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From equity to renewal: multi-factor evaluation of urban park accessibility in community life circles, Taijiang District, Fuzhou

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Urban development in China has entered a stage of stock-based renewal, with greater emphasis on optimizing existing resources. As a public resource, urban parks play a crucial role in promoting public health through equitable distribution. Traditional, extensive, top-down allocation models can no longer meet residents' needs, and the diverse demands of various social groups for parks are often overlooked. In response, the concept of community life circles has emerged as a more human-centered and efficient planning strategy. This study, focusing on spatial and social equity, approaches the issue through the perspective of community life circles. By incorporating park quality, group demand heterogeneity, and API-based path planning, it refines the dynamic age-grouped Gaussian-based two-step floating catchment area (D-AG2SFCA) method to assess park accessibility and supply–demand relationships under three community life circle scenarios (5-, 10-, and 15-min walking distances). From the perspective of group-differentiated equity, this study further identifies disadvantaged areas in park access under the three scenarios, as well as the degree of spatial differentiation in resource availability for disadvantaged groups. Finally, by integrating accessibility, supply–demand relationships, and location quotients, this study constructs a multi-factor evaluation system to determine priorities for urban park renewal and proposes targeted optimization strategies.

KEYWORDS

demand heterogeneity, accessibility, equitable distribution, 2SFCA, community life circles, urban park renewal, supply–demand relationship, disadvantaged groups

1 Introduction

Today, the social problems arising from accelerated global urbanization and rapid population growth pose significant challenges to the sustainable development of urban resources (Zhao, 2011). As a core public resource, urban parks are increasingly valued for their role in promoting the physical and mental health of residents in high-density urban areas (Mitchell, 2013; Chiesura, 2004). However, in the context of stock-based renewal, the traditional model of park allocation based on administrative districts or sub-districts is no longer sufficient to meet residents' diverse needs (Zhou et al., 2021. The concept of life circle planning, first proposed by Japanese scholars, has provided new insights into more refined approaches to resource allocation (Takahashi, 1987; He and Wang, 2004). In 2018, China's Ministry of Housing and Urban–Rural Development issued the Standard for Urban

Residential Area Planning and Design (GB50180-2018), which advocates the construction of community life circles as the basic unit of residents' daily lives. These circles are divided into three levels according to walking time: 5 min, 10 min, and 15 min. The objective is to provide disadvantaged groups with equitable opportunities to access parks and thereby promote public health (Yang, 2020; Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2018; Ministry of Natural Resources of the People's Republic of China, 2021). However, existing research indicates that in high-density urban areas, park resources are generally distributed unevenly—a problem especially acute for disadvantaged groups (Cong et al., 2023; Huang et al., 2023; Wu and Mei, 2021). This reality provides the entry point of this study: within the framework of community life circles, group demand heterogeneity must be taken into account to achieve "equity among groups" and to embody social equity.

Accessibility evaluation has become an important tool for studying issues of environmental justice (Hansen, 1959). However, when applying the 2SFCA method, existing research often overlooks the following factors: (1) On the supply side, park area is typically used as the sole indicator, neglecting the dimension of park usability (Fan et al., 2017); (2) On the demand side, analyses are usually based only on population size and structure, typically adopting a single-group perspective (Tan and Samsudin, 2017); (3) Although travel cost and distance decay are considered, calculations are still mostly based on straight-line distance, which cannot reflect actual travel conditions under real-time traffic (Wang et al., 2021).

Therefore, this study incorporates park quality (Du and Jin, 2022), group demand heterogeneity, and API-based path planning to construct an improved D-AG2SFCA model. This study aims to explore: (1) how differences in park demand across social groups can be quantified and converted into coefficients; (2) how park accessibility and supply–demand relationships vary under the three community life circle scenarios, and how they are affected by travel-time thresholds; and (3) whether accessibility and the number of available parks are correlated with the socioeconomic attributes of social groups.

2 Study area overview, data sources, and processing

2.1 Study area overview

Taijiang District, located on the north bank of the lower Min River, is one of the main urban districts of Fuzhou. According to China's Seventh National Population Census, Taijiang has a permanent population of 411,819, with an average density of approximately 23,000 persons/km^2, exceeding the global high-density urban threshold of 15,000 persons/km^2. It is the most densely populated district in Fuzhou. In such a high-density, older urban area, residents have stronger demands for green space, and issues of environmental equity are more pronounced. Therefore, Taijiang District serves as a representative case for studying park resource allocation within the framework of community life circle planning.

The "Usability-Equity" dual-dimension assessment framework developed in this study features modular and parametric design. Its core lies in the methodological approach rather than the use of fixed parameters, which enhances its broader applicability. Firstly, the social group classification model based on age and income can be locally adapted according to the specific context of the target city (for instance, by incorporating key local variables such as household registration or occupation), with the core principle being the adoption of a "demand difference" analytical perspective. Secondly, the accessibility calculation method integrating real road networks (such as the API-based route planning used in this study) is widely applicable; in data-limited regions, network analysis or buffer analysis can serve as effective alternatives. In summary, other cities can flexibly adjust key modules and calibrate parameters within this framework based on local data availability, thereby enabling effective diagnosis of park green space equity and providing support for local planning.

In addition, since urban residents often engage in cross-district activities, restricting the analysis strictly to administrative boundaries could affect the accuracy of results in edge areas. Therefore, the actual study area includes a buffer zone extending 1,000 m beyond the boundary of Taijiang District (Fan et al., 2017) (Figure 1).

2.2 Data sources and processing

2.2.1 Park data

Park data for Taijiang District were obtained from OpenStreetMap and 2022 Google satellite imagery, from which polygonal park data were extracted using ArcMap 10.6. Verification through Amap's route planning API confirmed that all parks within the study area fall within the 15-min community life circle; therefore, no parks were excluded. Table 1 summarizes the sources and processing methods of the datasets in the park database. Since the areas of hard-surfaced spaces and the density of recreational facilities cannot be captured through remote sensing due to vegetation coverage, these data were supplemented by field surveys.

Following the conclusions of Li et al. (2008), this study selects park entrances as the origin points for accessibility calculations to avoid misjudgments of park accessibility (Tong et al., 2021). The spatial locations of park entrances in the study area were recorded and cross-validated using online maps and field surveys. In total, 95 parks and 463 supply points were included in the analysis (Figure 1).

2.2.2 Population demand data

Residential community data for Taijiang District were obtained from Anjuke (https://fz.anjuke.com) and Lianjia (https://fz.lianjia.com), two of the largest and most comprehensive real estate transaction platforms in China. Between October 13 and 15, 2023, a Python program was developed to collect points of interest (POIs) for residential communities within the study area from these two platforms (Figure 2A). The datasets were then cross-checked, cleaned, and averaged. The resulting data included the names of residential communities, geographic coordinates (latitude and longitude), total number of housing units, and historical average transaction prices.

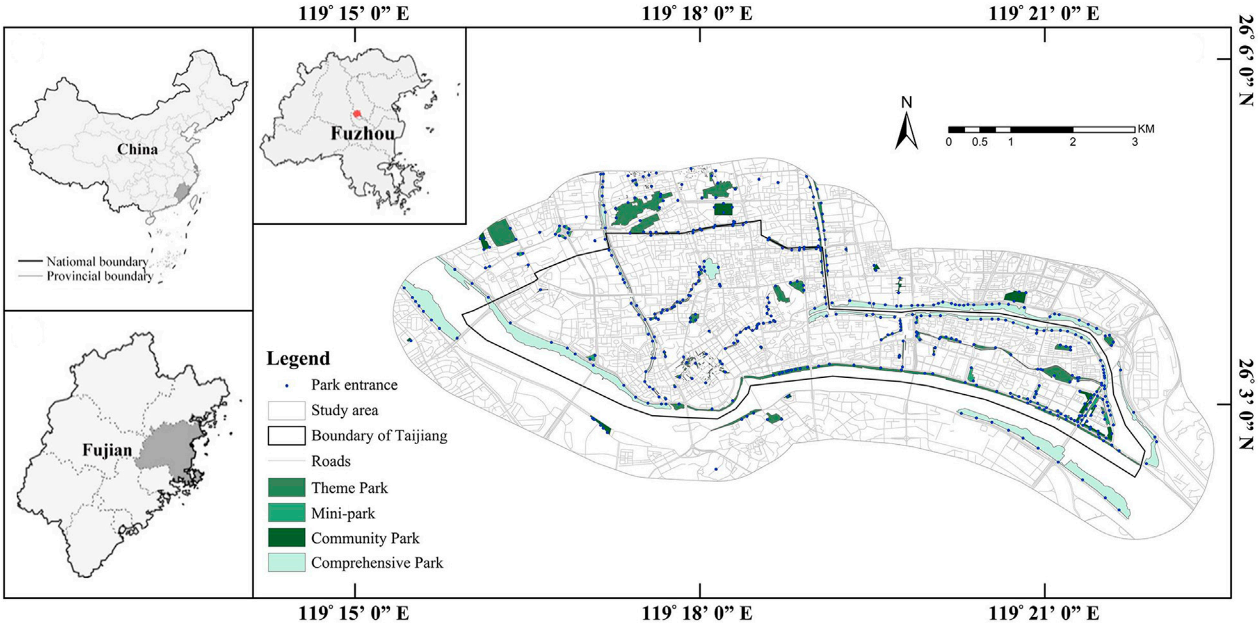

FIGURE 1
Study area and its spatial Scope.

TABLE 1 Park data information.

Data type	Data source	Processing method
Park boundaries and area	OpenStreetMap, 2022 high-resolution satellite imagery of Fuzhou	Manual digitization
Park entrances	2022 high-resolution satellite imagery of Fuzhou, field survey	Online retrieval, manual digitization
Water body area	2022 high-resolution satellite imagery of Fuzhou	Manual digitization
Hard-surfaced area	Field survey	Manual digitization
Vegetation coverage ratio	Landsat 8 OLI satellite imagery of Fuzhou	Calculation
Road networks	OpenStreetMap, 2022 high-resolution satellite imagery of Fuzhou	Online retrieval, manual digitization
Park roads		
Number of recreational facilities	Field survey	Calculation

Existing research has shown that, compared with traditional square grids, regular hexagonal grids can minimize aggregation errors caused by boundary effects when data are aggregated to centroids and reduce distortions caused by Earth's curvature, thereby yielding more accurate results. Therefore, this study used the Thiessen Polygon tool in ArcGIS 10.6 to construct a hexagonal grid with a side length of 100 m within the study area (Ren and Wang, 2021) (Figure 2A). Residential community points located within the same hexagonal grid were aggregated to the centroid of that hexagon, and their attribute data were summarized within the corresponding hexagon. These aggregated residential community points are regarded in this study as demand points. In total, 656 aggregated residential demand points were included in the analysis (Figure 2A).

The total population of each residential community was estimated by multiplying the total number of housing units by the average household size of the corresponding municipal district according to Formula 1:

$$P_k = \sum_{i \in A_k} H_i \times \overline{AVG} \tag{1}$$

where Pk is the total population at residential community point k; Ak is the hexagonal grid in which point k is located; Hi is the total number of housing units of all residential community points within grid Ak; and AVG is the average household size of the administrative district to which point k belongs, obtained from the 2020 Fuzhou Population Census Yearbook. In addition, because some housing units are vacant, the results were corrected using population data from the Seventh National Population Census Bulletin at the township and subdistrict levels. This produced the final population distribution within the study area (Figure 2A).

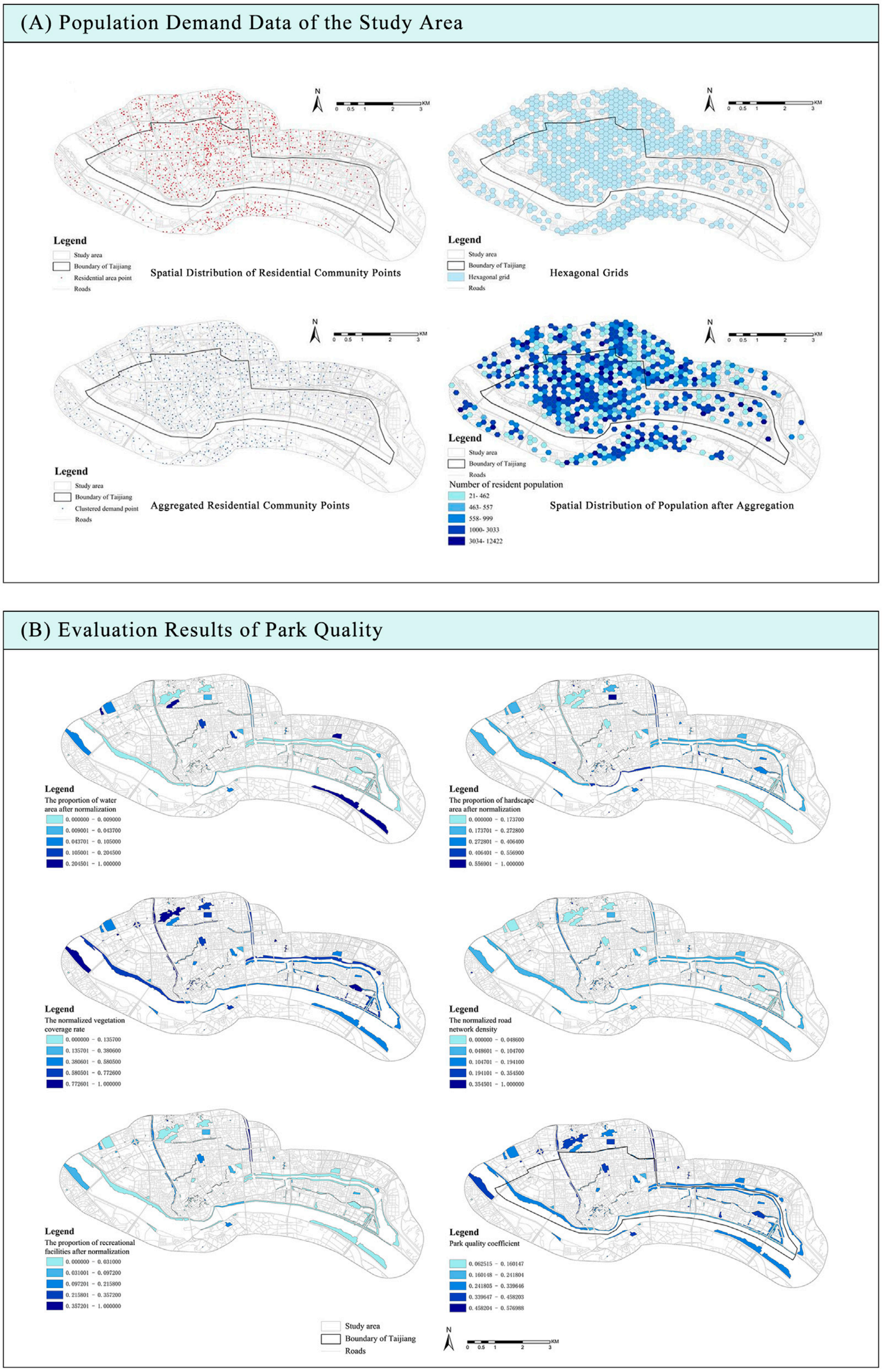

FIGURE 2
(A) Population demand data of the study area **(B)** evaluation results of park quality.

TABLE 2 Travel time cost data based on API.

SN	IN_FID	NEAR_FID	NEAR_DIST	NEAR_PANK	FROM_X	FROM_Y	NEAR_X	NEAR_Y	DIST	Time
1	0	302	253.84068148100	1	119.263527	26.061768	119.260998	26.061584	480	384
2	0	271	269.78167455500	2	119.263527	26.061768	119.262374	26.059567	357	286
3	0	202	664.61222011200	3	119.263527	26.061768	119.265100	26.055940	906	725
4	0	197	751.27016129000	4	119.263527	26.061768	119.267107	26.055808	850	680
5	1	197	230.97383466400	1	119.266990	26.057890	119.267107	26.055808	459	367
...	...	...	...	...	...	...	...	...	...	...

TABLE 3 Park quality evaluation system and indicator weights.

Evaluation indicator	Symbol	Indicator description	Weight (w)
Proportion of water body area	W	Reflecting the water environment of the park	0.1104
Proportion of hard-surfaced area	H	Reflecting the scale of activity space the park can accommodate	0.0698
Vegetation coverage rate	V	Reflecting the greenness and vegetation coverage of the park	0.4368
Road network density	R	Reflecting the transportation convenience of the part	0.1290
Density of recreational facilities	F	Reflecting the service level of recreational facilities in the park	0.2540

2.2.3 Travel time cost data

Using the aggregated residential community points as origins and park entrances as destinations, this study employed Amap's walking route planning API to calculate the travel time for each Origin-Destination (OD) pair, which was used as the travel time cost (Weiss et al., 2018). To reduce excessive computation time, the Near Table tool in GIS was used to filter the data. As a result, the number of OD matrices was reduced from the original 303,728 (463 × 656) to 22,524. In addition, based on the principles of community life circle delineation and considering the travel constraints of disadvantaged groups, walking was selected as the travel mode. A sample of the processed data is shown in Table 2.

3 Methods

3.1 Improved D-AG2SFCA

3.1.1 Park quality coefficient introduced to optimize park supply

At the current stage of urban stock development, improving the internal quality of parks is key to enhancing their service capacity and usability. To capture the heterogeneity of parks, this study applied a park quality coefficient to weight park area, thereby more accurately reflecting their actual supply capacity. The evaluation indicators of park quality include five aspects: proportion of water body area, proportion of hard-surfaced area, vegetation coverage, road network density, and density of recreational facilities. After normalizing all data, the quality coefficient Q_W was obtained using linear algebra according to Formula 2:

$$Q_W = Ww_1 + Hw_2 + Vw_3 + Rw_4 + Fw_5 \tag{2}$$

where W, H, V, R, and F represent the five indicators listed in Table 3, and w_1, w_2, w_3, w_4, w_5 are the corresponding weights of each indicator. The weights were determined based on the degree of association between each indicator and park service capacity, and were derived through field surveys and expert interviews, followed by calculation and analysis using Analytic Hierarchy Process software (YAAPH).

3.1.2 Evaluation of group demand heterogeneity

Improvements on the supply side alone cannot fully capture the extent of park demand among different social groups. Currently, the Theory of Planned Behavior (TPB) is widely applied in studies investigating the relationship between psychological factors and urban park use (Wang et al., 2015; Zhang and Tan, 2019). Drawing on TPB, this study evaluates residents' subjective demand levels from two dimensions—travel intention and actual demand—and subsequently derives the equity coefficient. Travel intention is further divided into three indicators: attitude, subjective norms, and perceived behavioral control (Amireault et al., 2008). Actual demand includes five indicators: comfortable travel distance, required park size, required facility density, green view index, and sky openness (Lin et al., 2012; Yang and Liao, 2023).

Following the categorization and identification methods for disadvantaged groups, and based on socio-economic (i.e., income) and physiological (i.e., age) attributes, urban residents are classified into nine groups (Table 4). It should be noted that adolescents do not have direct income, and their economic status is mainly influenced by their families; therefore, their family's economic level was directly recorded.

As adolescents and elderly adults rely less on social media in their daily lives, dynamic online big data are not suitable for this study. Therefore, questionnaire surveys and in-depth interviews were adopted to obtain data on the heterogeneity of park demand. The questionnaires, designed to assess residents' level of park demand within community life circles in Taijiang District, were

TABLE 4 Nine major social groups and their equity coefficients.

Social group	Average questionnaire score	Equity coefficient
Low-income adolescents	42.55	0.94
Low-income middle-aged adults	44.02	0.97
Low-income elderly adults	47.33	1.04
Middle-income adolescents	44.58	0.98
Middle-income middle-aged adults	44.48	0.98
Middle-income elderly adults	47.74	1.05
High-income adolescents	43.40	0.96
High-income middle-aged adults	43.18	0.95
High-income elderly adults	50.82	1.12

created using the Wenjuanxing platform (https://www.wjx.cn). In addition, self-photographed landscape images were used to illustrate the corresponding indicators (Zhou et al., 2022) and enhance participants' landscape perception.

Online questionnaires were distributed from March to May 2024, while offline interviews and paper-based surveys were conducted in Taijiang District on several weekends and holidays in April and May. This study defines the average score of all questionnaires as the total societal demand. By aggregating the disparities between the demands of each social group and this total demand, it employs standardized mean questionnaire scores to compute an "equity coefficient"—a composite metric for gauging the degree of equity experienced by each group. The equity coefficient was calculated based on each questionnaire's score and the average questionnaire score according to Formula 3:

$$\alpha_h = \frac{\sum_{j=1}^{n} \frac{D_{ij}}{\overline{D}}}{n} \tag{3}$$

where α_h is the equity coefficient of social group i; D_{ij} is the score of the *j*th questionnaire from social group i, where j = 1, 2, . . . , n; and $\overline{D}$ is the average score of all questionnaires.

P_i is the corrected equity population at residential community point i and was calculated according to Formula 4:

$$P_i = \sum_{h=1}^{9} P_h \times \alpha_h \tag{4}$$

where P_h is the population of social group hat residential community point i; α_h is the equity coefficient corresponding to that group, where h = 1, 2, . . . , 9 represent the nine social groups.

3.1.3 Search step optimization

Step 1: Starting from each supply point, demand points within the search radius were identified. It should be noted that, because multiple park entrances may be linked to the same residential community point, this study selected only the entrance–residence pair with the lowest travel time to avoid repeated calculations. In addition, the walking time returned by the API was used as the travel cost to calculate the distance decay coefficient according to Formula 5:

$$G\left(t_{ij}, t_0\right) = \begin{cases} \dfrac{e^{-\left(\frac{1}{2}\right)\times\left(\frac{t_{ij}}{t_0}\right)^2} - e^{-\left(\frac{1}{2}\right)}}{1 - e^{-\left(\frac{1}{2}\right)}}, \text{if } t_{ij} \le t_0 \\ 0, \text{if } t_{ij} > t_0 \end{cases} \tag{5}$$

where t_{ij} is the travel time from the centroid of residential community point i to park entrance j; t_0 is the specified search time threshold; and $G(t_{ij}, t_0)$ is the Gaussian function accounting for distance decay. Based on the above, the supply-to-demand ratio R_j was calculated according to Formula 6:

$$R_j = \frac{S_j Q_{Wj}}{\sum_{i\in\{t_{ij} \le t_0\}} G\left(t_{ij}, t_0\right) P_i} \tag{6}$$

where S_j is the area of park j, and Q_{Wj} is the quality coefficient of park j.

Step 2: Starting from each demand point, supply points within the search radius were identified. Pre-experiments showed that calculating Rj separately for each park entrance could introduce errors when matching the two search steps. Therefore, this study aggregated results by park and assigned them to each supply point. The Rj values of all eligible supply points were then summed to obtain the park accessibility A_i of each residential community point i according to Formula 7:

$$A_i = \sum_{j\in\{t_{il} \le t_0\}} G\left(t_{ij}, t_0\right) R_j \tag{7}$$

3.2 Spatial matching degree

Although the 2SFCA method considers both supply and demand, its results do not reflect the degree of matching between them. To maximize the utilization efficiency of urban parks and promote social equity, it is necessary to identify and improve areas where park supply and demand are mismatched. Therefore, this study used the ratio of the actual number of people able to access a park to its population carrying capacity as the park's minimum service standard. The standardized supply–demand balance value was then calculated by transforming the accessibility results according to Formula 8:

$$E_i = A_i \times \frac{Max\left(G\left(t_{ij}, t_0\right)R_j\right)}{Max\,(A_i)} \tag{8}$$

where E_i is the level of supply-demand balance under the minimum service standard. Based on an interval of 0.25, it is categorized into six levels: $E_i = 0$ for no supply; $0 < E_i \le 0.25$ for severely insufficient supply; $0.25 < E_i \le 0.5$ for insufficient supply; $0.5 < E_i \le 0.75$ for balanced supply and demand; $0.75 < E_i \le 1$ for insufficient demand; $E_i > 1$ for severely insufficient demand.

3.3 Bivariate spatial autocorrelation

Spatial autocorrelation is used to analyze the interdependence of geographic features at different locations within a region and serves as a measure of spatial clustering (Sharifi et al., 2021). Moran's I is the most commonly used indicator for measuring spatial autocorrelation. The sign of Moran's I indicates the direction of correlation between two variables: a positive value suggests clustering, while a negative value suggests dispersion. The strength of clustering or dispersion corresponds to the absolute value of Moran's I. In this study, GeoDa 1.20 was used to conduct the spatial autocorrelation analysis.

3.4 Location quotient

Originally developed as an indicator for studying industrial spatial structures, the location quotient (LQ) is now widely used to assess the equity of public resource allocation. It reflects the relationship between the distribution of a particular public resource within a spatial unit and the average distribution level across the entire study area. This study adopted LQ to examine spatial differences in park accessibility among various disadvantaged groups, as well as differences between these groups, according to Formula 9:

$$LQ_i = \frac{T_i/P_i}{T/P} \tag{9}$$

where LQi is the location quotient of grid cell i; Ti is the level of park accessibility in grid cell i; Pi is the population of a specific disadvantaged group in grid cell i; T is the overall level of park accessibility across the entire study area; and P is the total population of that disadvantaged group in the entire study area. If LQi is greater than 1 or less than 1, it indicates that the level of park resources available to that disadvantaged group in grid cell i is higher or lower, respectively, than the average level for that group across the study area.

4 Results

4.1 Evaluation of the supply-demand capacity of urban parks

4.1.1 Overall supply of urban parks

The quality assessment results of each park, obtained using the natural breaks method, are shown in Figure 2B. The mean park quality coefficient in the study area (Figure 2B) is 0.29, with a standard deviation of 0.11, indicating significant disparities in construction quality. Jin'an River Park shows the highest quality (coefficient = 0.5770), yet it ranks only 18th in area. Minjiang Park North has the largest area; however, field surveys indicate that it does not attract significantly more visitors than other parks, possibly due to its lower construction quality (coefficient = 0.3246). Overall, park size and quality are poorly matched. Spatial analysis shows that high-quality parks are concentrated in the northern and northwestern parts of the study area, with a few scattered in the east. Their distribution is uneven, and overall quality remains low due to size limitations. Parks with high comprehensive supply are mainly located in the peripheral zones (Figure 3).

4.1.2 Degree of disparities in resident demand

The mean questionnaire score was 30.23 out of 40, with a standard deviation of 3.10 and a coefficient of variation of 0.10, indicating moderate dispersion, a compact data distribution, and good internal consistency (Figure 4A). Among the groups, high-income elderly adults had the highest equity coefficient (1.12), whereas low-income adolescents had the lowest (0.94). Regardless of income level, elderly adults showed the highest demand for parks. Lower scores for the other two major groups were influenced by the following factors: adolescents' park visits are constrained by family limitations, and middle-aged adults have limited discretionary time due to work commitments and are often unwilling to walk more than 5 min to a park. Based on the equity coefficients, Figure 3 shows the distribution of the weighted residential population.

4.2 Park accessibility

To ensure accuracy, only results within administrative boundaries were retained and analyzed (Figures 4B, C). The data reveal significant differences in accessibility values across the different community life circles, with most values concentrated in the lower range and showing a long-tail distribution. To minimize interference from outliers, the geometric interval method was used to classify park accessibility results into ten levels (Figure 4B).

As shown in Table 5, A1 has the highest mean accessibility (1.15) and includes two special areas (green boxes in Figure 4B): Nan Park and Liming Lake Park. Due to their limited number of entrances, these parks can serve only these two areas within a 5-min walking distance, and their service capacity falls short of expectations. From A1 to A2, the maximum value decreases by 67.44%, and the proportion of apparent blind spots decreases by 27.11%, indicating that the service potential of parks has been more fully utilized. From A2 to A3, the mean value increases from 1.16 to 1.22, showing that residents enjoy better park services as they preferentially choose closer and higher-quality parks. The accessibility values in A3 are more concentrated, indicating the best overall accessibility evaluation.

In terms of spatial distribution (Figure 4B), accessibility has consistently been high in the northern part of the study area (highlighted in purple boxes), roughly corresponding to Shanghai Subdistrict and Xingang Subdistrict. These parks are more open, have more entrances, and are located in areas with higher road network density. In contrast, accessibility has consistently been low in the southern part of the study area (highlighted in yellow boxes). On one

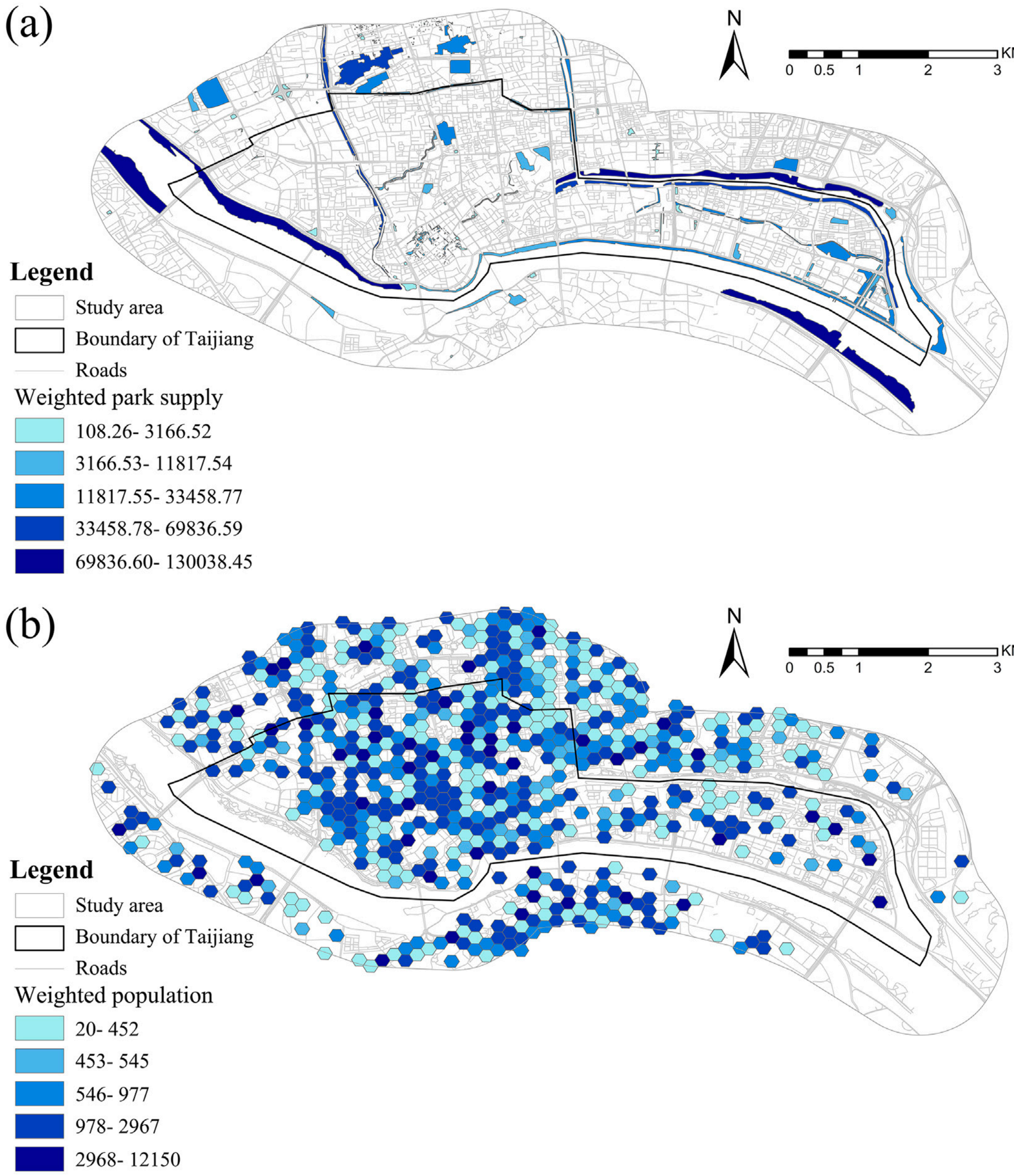

FIGURE 3
(a) Spatial distribution of comprehensive park supply capacity **(b)** spatial distribution of residents' comprehensive demand capacity.

hand, Jiangbin West Avenue, a major urban road, disrupts the continuity of the east–west pedestrian network. On the other hand, the spacing of entrances in the linear waterfront parks in this area is too large, further increasing residents' effort and time costs to access parks.

4.3 Supply-demand relationship of urban parks

The supply–demand matching types of parks in Taijiang District were calculated, and their distributions under the three community life circle scenarios were statistically analyzed. Under the A1 scenario, the distribution is mainly characterized by grids with no supply (38.67% of grids) and oversupplied grids (19.71%), forming a clear "dumbbell-shaped" pattern, while balanced supply–demand grids account for only 5.92%. Under the A2 scenario, similar to accessibility, the supply–demand situation improves significantly with the increased number of available parks; however, the proportion of oversupplied areas is the highest among the three scenarios (33.64% of grids, 32.46% of the population). Under the A3 scenario, the proportion of no-supply areas continues to decrease, whereas the proportion of balanced supply–demand areas continues to increase. However, the most prevalent type in the 15-min scenario is the undersupplied type (40.86% of the population), rather than the balanced type. Meanwhile, the coefficient of variation for A3 (0.75) is higher than that of the 10-min community life circle (0.50), indicating

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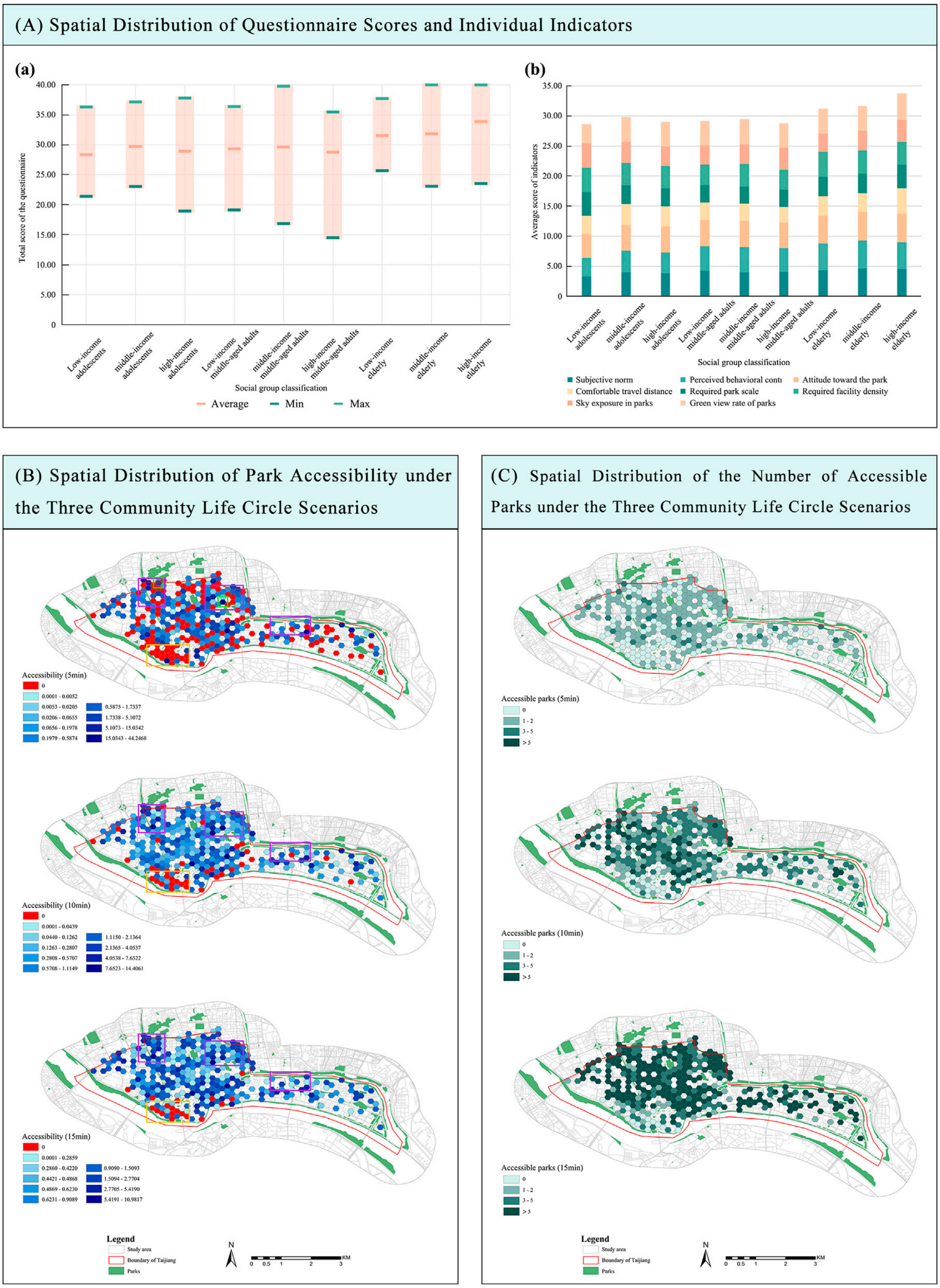

FIGURE 4
(A) Spatial distribution of questionnaire scores and individual indicators **(B)** spatial distribution of park accessibility under the three community life circle scenarios **(C)** spatial distribution of the number of accessible parks under the three community life circle scenarios.

TABLE 5 Accessibility characteristics at different community life circles.

Community life circle	Accessibility characteristics					
	Maxi-mum value	Mini-mum value	Mean value	Median	Standard deviation	Proportion of grid cells with accessibility value of 0
5-min life circle (A1)	44.25	0.00	1.25	0.17	4.17	38.32%
10-min life circle (A2)	14.41	0.00	1.16	0.51	1.80	11.21%
15-min life circle (A3)	10.98	0.00	1.22	0.88	1.36	5.61%

that although extending the time threshold enlarges service coverage, it may also exacerbate supply–demand imbalances in certain high-density areas.

Spatially, the supply–demand matching patterns at different time thresholds in Taijiang District show a significant spatial locking effect: the southern riverside area, represented by Cangxia Subdistrict, consistently exhibits clusters of no-supply and undersupplied grid cells across all three community life circle scenarios. Further observation reveals that under the A1 scenario (Figure 5a), the spatial differentiation of supply–demand matching is most pronounced. The supply-saturated zone, concentrated in high-density built-up areas like Chating and Yangzhong sub-districts, experiences sustained housing price inflation and high-income resident attraction due to historical locational advantages amplified by "spatial capitalization" (Gould and Lewis, 2016). Proximity to medium-scale parks like Chating Park and Nan Park further reinforces this spatial inertia, perpetuating the area's socio-economic advantage and unequal access to premium resources. This pattern highlights environmental injustice within the 5-min community life circle, where high-quality public resources disproportionately cluster around privileged groups (Martin and Sunley, 2006). Under the A2 scenario (Figure 5b), oversupplied areas begin to extend toward peripheral parts of Taijiang District, such as Xingang and Shanghai subdistricts. The supply saturation in Shanghai and Xingang sub-districts stems primarily from the lower population density and limited demand within certain research units. Under the A3 scenario, supply–demand conflicts show signs of spatial shift. For example, older urban areas such as Yangzhong Subdistrict, which originally had a relatively good supply–demand balance, have shifted to an undersupplied status (Figure 5c). Mechanism analysis reveals that the expansion of life circles leads to an influx of non-local users, significantly increasing pressure on park services and creating an excessive supply load. This exposes the limitations of high road network density in meeting medium-to-long-term demand: while it ensures basic accessibility, it struggles to accommodate large-scale usage. Therefore, expanding service coverage must be coupled with enhancing green space quality in high-pressure areas to maintain a supply-demand balance.

4.4 Cluster identification analysis

4.4.1 Disadvantaged group cluster identification based on socioeconomic attributes

The global Moran's I values for the two variables under the A1, A2, and A3 scenarios are 0.08, 0.16, and 0.22, respectively, with p-values of 0.001 for all three (Table 6), indicating a significant positive spatial correlation between residents' socioeconomic status and park accessibility in all community life circle scenarios. Under the A1 scenario, the proportion of high–high clusters reaches 9.35%, indicating that high-income groups have already formed a dominant advantage in accessing high-quality park resources, and this advantage shows a gradient-strengthening trend (Z-value increasing from 5.0 to 12.3). This finding contradicts the survey results in Section 4.1.2, suggesting that income itself may not be a decisive factor influencing park accessibility. Disparities in economic status can indirectly influence residents' opportunities and willingness to use urban green spaces, as these disparities manifest in unequal living environments, varying perceptions of the restorative benefits of parks, and differing levels of environmental belonging. For instance, a self-reinforcing cycle may emerge: higher-income groups can induce improvements in park quality through price-driven filtering, which in turn subsequently increases property values in the surrounding area. This process may displace lower-income residents or reduce their use of nearby parks, ultimately reinforcing their disadvantaged position in accessing green space resources. Under the A2 scenario, the number of low–low clusters increases from 0 to 16, whereas the number of high–low clusters decreases by 60%, indicating a more pronounced spatial pattern of environmental injustice. Under the A3 scenario, high–high and low–low clusters become spatially interwoven. Subsequently, a spatial autocorrelation analysis of the number of accessible parks was also conducted (Figure 6c). Comparing Figures 6a, c shows that the results are largely consistent, further supporting the reliability of the previous findings. Overall, high–high clusters are mainly located east of the Shangxiahang Historic and Cultural Block and around South Park, whereas low–low clusters are concentrated in the southeastern part of the study area, likely because this area contains many newly built residential communities where park facility construction has lagged behind.

4.4.2 Disadvantaged group cluster identification based on population density

A significant positive spatial correlation exists between the two variables in all community life circle scenarios. However, under the A1 scenario, the global Moran's I value of the two variables is only 0.04, with a p-value of 0.019, indicating limited clustering and weak correlation strength (Table 6). Within short-term circles, residents have fewer park choices, and cross-district mobility is significantly reduced, resulting in low service pressure on parks and the inevitable underutilization of resources. Therefore, park entrances may be the key factor affecting accessibility under the A1 scenario. In addition, this study finds that low–high clusters under all three community

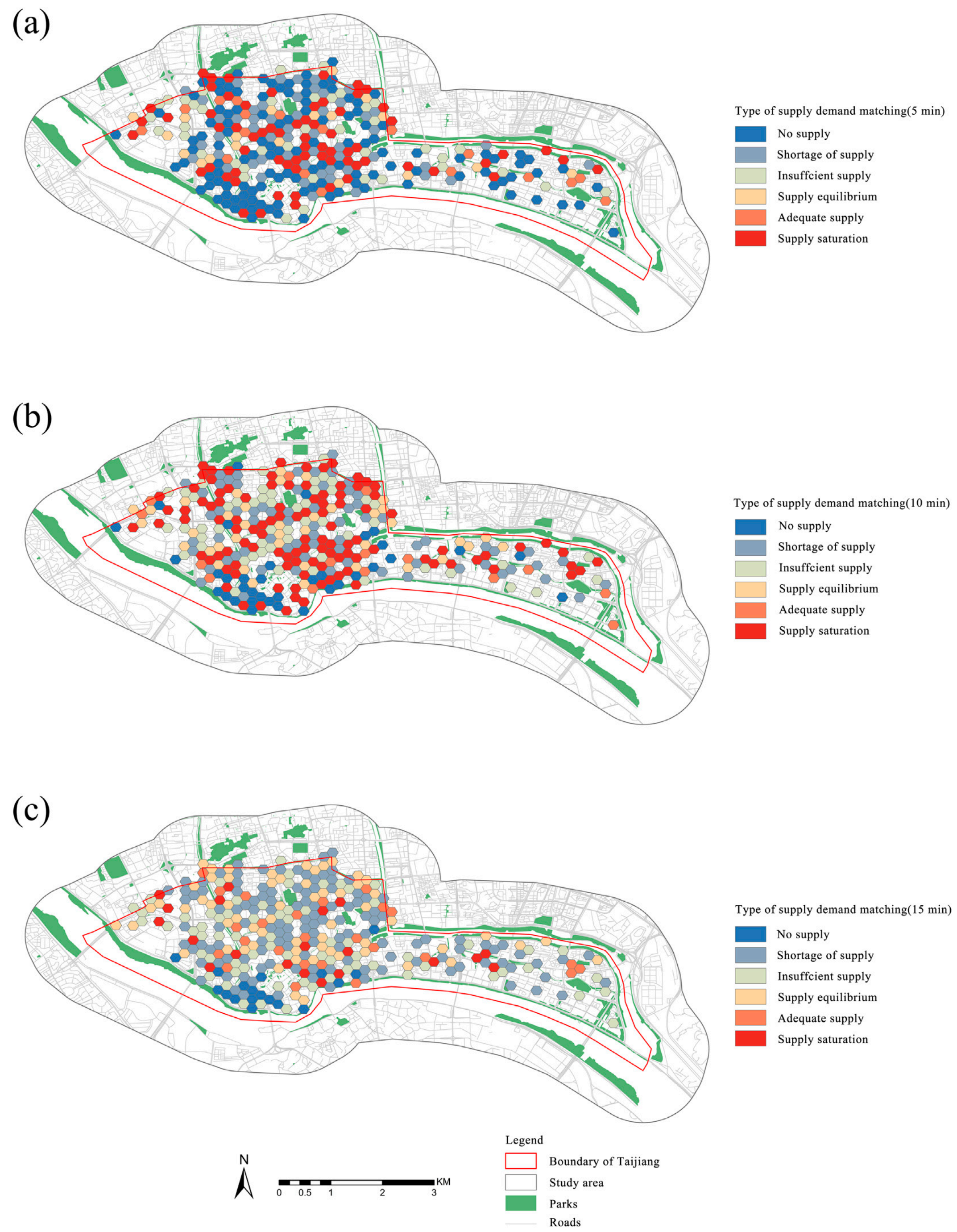

FIGURE 5
Spatial distribution of supply-demand matching types of parks in taijiang district.

life circle scenarios are scattered and numerous, mainly located south of Yushan Scenic Area, east of the Shangxiahang Historic and Cultural Block, and around Taijiang No. 5 Central Primary School (Figure 6b). The underlying causes of this phenomenon include resource underutilization caused by traditionally extensive park layouts, as well as the advantageous locations of these parks, which—due to cultural and historical factors—naturally allow them to enjoy the benefits of high-quality park resources.

4.5 Spatial differentiation analysis

This study used the quantile classification method in ArcGIS to conduct a spatial analysis of the location quotient and spatial equity patterns of three disadvantaged groups—adolescents, the elderly, and low-income groups—with respect to park resources. Using this method, five-level location quotient classification results were produced (Figure 7; Table 7).

TABLE 6 Spatial autocorrelation characteristics of research variables and park accessibility.

Variable 1	Variable 2: accessibility	Moran's I index	Characteristic value	Mann–Whitney U test	
			Standard deviation	Z value	P value
Social economic attributes	5 min (A1)	0.0820	0.0164	5.0088	0.001**
	10 min (A2)	0.1617	0.0168	9.6385	0.001**
	15 min (A3)	0.2172	0.0175	12.3456	0.001**
Population density	5 min (A1)	0.0393	0.0159	2.4837	0.019*
	10 min (A2)	0.0877	0.0163	5.3737	0.001**
	15 min (A3)	0.1166	0.0169	6.8659	0.001**
Number of accessible parks	5 min (A1)	0.0438	0.0166	2.6845	0.008**
	10 min (A2)	0.1482	0.0176	8.5115	0.001**
	15 min (A3)	0.2279	0.0176	12.9432	0.001**

*p < 0.05; **p < 0.01; ***p < 0.001.

Areas where adolescents enjoy high levels of park resources show a distinct "southeast-to-northwest" axial shift as the community life circle expands. Although the elderly exhibit a similar time-threshold effect, their spatial equity patterns differ markedly. For the low-income group, most medium-level location quotient values are below 1, indicating that over half of the low-income grid cells have disadvantaged access to park resources. The sharp contrast between extremely low and extremely high location quotient values reveals a contradictory pattern in which "absolute deprivation" coexists with "localized privilege." Further observation shows that some grid cells along the northern boundary of Taijiang District and southeast of the Fuzhou First General Hospital, affiliated with Fujian Medical University, consistently fall into the extremely high location quotient classification under all community life circle scenarios.

5 Conclusion and discussion

5.1 Conclusion

Taking Taijiang District of Fuzhou as an example, this study aims to provide scientific guidance for allocating park resources in high-density urban areas under community life circle planning, from the perspective of group demand heterogeneity. Based on the dual optimization of "equitable availability" and "equitable differentiation" in the supply-demand evaluation, the study incorporated API-based walking route planning to improve the accessibility calculation model and applied it to assess the equity of park allocation under three community life circle scenarios. The main conclusions are as follows: (1) There is a structural imbalance in the park-supply capacity within the study area, coupled with pronounced disparities in demand across different social groups. (2) The travel time threshold exhibits a positive correlation with park accessibility, while significant deficiencies in spatial equity were identified. (3) The supply-demand matching demonstrates heterogeneous patterns across concentric zones, with service efficacy being constrained by quality shortcomings (Li et al., 2021). (4) Disadvantaged areas show significant spatial differentiation and a pronounced tendency for multiple disadvantages to cluster. Moreover, disadvantaged groups consistently experience lower resource accessibility across all three zones, highlighting a challenge to spatial justice.

5.2 Urban park renewal strategies

Based on park accessibility, spatial supply–demand relationships, and the location quotient of disadvantaged groups, this study developed a multi-factor integrated evaluation method and applied coupling analysis to determine the renewal priority of parks in Taijiang District. Each factor was reclassified into five levels from low to high, with scores from 5 to 1 assigned according to the principle of inverse scoring (e.g., the higher the accessibility, the lower the renovation potential). The study assumes that the three factors have equal guiding value, so their scores were summed to comprehensively assess the overall performance of each grid cell across these three aspects. The final results classified park renovation priority into three levels: urgent improvement (high), optimization (medium), and intensified composition (low) (Figure 8). Among parks within the 5-min community life circle, the majority fall into the "urgent improvement" level (169 grid cells, 52.65%). For those within the 10-min circle, the largest proportion falls into the "intensified composition" level (117 grid cells, 36.45%). Within the 15-min circle, the largest proportion falls into the "optimization" level (113 grid cells, 35.20%). Based on the existing problems of parks under each community life circle scenario and common development issues at different priority levels, this study formulated targeted optimization strategies for each of the three priority levels.

In the stage of stock-based development, the renewal and optimization of high-density urban areas should adopt a strategy of "quality improvement and functional integration," supplemented by refined design and management, to achieve diversified functions and efficient spatial utilization. Given the limited availability of

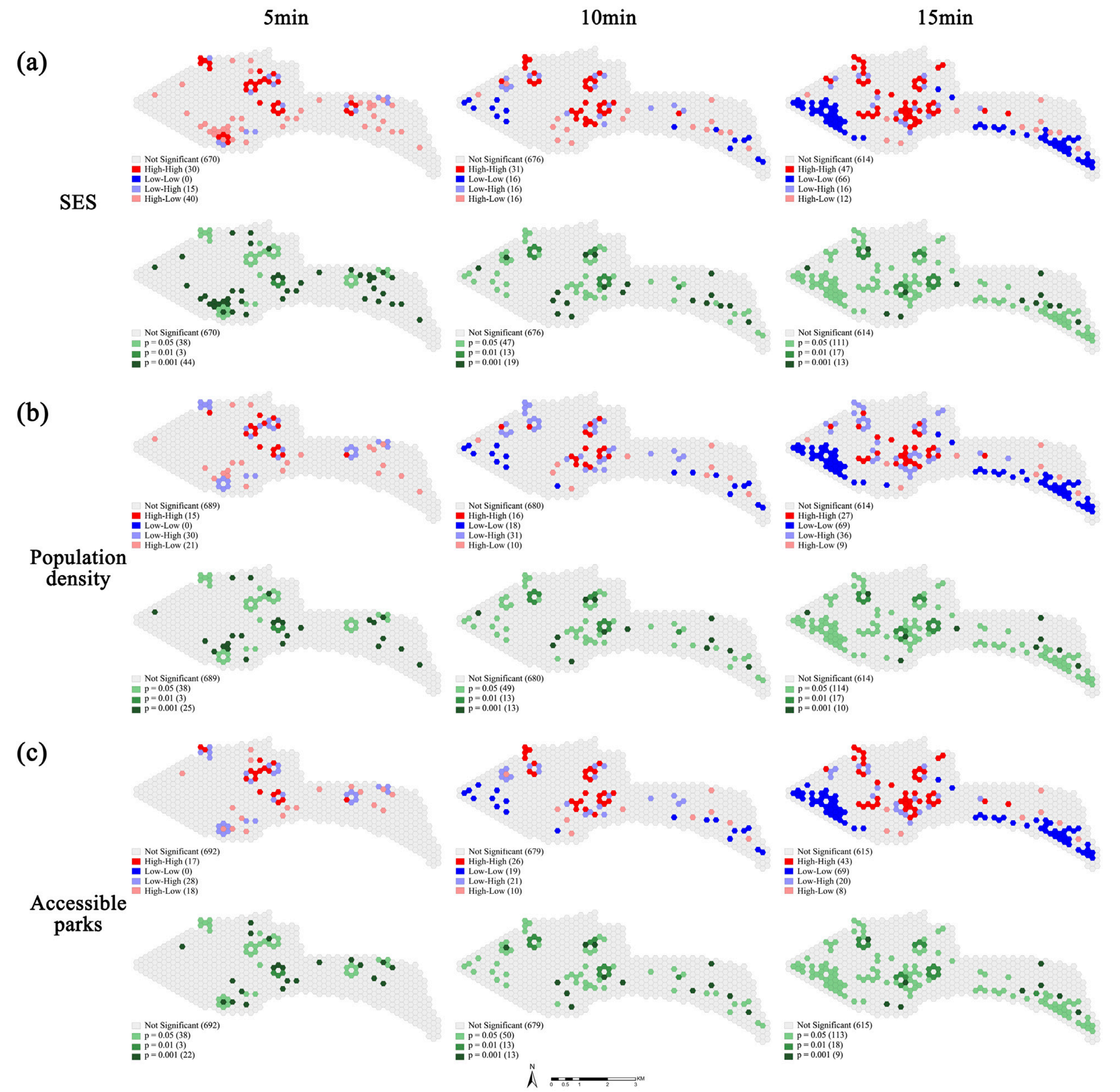

FIGURE 6
Spatial clustering of multivariate factors and park accessibility under different travel thresholds.

resources, this study focuses on areas classified as urgent improvement and explores their design strategies across the three community life circles, aiming to strengthen the equity and sustainability of park supply in Taijiang District, Fuzhou.

5.2.1 Urgent improvement

5.2.1.1 Entrance optimization

Some spatial roads are not connected, pedestrian overpasses of appropriate height could be installed to connect park entrances, providing safe and continuous pedestrian access while ensuring the normal operation of the expressways. For those parks that have insufficient entrances and exits, the number of park entrances could be appropriately increased, or park boundaries could be softened to create "borderless" parks that better integrate with the surrounding urban built environment.

5.2.1.2 Incremental greening

Some spaces can be optimized by identifying and transforming small non-park green spaces in the surrounding environment with development potential, or by shaping them into micro-scale community pocket parks or roadside green spaces. Additionally, selectively opening the green spaces of university campuses and highly enclosed residential communities to the public offers an effective, low-cost improvement strategy.

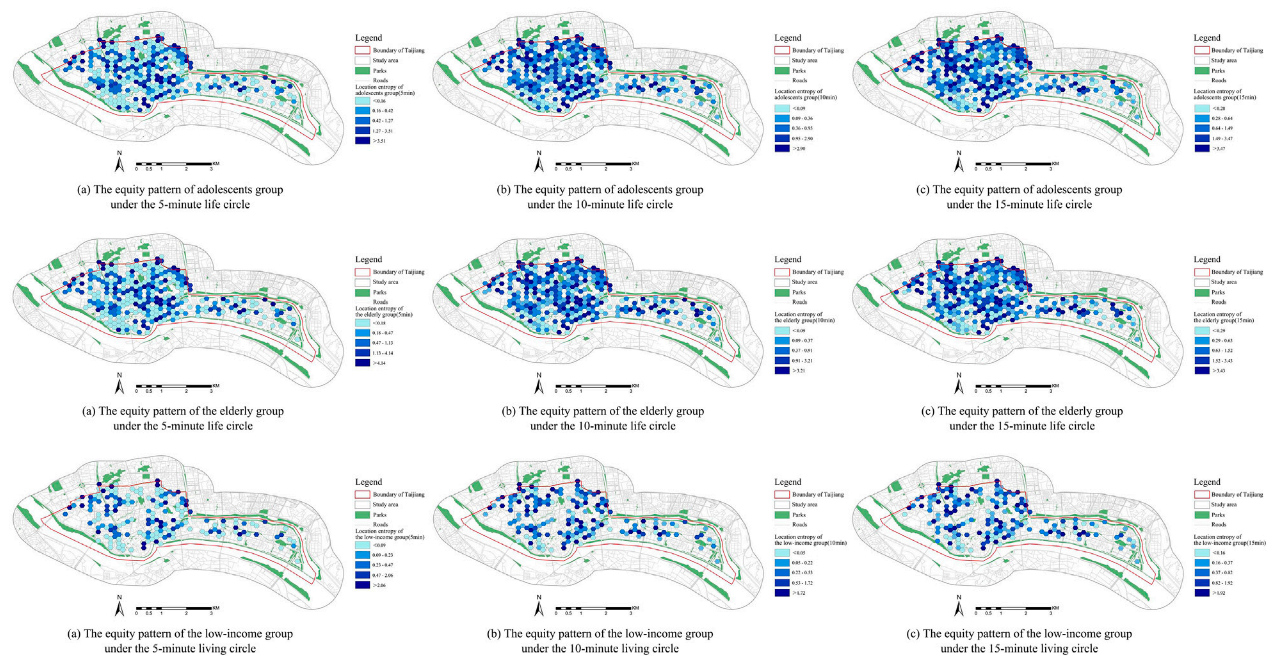

FIGURE 7
Equity patterns of different groups under the three community life circle scenarios.

TABLE 7 Location quotient classification of equity patterns of different groups under the different community life circle scenarios.

Group type	Location entropy classification	Number of units			The proportion			Location entropy value		
		A1	A2	A3	A1	A2	A3	A1	A2	A3
Adolescents	Extremely low	162	65	65	50.47	20.24	20.24	<0.16	<0.09	<0.28
	Lower	40	64	64	12.46	19.94	19.94	0.16–0.42	0.09–0.36	0.28–0.64
	Medium	40	64	64	12.46	19.94	19.94	0.42–1.27	0.36–0.95	0.64–1.49
	Higher	40	64	64	12.46	19.94	19.94	1.27–3.51	0.95–2.90	1.49–3.47
	Extremely high	39	64	64	12.15	19.94	19.94	>3.51	>2.90	>3.47
Elderly	Extremely low	162	65	65	50.47	20.24	20.24	<0.18	<0.09	<0.29
	Lower	40	64	64	12.46	19.94	19.94	0.18–0.47	0.09–0.37	0.29–0.63
	Medium	40	64	64	12.46	19.94	19.94	0.47–1.13	0.37–0.91	0.63–1.52
	Higher	40	64	64	12.46	19.94	19.94	1.13–4.14	0.91–3.21	1.52–3.43
	Extremely high	39	64	64	12.15	19.94	19.94	>4.14	>3.21	>3.43
Low-income group	Extremely low	69	35	35	39.43	20.00	20.00	<0.09	<0.05	<0.16
	Lower	40	35	35	22.86	20.00	20.00	0.09–0.23	0.05–0.22	0.16–0.37
	Medium	22	35	35	12.57	20.00	20.00	0.23–0.47	0.22–0.53	0.37–0.82
	Higher	22	35	35	12.57	20.00	20.00	0.47–2.06	0.53–1.72	0.82–1.92
	Extremely high	22	35	35	12.57	20.00	20.00	>2.06	>1.72	>1.92

5.2.1.3 Public participation

Under the A3 scenario, the voices of certain minority groups—especially low-income residents—regarding green spaces are often underrepresented. These spaces can adopt the "Sufficient Green Strategy" used in some Western countries, which emphasizes empowering residents of low-income areas to participate in the design, management, and decision-making of green spaces (Wolch et al., 2014).

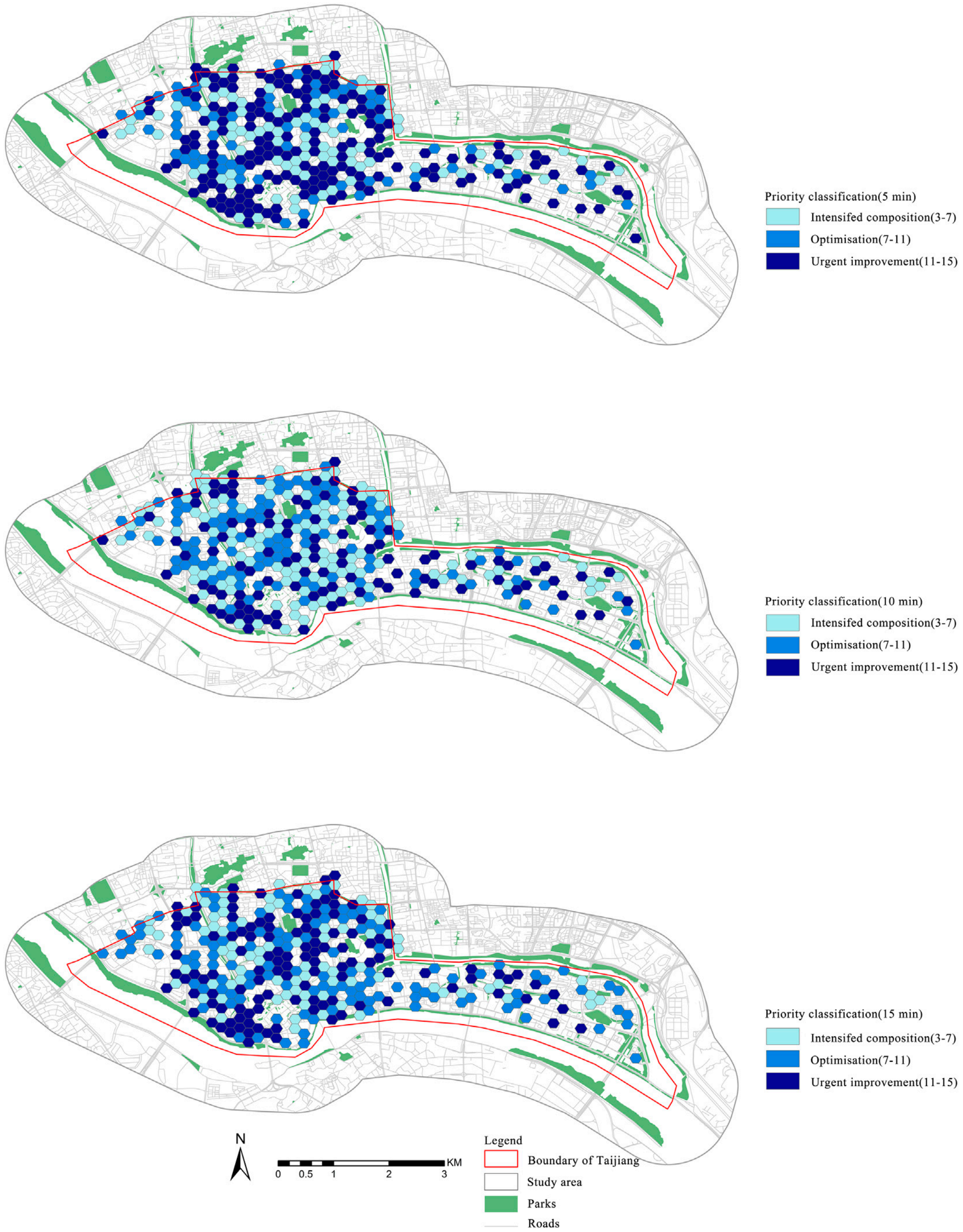

FIGURE 8
Renewal priority levels of parks under the three community life circle scenarios.

5.2.2 Optimization

For grid cells classified as optimization under the A2 and A3 scenarios, park service quality and attractiveness are the dominant factors. In areas dominated by low-quality small and medium-sized parks, or by small parks with low comprehensive supply capacity, it is recommended to enhance park quality and attractiveness by adding service facilities, improving internal and external road connectivity, and strengthening operation and maintenance.

5.2.3 Intensified composition

Grid cells classified as intensified composition are widely distributed under the A2 scenario. In these areas, the distribution of parks has largely reached a balanced state. These parks can further enhance their roles in cultural heritage preservation and resource conservation to improve overall service efficiency. They may also integrate rain gardens, ecological dry streams, and vertical greening installations to strengthen their contribution to the urban ecological environment.

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Guided by the three core principles of local adaptation, high-quality development, and cost-effectiveness, the foregoing analysis has systematically examined the common challenges associated with different renovation tiers. In light of this examination, a series of targeted, actionable optimization strategies are proposed. Furthermore, it is imperative for relevant government departments to employ inter-departmental coordination and technical measures to ensure the effective implementation of supportive policies, projects, and renewal optimizations.

5.3 Limitations and prospects

While this study offers insights into the allocation of park resources within community life circles at a refined planning scale and contributes to existing research on park accessibility—which has often overlooked ground demand heterogeneity—it has several limitations that warrant further exploration in future research: (1) This study only covers established parks and does not include non-park green spaces such as street trees and small-scale green patches, where green inequity is often even more pronounced (Nesbitt et al., 2019). Future research could incorporate these types of green spaces to examine their impacts on urban green space accessibility and environmental injustice. (2) In terms of travel modes, this study only considered walking. However, cycling and public transportation are also important ways for many residents to reach parks (Park et al., 2021). Future research could explore the role of multi-modal travel in alleviating pressure on walking-based park accessibility or incorporate residents' travel mode preferences into accessibility calculations. (3) Regarding travel time, future research could integrate the effects of holidays and weather conditions on travel time into the 2SFCA method and conduct multi-period comparative validation to further improve the accuracy and generalizability of the method.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the [patients/ participants OR patients/participants legal guardian/ next of kin] was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

YW: Conceptualization, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review and editing. JY: Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review and editing. YH: Data curation, Formal Analysis, Visualization, Writing – review and editing. GM: Investigation, Visualization, Writing – review and editing. YF: Visualization, Writing – review and editing. YL: Data curation, Investigation, Writing – review and editing. SL: Funding acquisition, Writing – review and editing. FL: Project administration, Supervision, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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