages (UVs), with G_{RQ} and G_{UV} denoting the respective values for RQs and UVs. An $R>1$ indicates that RQs have greater access to GS benefits compared to UVs, while $R<1$ suggests the opposite.

3. Results

3.1. Spatial Distribution Differences in Green Space Characteristics Between UV and RQ

The spatial distribution of residential quarters (RQs) and urban villages (UVs) is illustrated in Figure 2. RQs are primarily clustered within Beijing's central urban core, while UVs are predominantly located in peripheral and surrounding regions. with higher green space (GS) density within the urban core. In 2021, the total GS area in Beijing's urban core was approximately 47,058.79 hectares, accounting for 34.15% of its total territory. Notably, the GS concentration was higher on the periphery of the urban core compared to other surveyed regions (Fig. 1). The per capita inner-GS of RQ was generally lower in the southwestern and central regions but relatively higher elsewhere, particularly in the northern areas. In contrast, the per capita inner green space (GS) of urban villages (UVs) was significantly higher in the southwestern region relative to other areas (Fig. 2).

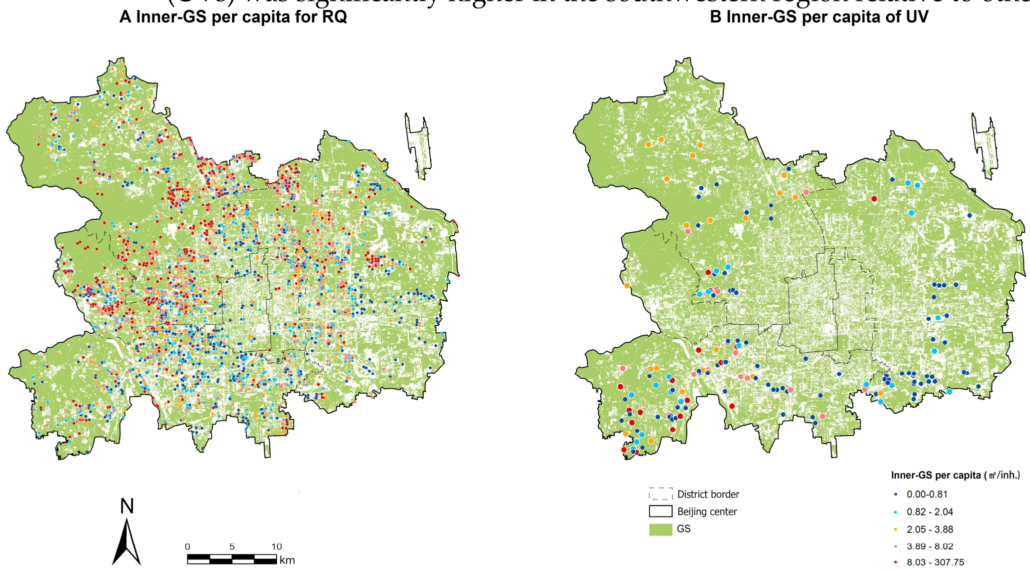

Figure 2: Spatial distribution patterns of per capita inner green space (GS) for residential quarters (RQs) (A) and urban villages (UVs) (B).

The spatial distribution of urban villages (UVs) and residential quarters (RQs) in relation to NDVI levels is illustrated in Figure 3. The NDVI for RQ is relatively higher in the northwestern region and lower elsewhere, particularly in the southwest. Compared to per capita green space, the southeastern region shows an improvement in NDVI levels, This indicates that, although the per capita green space (GS) for residential quarters (RQs) in this area is limited, the vegetation quality remains comparatively higher. For UV, the NDVI levels are consistently low, suggesting that even where green spaces are relatively abundant, such as in the southwestern region, the vegetation quality remains poor.

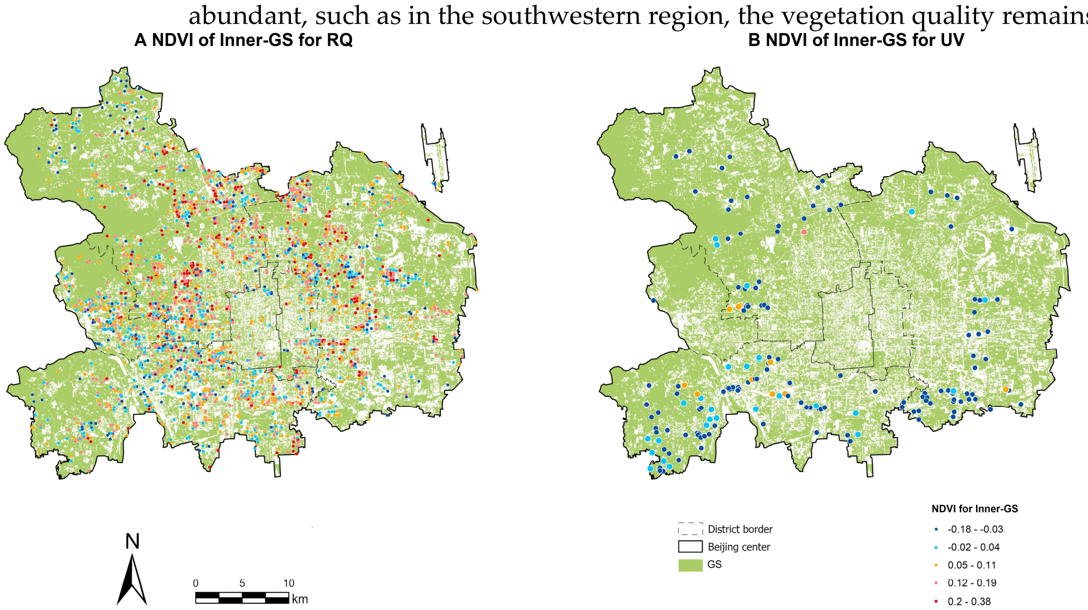

Figure 3: Spatial distribution patterns of NDVI for inner green space (GS) in residential quarters (RQs) (A) and urban villages (UVs) (B).

Similarly, Figure 4 illustrates the spatial distribution of Fractional Vegetation Cover (FVC) for urban villages (UVs) and residential quarters (RQs). The FVC distribution mirrors the patterns observed for NDVI, with minor differences in a few neighborhoods. This suggests that FVC and NDVI exhibit similar spatial trends.

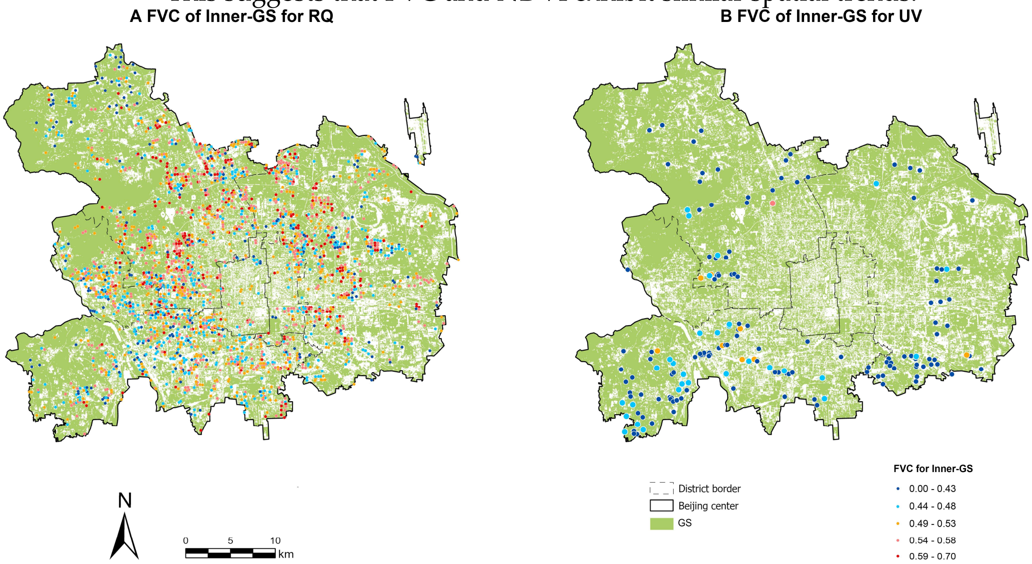

Figure 4: Spatial distribution of Fractional Vegetation Cover (FVC) within inner green space (GS) for residential quarters (RQs) (A) and urban villages (UVs) (B).

The spatial distribution characteristics of per capita inner green space (GS), NDVI, and Fractional Vegetation Cover (FVC) are integrated for urban villages (UVs) and residential quarters (RQs). it is evident that NDVI and FVC show consistent trends. However, areas with higher per capita GS may not always correspond to better vegetation quality or coverage. In Beijing's urban core, UV areas are characterized by low vegetation quality and coverage, while some UV neighborhoods in the southwestern region have relatively higher per capita GS. For RQ, the northern region consistently exhibits higher per capita GS, vegetation quality, and coverage, while the southwestern region shows lower values. Interestingly, the southeastern region displays low per capita GS but higher vegetation quality and coverage.

Figure 5 illustrates the spatial distribution patterns of external green space (GS) for urban villages (UVs) and residential quarters (RQs) across distances ranging from 500 to 2000 meters. Compared to internal GS, UV in the southwestern and northwestern regions exhibits significantly higher per capita GS than other areas, while RQ demonstrates higher values in the northern regions and lower values in the south. This pattern becomes increasingly pronounced with greater distances (Fig. 5).

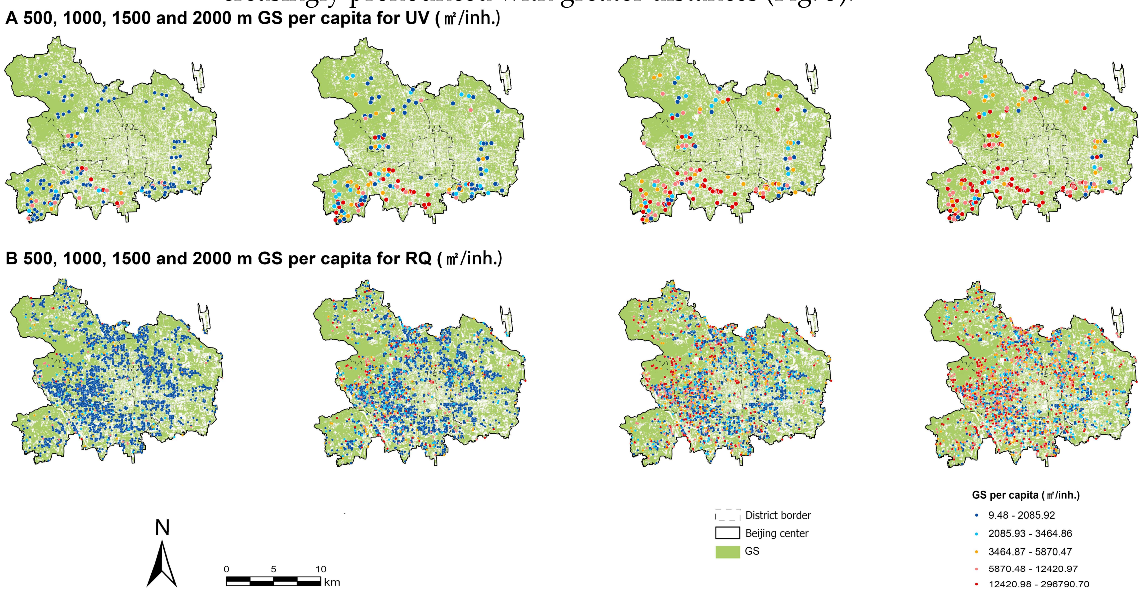

Figure 5: Spatial characteristics of per capita green space (GS) availability for urban villages (UVs) (A) and residential quarters (RQs) (B) at varying accessible distances.

The spatial distribution of external NDVI for UV and RQ is shown in Figure 6. For UV, NDVI levels increase significantly compared to internal GS, with particularly high levels in the southwestern region. This trend becomes more evident with increasing distance. In contrast, RQ displays overall lower NDVI levels. While the western regions show higher NDVI than the eastern regions, this pattern is less pronounced than in UV's external NDVI or RQ's internal NDVI.

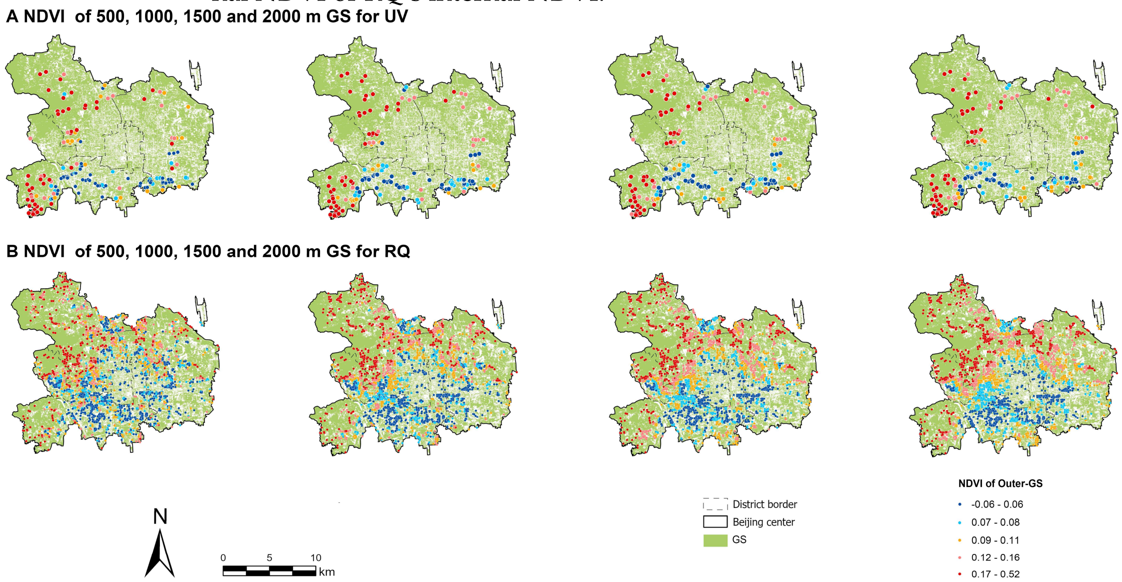

Figure 6: Spatial characteristics of NDVI for green space (GS) availability in urban villages (UVs) (A) and residential quarters (RQs) (B) across varying accessible distances.

Similarly, Figure 7 shows the external FVC distribution. The spatial characteristics patterns of FVC for UV and RQ align with those of NDVI, with consistent trends across all distances.

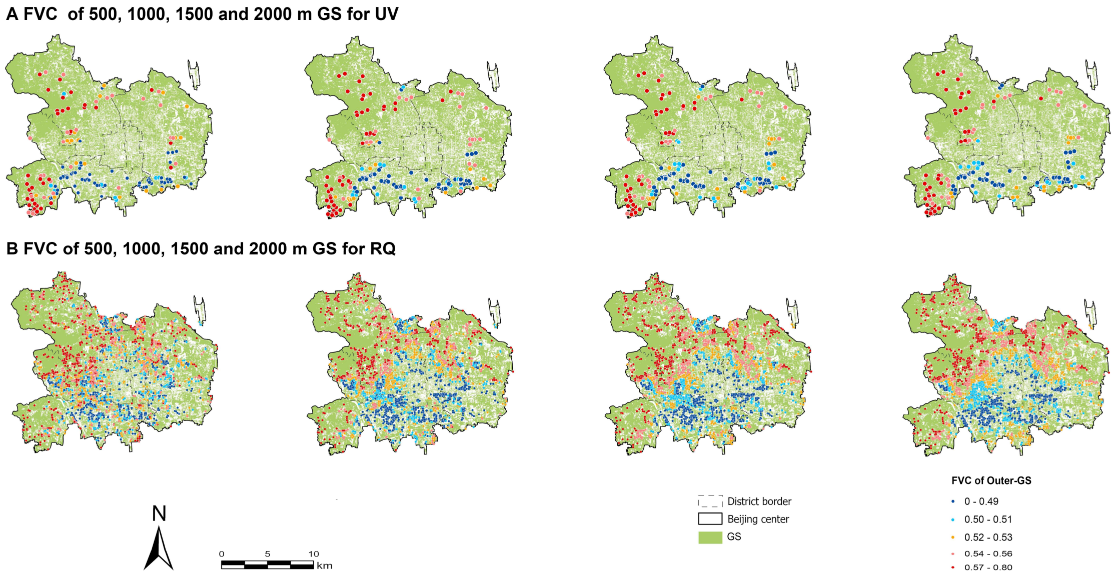

Figure 7: Spatial characteristics of Fractional Vegetation Cover (FVC) for green space (GS) availability in urban villages (UVs) (A) and residential quarters (RQs) (B) at varying accessible distances.

In summary, external green space patterns for UV and RQ reveal that FVC and per capita GS exhibit similar trends, while NDVI shows distinct differences. UV's external GS performs better in the southwestern and north- western regions across all three characteristics, whereas the southeastern region consistently underperforms. For vegetation quality, areas other than UV's external GS in the southwestern region require improvement. Comparing internal and external green spaces, UV areas show poor internal vegetation quality but relatively better external GS in the southwestern and northwestern regions. For RQ, both internal and external GS exhibit higher levels in the northern areas, while external vegetation quality requires further enhancement.

3.2. Inequalities in Inner-GS between UV and RQ

The mean per capita inner green space (GS) for urban villages (UVs) and residential quarters (RQs) was calculated as 2.89 m^2/inh and 4.98 m^2/inh, respectively (Fig. 8). After confirming data normality and homogeneity of variance, the Mann-Whitney U test was employed to evaluate differences in per capita inner-GS between the two regions. The results indicated a statistically significant disparity, with RQs demonstrating substantially higher per capita inner-GS compared to UVs. Similarly, the mean NDVI values were -0.0537 for UV and 0.0827 for RQ, again showing a significant difference favoring RQ (Fig. 8). Furthermore, the mean FVC values for UV and RQ were 0.4175 and 0.5075, respectively (Fig. 8). These results consistently showed significant differences, with RQ exhibiting significantly higher inner-FVC compared to UV. Among the three green space indicators, disparities in NDVI and FVC were more pronounced across all scenarios, with residential quarters (RQs) consistently outperforming in per capita green space (GS) availability.

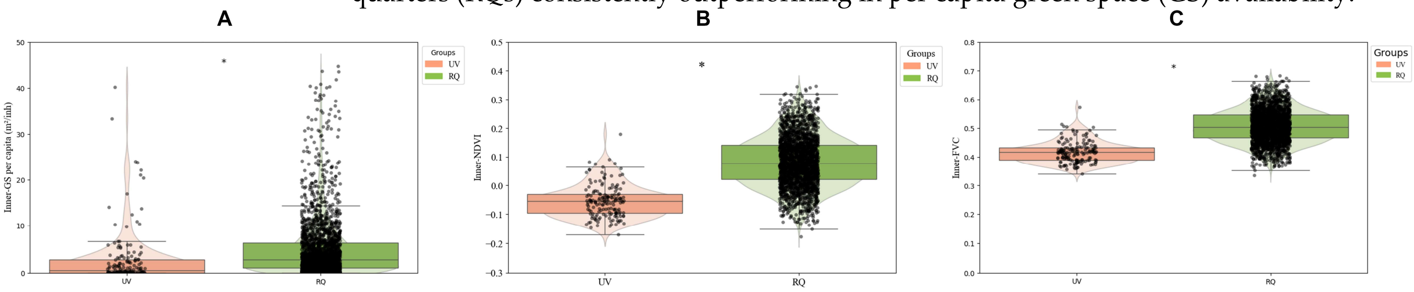

Figure 8: Average values of per capita inner green space (GS) (A), NDVI (B), and FVC (C) for urban villages (UVs) and residential quarters (RQs) are presented. An asterisk above the boxes indicates statistically significant differences between UVs and RQs at the $p < 0.05$ level, as determined by the Mann-Whitney U test.

This study utilized the Theil index and its decomposition to assess disparities in the distribution of inner green spaces (GS), normalized difference vegetation index (NDVI), and fractional vegetation cover (FVC). To ensure the robustness of the equity assessment, the findings were cross-validated against Gini coefficients.

The assessment of inner green space (GS) equity yielded a total Theil index of 0.8936 across all residential areas, with the within-group component contributing 0.8933 and the between-group component accounting for a mere 0.0003 (Fig. 9). These findings highlight substantial disparities in GS distribution between urban villages (UV) and residential quarters (RQ). Strikingly, within-group inequalities accounted for the entirety of the total inequity (100%), underscoring their pivotal role as the primary driver of unequal GS availability in central Beijing.

The equity assessment of the normalized difference vegetation index (NDVI) revealed a total Theil index of 0.225 across all residential areas, with within-group disparities contributing 0.222 and between-group differences accounting for only 0.003. (Fig. 9). The within-group index accounted for 99.07% of the total, indicating that intra-group disparities were the main driver of inequities in NDVI, contrasting significantly with the inequities in GS availability.

Regarding FVC equity, the total Theil index was 0.007, with a within- group Theil index of 0.006 and a between-group Theil index of 0.001 (Fig. 9). The within-group component contributed 86.08% of the total, suggesting that intra-group disparities were the dominant factor. However, the proportion of between-group inequities was higher for FVC compared to GS availability and NDVI, reflecting a more notable contribution of inter-group differences to FVC disparities.

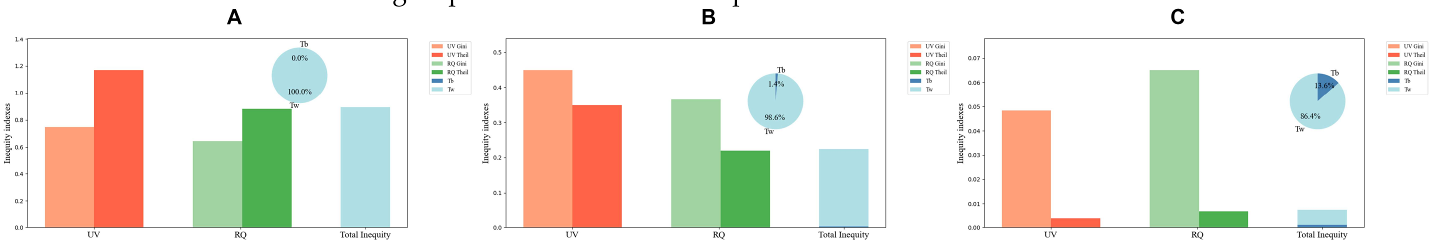

Figure 9: Inequity in inner-GS availability (A), NDVI (B), and FVC (C) for UV and RQ, along with the decomposition of total inequities.

In summary, per capita GS and NDVI exhibited greater inequities within UV compared to RQ, whereas FVC showed the opposite trend. A comparison using the Gini index confirmed that the results aligned with the Theil index, showing larger disparities in per capita GS and NDVI for UV and RQ, while FVC exhibited smaller differences.

3.3. Variations in Green Space Inequalities with Accessible Distance

The analysis of external green space (GS) availability in urban villages (UV) and residential quarters (RQ) revealed a more pronounced increase in per capita GS availability for UV as the accessible distance expanded (Fig. 10). At all distances, UV consistently exhibited greater per capita GS availability than RQ, with the disparity widening at larger distances. Likewise, mean normalized difference vegetation index (NDVI) values remained higher in UV than in RQ across all distances, as shown in Fig. 10, but the disparities were smaller compared to per capita GS and diminished with increasing distance. The analysis of FVC (Fig. 10) revealed trends similar to NDVI, with UV consistently outperforming RQ at all distances and disparities narrowing with greater accessible distances. Overall, UV exhibited superior external green space performance across all three indicators compared to RQ.

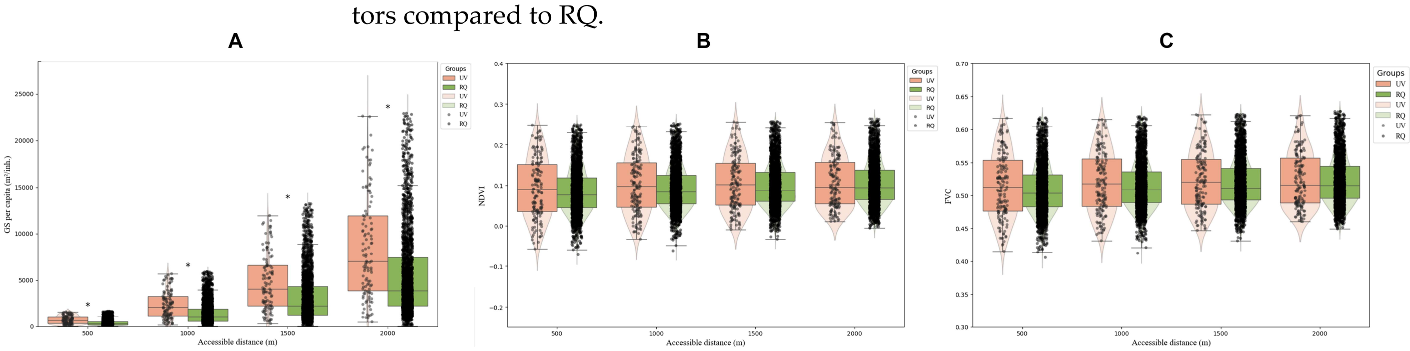

Figure 10: Mean per capita inner green space (GS) (A), normalized difference vegetation index (NDVI) (B), and fractional vegetation cover (FVC) (C) for urban villages (UV) and residential quarters (RQ). Asterisks above the boxplots denote statistically significant differences between UV and RQ at the $p < 0.05$ level, as determined by the Mann-Whitney U test.

The Theil index analysis (Fig. 11) indicated that the equity of UV and RQ's GS availability improved with accessible distance. UV's Theil index dropped sharply between 0 m and 100 m, suggesting improved equity, then increased gradually with slower rates. RQ exhibited a similar but less pronounced trend. NDVI's Theil index (Fig. 11) decreased sharply between 0 m and 100 m for UV, then fluctuated with a peak at 1000 m and another at 1600 m. For RQ, the index rose sharply within 0–200 m but declined gradually thereafter.

For FVC (Fig. 11), UV's Theil index spiked initially but then declined at a slower rate. RQ's Theil index showed a rapid decrease within 0–400 m, stabilizing thereafter.

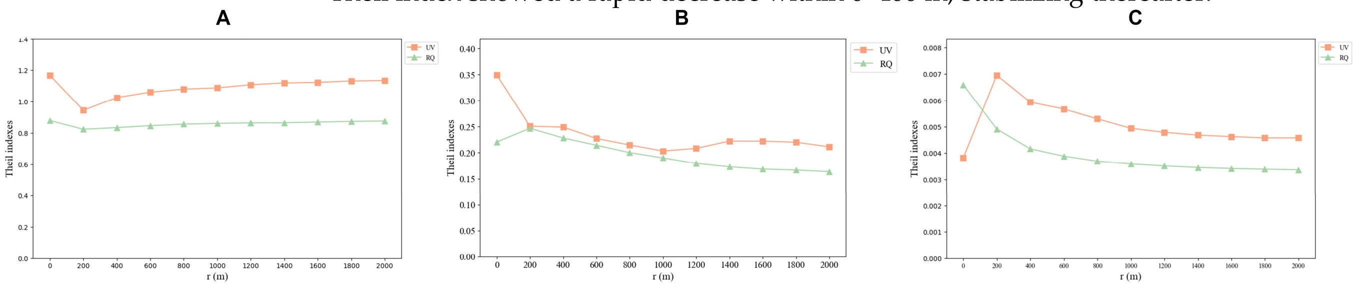

Figure 11: Changes in Theil indices for per capita green space (GS) availability (a), normalized difference vegetation index (NDVI) (b), and fractional vegetation cover (FVC) (c) across urban villages (UV) and residential quarters (RQ) at progressively increasing accessible distances.

Across all three indicators, UV and RQ displayed distinct equity trends. Notably, UV's NDVI equity fluctuated significantly within 1000–1600 m, while GS and FVC equity exhibited opposing trends. Overall, UV showed greater inequities compared to RQ, except in inner-FVC.

As described in Section 3.1, within-group inequities accounted for 100% of total inequities in GS availability when only internal GS was considered (Fig. 9). When external green space (GS) was considered, the contribution of between-group inequities to overall inequity increased within a 200-meter radius (Fig. 15a). This highlights the role of external GS in reducing within-group disparities in GS availability between urban villages (UV) and residential quarters (RQ). However, with increasing distance, between-group contributions declined, and within-group inequities rose.

For NDVI (Fig. 12), external GS had a limited impact on mitigating within-group inequities. In contrast, FVC (Fig. 12) showed a rapid decline in between-group inequities within 100 m, approaching zero, while within- group inequities surged to nearly 100%. These results emphasize the role of external GS in alleviating disparities in FVC between UV and RQ in central Beijing.

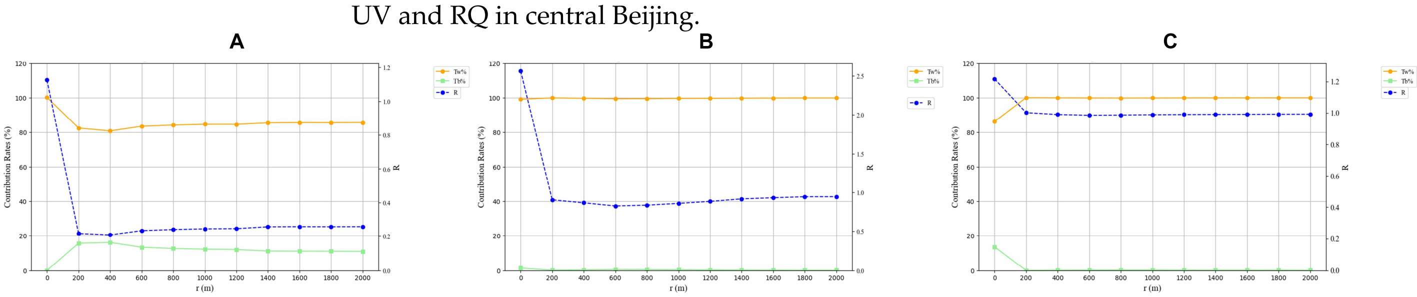

Figure 12: Decomposition of total inequities in per capita green space (GS) availability (A), normalized difference vegetation index (NDVI) (B), and fractional vegetation cover (FVC) (C) between urban villages (UV) and residential quarters (RQ) at progressively increasing accessible distances.

4. Discussion

4.1. Spatial Distribution Patterns

Our research reveals distinct spatial distribution patterns in the quantified green space (GS) characteristics for UV and RQ. UV exhibits poorer internal GS characteristics overall, while external GS quality is higher in the southwest and northwest, but poorer in the east. In contrast, RQ demonstrates higher GS levels in the north for both internal and external green spaces, though the vegetation quality of external GS remains suboptimal.

This disparity is largely driven by differences in policy frameworks, land-use planning approaches, and geographical contexts between urban villages (UV) and residential quarters (RQ). Residential quarters (RQs) are typically situated in high land-price urban centers, which limits their proximity to natural green spaces (GS) in peripheral regions. This spatial disconnection contributes to significantly lower normalized difference vegetation index (NDVI) values in RQs compared to areas with greater access to natural GS. Additionally, Beijing's central urban districts in the southwest and northwest are endowed with richer GS resources (Figure 1). Consequently, UVs in western areas benefit from better external GS resources, while RQs in the northwest also enjoy superior GS conditions.

Areas closer to natural environments feature higher vegetation quality and coverage than those near urban cores, leading to a consistent trend of lower NDVI and FVC in central urban areas compared to western regions. External GS in RQs is primarily composed of artificial parks, which constitute a smaller proportion of total GS and generally have lower NDVI and FVC than natural environments.

Therefore, compared to UVs, RQs' GS availability is less affected by the overall distribution of GS. Notably, while RQ's GS availability seems to benefit from rigorous urban planning, studies show that high-end RQ developments are typically closer to parks, making GS more accessible (Chen et al., 2020). Future urban GS planning in Beijing's central urban districts should prioritize addressing the green space challenges of communities distant from natural GS areas. These communities show consistently lower levels of GS in terms of both area and vegetation quality, whether internally or externally.3.3. Variations in Green Space Inequalities with Accessible Distance

4.2. Internal Distribution Patterns

Our findings also indicate that internal GS equity in UVs is inferior to that in RQs, although FVC equity shows the opposite trend. On average, RQs outperform UVs in both internal GS levels and equity. While significant disparities exist in vegetation quality and coverage between UVs and RQs,

per capita green space differences are smaller, although UVs still show greater inequity in both metrics. These findings align with previous studies in other cities.

Interestingly, FVC shows an opposite trend, with UVs demonstrating slightly better equity. This result supports the broader consensus that socio-economically disadvantaged communities tend to have poorer vegetation conditions (Allegretto et al., 2022; Watkins and Gerrish, 2018). The internal GS inequality in UVs and RQs is largely driven by differences in their construction models and economic factors.

UVs, often inhabited by populations unable to afford high rents, are typically characterized by limited material resources. Studies suggest that areas with higher material deprivation or more minority populations tend to have less green space or tree cover (Kiani et al., 2023), which explains the lower NDVI mean and equity within UVs. Similarly, studies using census data emphasized reduced vegetation exposure in minority or low-income communities (Sharifi et al., 2021b).

In contrast, RQs, with their higher economic status, feature higher-quality internal GS and larger GS areas. However, the predominance of artificial GS in RQs, likely influenced by plant growth periods and species selection, results in greater inequity in vegetation coverage. UVs' collective land ownership structure further exacerbates the issue. Legal restrictions on land sales and limited regulatory oversight lead to densely packed buildings as villagers expand housing areas to increase rental income, which encroaches on internal GS and degrades the living (Hao, 2015).

In contrast, RQ is governed by stricter urban planning regulations. For example, Article 20 of the Beijing Greening Ordinance mandates that construction projects adhere to prescribed greening land use standards. Specifically, newly constructed residential areas must allocate at least 30% of their land for greenery (lPeople's Government, 2009). Furthermore, centralized green spaces must be developed at a minimum of 2 square meters per capita for residential areas and 1 square meter per capita for residential communities. As a result, the availability of green spaces (GS) within RQ is significantly higher than that in UV. This results in better internal GS availability in RQs compared to UVs.

Based on our findings, we propose several recommendations for improving GS equity within Beijing's central urban districts. Since internal GS is used more frequently than external GS (S¨aumel et al., 2021), priority should be given to greening UVs, with a particular focus on eastern and southern areas of RQs that are distant from natural GS. Beyond expanding GS area, efforts should also enhance vegetation quality and coverage. Considering the high building density in urban villages (UVs), innovative strategies such as rooftop gardens, green walls, street tree planting, and roadside vegetation could provide effective solutions for enhancing green infrastructure. These measures, widely recognized as critical components of urban green infrastructure, have demonstrated effectiveness in mitigating heat stress, managing stormwater runoff, and improving air quality. (Park et al., 2024; Esuman Quainoo and Jim, 2023). Their minimal spatial requirements make them particularly suitable for urban cores with limited land resources.

4.3. *External Distribution Patterns*

Finally, our analysis highlights that intra-group inequality dominates overall GS inequity in both UVs and RQs. The NDVI for UVs shows anomalies between 1000-1600m, whereas fairness trends for per capita green space area and FVC are opposite. For RQs, per capita green space fairness and NDVI fairness diverge, while FVC trends align with external GS changes at 0-200m.

Group-level Theil index analysis reveals that GS inequity in Beijing's central urban districts primarily stems from intra-group disparities. Only minor inter-group inequity is observed in per capita GS accessibility and FVC fairness for internal GS. This contrasts with findings from other cities, where inter-group disparities often play a more significant role (Xu et al., 2024).

Existing research suggests that the unequal distribution of natural GS and economic disparities between UVs and RQs underpin this phenomenon. Extending GS accessibility to 100m significantly reduces the Theil index for UVs, indicating that external GS effectively mitigates inequities caused by inadequate internal GS. Green spaces improve quality of life in dense urban areas (Chiesura, 2004).

However, RQs' reliance on artificial GS, characterized by inferior vegetation quality and greater inequity, results in higher fairness in per capita GS area but poorer vegetation growth conditions. While external GS improves the quality of life for UV residents, disparities in GS levels and quality be- tween inner-city UVs and surrounding green spaces persist.

Urban planning strategies for RQs often leverage high-quality park systems to attract affluent residents and tourists (Braiterman, 2011), ensuring adequate GS levels even in areas distant from natural environments. However, UVs, particularly those in urban cores, struggle to maintain sufficient greenery levels, resulting in lower equity compared to suburban green spaces. To address these issues, future GS planning in Beijing's central urban districts should prioritize the development of green spaces near vulnerable communities. Enhancing GS equity across such areas is crucial for improving

5. Conclusions

Investigating the equity of green space (GS) accessibility for disadvantaged groups in urban environments is crucial for promoting environmental justice. Urban villages (UVs) and residential quarters (RQs), two prevalent types of residential communities in Chinese cities, serve as key focal points for such analyses. Enhancing the living conditions of socially and economically disadvantaged residents, primarily residing in urban villages (UVs), and ensuring equitable access to green space (GS) relative to residential quarters (RQs) are crucial for advancing the United Nations' Sustainable Development Goal of reducing inequalities. However, research on GS inequities among disadvantaged groups remains scarce.

This study examines the equity of green space (GS) accessibility between urban villages (UVs) and residential quarters (RQs) in the central urban area of Beijing, with a focus on varying buffer distances. The findings reveal that when considering internal GS only, RQs possess significantly more GS and demonstrate better equity compared to UVs. Intra-community disparities, rather than differences between community types, are the primary contributors to GS inequity within the central urban areas of Beijing. Furthermore, inequity in per capita GS is identified as the dominant factor driving overall GS inequity in the study area.

Based on these findings, a series of recommendations have been proposed to reduce GS disparities in central Beijing. This research holds broader significance for examining green space (GS) equity in marginalized housing typologies, including informal settlements prevalent in developing regions. (Cobbinah et al., 2021). Moreover, from an environmental justice perspective, it underscores the importance of prioritizing the needs of residents in disadvantaged areas through green space (GS) strategies integrated into urban renewal initiatives, with a particular focus on enhancing internal GS availability.

Despite the insights provided, several limitations should be acknowledged and addressed in future studies. First, this research primarily focused on green space (GS) inequities between residents of urban villages (UVs) and residential quarters (RQs). However, given the distinct socio-economic characteristics of these two groups, disparities in GS accessibility may also exist in other daily environments, such as workplaces or shopping areas, potentially influencing health outcomes. Due to the unavailability of relevant data, this study did not examine environmental inequities in these additional contexts. Future research could investigate this dimension as soon as the necessary data becomes accessible.

Second, this study focused on the overall availability of green spaces (GS) within and around residential communities, without differentiating between specific types or configurations of GS. Different GS categories, such as parks and community gardens, offer unique benefits, including cultural ecosystem services, air pollution mitigation, and urban cooling effects. (Sharifi et al., 2021b). Future studies are encouraged to adopt a weighted evaluation approach that considers different GS types to enable more comprehensive and detailed analyses.

Finally, by relying on remote sensing data, this study assessed GS quality on a macro level, excluding evaluations of micro-level GS services and amenities. The quality of green spaces (GS), which encompasses factors such as recreational facilities, safety, accessibility, and aesthetic appeal, plays a critical role in shaping residents' perceptions and usage patterns (Wolff et al., 2022). Future research should integrate evaluations of micro-level attributes, including service facilities and visual quality, to advance our understanding of GS equity.

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Abbreviations

The following abbreviations are used in this manuscript:

UV	Urban Village
RQ	Residential Quarter
NDVI	Normalized Difference Vegetation Index
FVC	Fractional Vegetation Cover

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