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Evaluation of Urban Green Space Supply and Demand Based on Mobile Signal Data: Taking the Central Area of Shenyang City as an Example

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Abstract: The degree of coordination between the supply and demand for urban green spaces serves as a vital metric for evaluating urban ecological development and the well-being of residents. An essential principle in assessing this coordination is the precise quantification of both the demand and supply of green spaces, as well as the differential representation of their spatiotemporal structures. This study utilizes the entropy weight method (EWM) and principal component analysis (PCA) to comprehensively measure supply indicators for green space quantity and quality in the central urban area of Shenyang, China. To establish reliable and quantifiable demand indicators, mobile signaling spatial-temporal data are corrected by incorporating static population cross-sectional data. The Gaussian two-step floating catchment area method (Ga2SFCA) is employed to calculate the accessibility of green spaces in each community with ArcGIS 10.2 software, while the Gini coefficient is utilized to assess the equity of green space distribution within the study area. This study employs location entropy to determine the levels of supply and demand for green spaces in each subdistrict. Furthermore, the priority of community-scale green space regulation is accurately determined by balancing vulnerable areas of green space supply and replenishing green space resources for the ageing population. The findings suggest a Gini coefficient of 0.58 for the supply and demand of green spaces in Shenyang's central metropolitan region, indicating a relatively low level of equalization in overall green space allocation. Based on location entropy, the classification of supply and demand at the street level yields the following outcomes: balanced areas comprise 21.98%, imbalanced areas account for 26.37%, and highly imbalanced regions represent 51.65%. After eliminating the balanced regions, the distribution of the elderly population is factored in, highlighting the spatial distribution and proportions of communities with distinct regulatory priorities: Level 1 (S1) constitutes 7.4%, Level 2 (S2) accounts for 60.9%, and Level 3 (S3) represents 31.7%. Notably, the communities in the S1 category exhibit spatial distribution characteristics of aggregation within the inner ring and the northern parts of the third ring. This precise identification of areas requiring urgent regulation and the spatial distribution of typical communities can provide reliable suggestions for prioritizing green space planning in an age-friendly city.

Keywords: multisource data; parks; fairness; accessibility; GIS; supply-demand matching

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1. Introduction

1.1. Research Background

In 2018, the Chinese government introduced the concept of the "park city" in response to the new challenges faced regarding China's urbanization process. The primary objective of this concept is to establish a new urban form known as "Shan Shui Lin Tian Hu", (mountains, rivers, forests, farmlands, and lakes), which embodies a highly integrated and unified paradigm of urban development. The concept aims to encompass people, cities, environments, and industries, making it an ideal urban model for the knowledge, information, and innovation society of the 21st century.

The core values of the park city concept revolve around "public" and "fairness", seeking to strike a balance between ecological values and humanistic care. It encompasses various aspects, such as ecological foundations, urban-rural patterns, the construction of the "three domains" (living, production, and ecology), urban quality enhancement, and the promotion of social fairness and justice. The concept emphasizes the construction of a comprehensive regional park system that covers both large-scale regions and small-scale communities. It encourages the integration of park forms and functions with urban spaces; the creation of a comprehensive territorial space that integrates living, production, ecology, and life; and simultaneous planning within the framework of urban spatial strategic development.

Therefore, it is evident that China's current stage of urban development requires a balance between optimizing the existing built environment and creating a favorable natural environment. Moreover, optimizing green spaces to cater to the needs of the elderly population addresses current social needs and aligns with the principles of urban development. This approach acknowledges the importance of creating sustainable and equitable urban environments while improving the overall quality of life for residents. By promoting ecological preservation, balancing urban and rural growth, and fostering social fairness, the park city concept aims to create livable and harmonious communities that serve as models for future urban development in China.

1.2. Evaluation Content on the Supply and Demand of Urban Green Space

Urban green spaces, as essential public service facilities in the construction of a park city, play a significant role in improving both residents' well-being and the ecological environment. The supply-demand relationship of these spaces reflects the rational allocation of government resources and is closely related to the "quantity" and "quality" of green space products and services available to the public. The study of urban green space supply and demand is essentially a discussion on social fairness, aiming to achieve Pareto optimality in resource allocation among different demand entities through a reasonable structural configuration. Omer argues that the spatial fairness of public service facilities focuses more on human needs, referring to the fair distribution of these facilities among different regions and social groups, considering the needs of vulnerable populations [1].

In addition to examining the demand side, the supply side of green space services is also considered, specifically the volume of services that green spaces can provide and their degree of utilization. Studies often explore the supply-demand relationship between green spaces and urban residents in terms of green space accessibility [2], exposure to green environments [3], ecological and social service benefits [4–6], spatial layout characteristics [7,8], and comprehensive benefit assessment [9,10]. These investigations help identify blind spots in green space resource services [11] and ecologically vulnerable areas [12], leading to the proposal of corresponding optimization strategies. The following table provides a partial summary of the evaluation content of the supply-demand relationship of green spaces based on existing research.

As indicated in Table 1, the evaluation of green space distribution on the supply side often centers around assessing green space accessibility. This accessibility evaluation can be classified into two types, namely, geometric networks and topological networks, depending on the data type and analytical elements employed. Geometric network-based methods for calculating accessibility encompass distance-based methods [13,14], cumulative opportunity methods [15], contour line methods [16], gravity model methods [17], balance coefficient methods [18], spatiotemporal methods [19], and utility methods [20].

An influential approach for evaluating accessibility is the Gaussian two-step floating catchment area method (Ga2SFCA). This method, which is a variant of the gravity model, integrates the interactions between supply, demand, and transportation costs within the spatial representation [21]. It is widely employed in researching the supply-demand relationship of urban public spaces and has been extended in various ways, including the establishment of search thresholds, the consideration of distance decay, and the quantification of supply points and demand points [7,22,23].

Table 1. Evaluation contents and methods of urban park service efficiency.

	Object	Content	Evaluation Methodology
Supply side	Green space Road network	Spatial Distribution	Green space accessibility: geometric network method; Topological network method
		Supply volume	Number and area of green spaces, Green Vision [24]
		Supply quality	Ecological service benefits: landscape pattern index
Demand side	City residents	Spatiotemporal distribution Demand preference	1. Quantification of spatiotemporal differences: location-based service data; travel log survey 2. Description of population differences: age differences [25]; socioeconomic status differences [26]; gender differences [27]; occupational differences [28]; cultural background differences [29] 3. Public willingness to pay [30]
Supply and demand	Mesoscopic level	Regional match	Accessibility analysis considering supply and demand: Ga2SFCA [31]
			Social equity performance: Gini coefficient and Lorenz curve; zone entropy
			Greenfield service efficiency: service area ratio [32]; service population ratio [32]; effective service ratio (ESR) [33]
	Microscopic level	Park monolith	Park environmental carrying capacity [34]
			Local service efficiency: evaluation of landscape vitality; walkability; convenience perception, and safety perception

1.3. Demand Differences in the Supply and Demand of Urban Green Space

In the latter half of the 20th century, the issue of resource allocation for public services in Western countries became more prominent, leading to a deepening contradiction between physical space and social space. If public services are not planned based on the needs of the population, it may result in discriminatory distribution [35]. The fairness of distributing public service resources should align with the needs and preferences of residents [36]. The core issue of fairness in the allocation of urban green space resources lies in the spatial configuration of green space and whether the allocation process caters to the diverse needs of different groups. In research on the equity evaluation of urban green space, not only regional differences in green space but also the socioeconomic attributes of the population are considered, leading to the investigation of the differentiation in green space utilization and demand among different groups. Studies have observed whether there is a correlation between green space attributes within spatial units and the socioeconomic status or social needs of residents [37]. In regions with a higher concentration of disadvantaged groups, there is a greater need for better public goods and services [38].

In addition, vulnerable populations have different behaviors, attitudes, and preferences in terms of green space utilization. Therefore, the behavioral characteristics, attitudes, preferences, and other factors of elderly individuals, women, and children in using green spaces have become major evaluation criteria for fairness [39]. Studies have also identified areas with high demand for parks based on the Neighborhood Social Deprivation Index (NSDI); researchers have pointed out that even if highly accessible green spaces do not align with the needs and spatiotemporal behavioral characteristics of residents, it is difficult to achieve high levels of usage activity [40]. Therefore, many scholars believe that in the supply of green space resources, accurately identifying the green space usage needs of different groups and optimizing spatial supply accordingly is an important intrinsic logic for ensuring fairness in resource allocation. With the integration of geographic information system (GIS) information and multisource data, technologies such as mobile signaling data [41], transportation trajectory data [42], and social media data [43] can provide a technical approach to obtaining spatial imaging information on the spatial clustering patterns and usage preferences of green space users. Such approaches facilitate the analysis of different groups' green space usage needs and spatial behavioral preferences.

1.4. Article Innovations

This study employs the Ga2SFCA model as a pivotal computational framework for evaluating the supply and demand of green spaces. It aims to analyze the green space supply-demand relationships and overall accessibility at the administrative, street, and community scales within the research area. The study focuses on optimizing the measurement indicators for demand and supply points, considering multidimensional quantification standards for both the quantity and quality of the supply.

Additionally, the study area exhibits significant population ageing, making the exploration of elderly needs relevant to the development of age-friendly cities. Therefore, this research considers the proportion of the elderly population within areas that are experiencing supply vulnerability to further analyze the urgency of demand within these vulnerable areas, thereby providing guidance for subsequent update strategies.

2. Materials and Methods

2.1. Study Area

Shenyang city is located in the southern part of Northeast China, between approximately 122°25′09″ E to 123°48′24″ E longitude and 41°11′51″ N to 43°02′13″ N latitude. It has a permanent population of approximately 9.07 million, with the proportion of the population aged 60 and above reaching 23.24%. The city's administrative region is divided into 10 districts, 1 county-level city, and 2 counties, covering an area of approximately 12,980 square kilometers.

In the strategic planning documents for revitalization and development, the local government of Shenyang city emphasizes the need to establish ecological corridors within urban renewal and construction projects, specifically targeting the "Three Rings, Three Belts, and Four Wedges." The "Three Rings" refer to the urban water systems surrounding the main city areas of Hunbei and Hunnan and the protective green belt along the Third Ring Expressway. The spatial scope of this study focuses on the central urban area designated by these rings (Figure 1). Within the central area, there are 91 street offices and 2420 community units.

According to the "Statistical Bulletin on National Economic and Social Development of Shenyang city in 2021" released by the Shenyang Municipal Bureau of Statistics, the total green space area in the built-up areas of Shenyang city comprises 221.55 square kilometers. This includes the construction of 5 new parks and 51 new green areas. The green space rate in the built-up areas is 38.87%, while the green coverage rate is 40.68%. The per capita park and green space area consist of 13.65 square meters, which meets the national minimum standard of 11 square meters per capita. However, there are variations in the accessibility of green spaces for residents in the central urban area. This study aims to further identify the distribution of streets and communities with low levels of ecological services and an inadequate overall supply of green spaces.

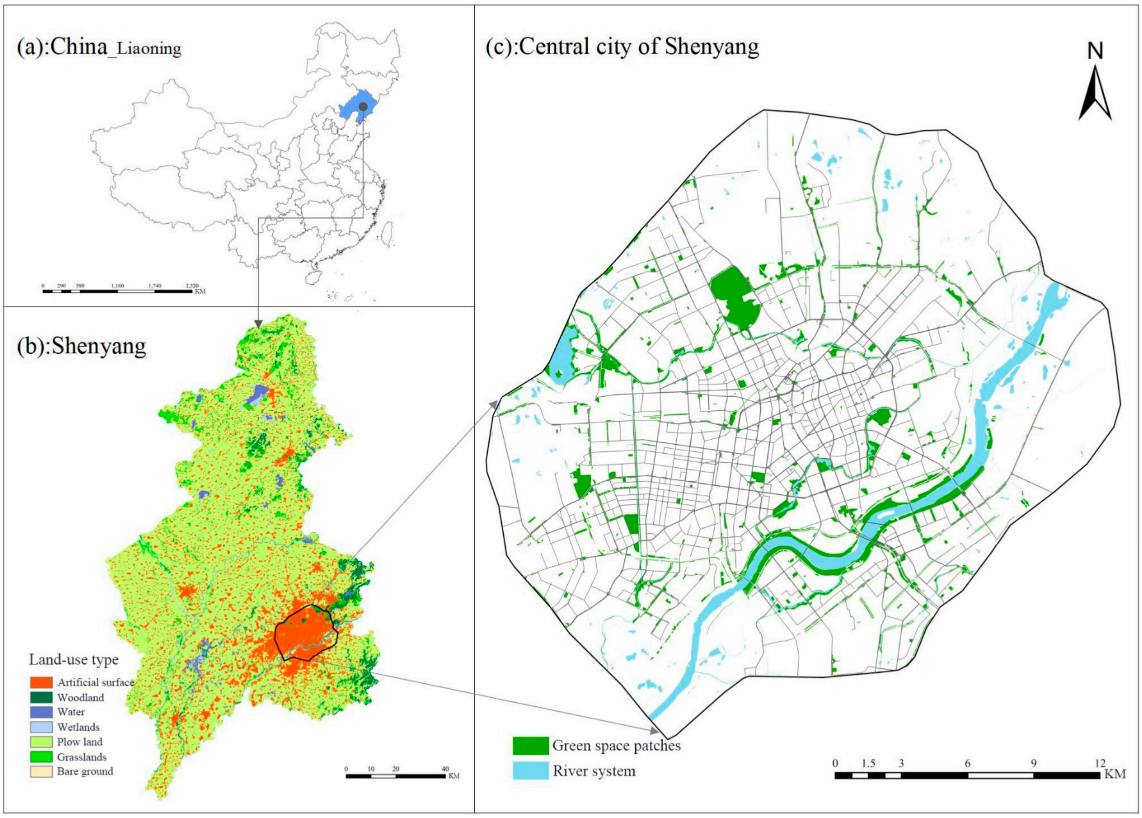

Figure 1. Study area in the central area of Shenyang.

2.2. Data Acquisition and Preprocessing

2.2.1. Population Data

The population data used in this study are derived from static population cross-sectional data, which are corrected and integrated with mobile signaling spatiotemporal data. Initially, the "Regional Land Area and Population Density" data obtained from the 2022 Shenyang Statistical Yearbook are used to validate the WorldPop population distribution data at the administrative-district level. Subsequently, the validated WorldPop data are used as a reference to fill in missing values and correct anomalies in the mobile signal data (MSD) (Figure 2).

The WorldPop population distribution data consist of 100–m grid data representing the spatial distribution of the Chinese population in 2019. The MSD are obtained for representative months (January, April, July, and October) and typical days (6th, 10th, 16th, 21st, and 26th) in 2019. During the period of 1:00–5:00 a.m., using the optimized density based clustering of applications with noise (DBSCAN) method, the MSD captures the population values (POP) for durations exceeding 30 min and their corresponding grid coordinates. The study integrates the corrected population data with the area of interest (AOI) data for each residential community within the streets to characterize the population distribution of each community (Figure 3). Furthermore, based on the age group attributes of the monthly data in the MSD, the study identifies the POP values for the age group of 60 years and above and calculates the proportion of the elderly population in each community, considering the overall population distribution (Figure 4).

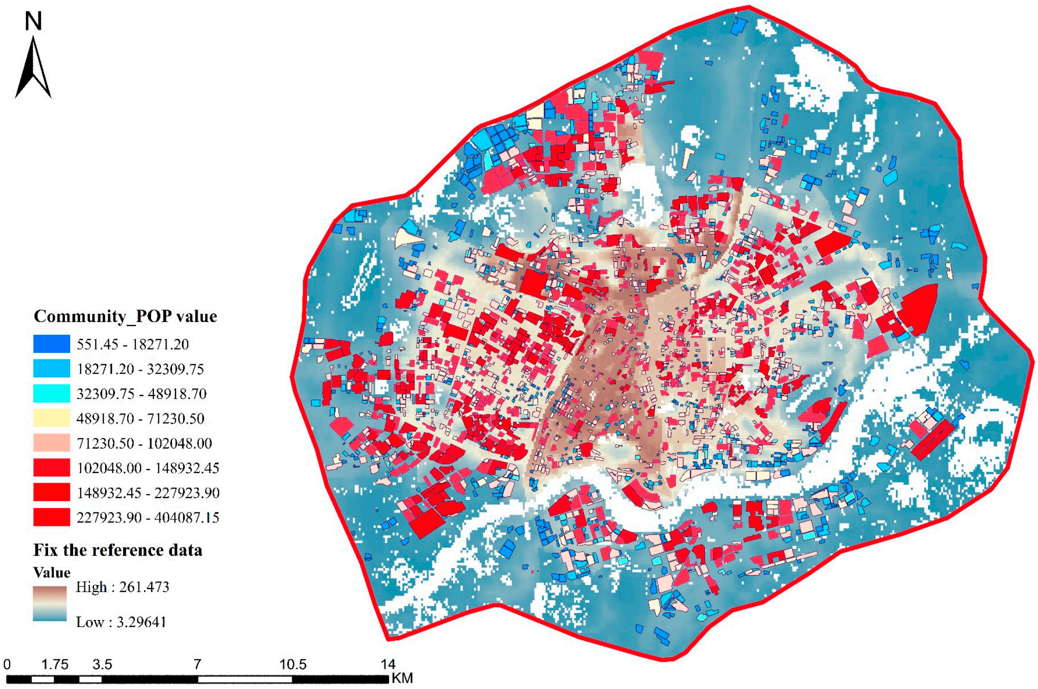

Figure 2. Comparison of 100 m grid space distribution (collated WorldPop data and mobile signal data).

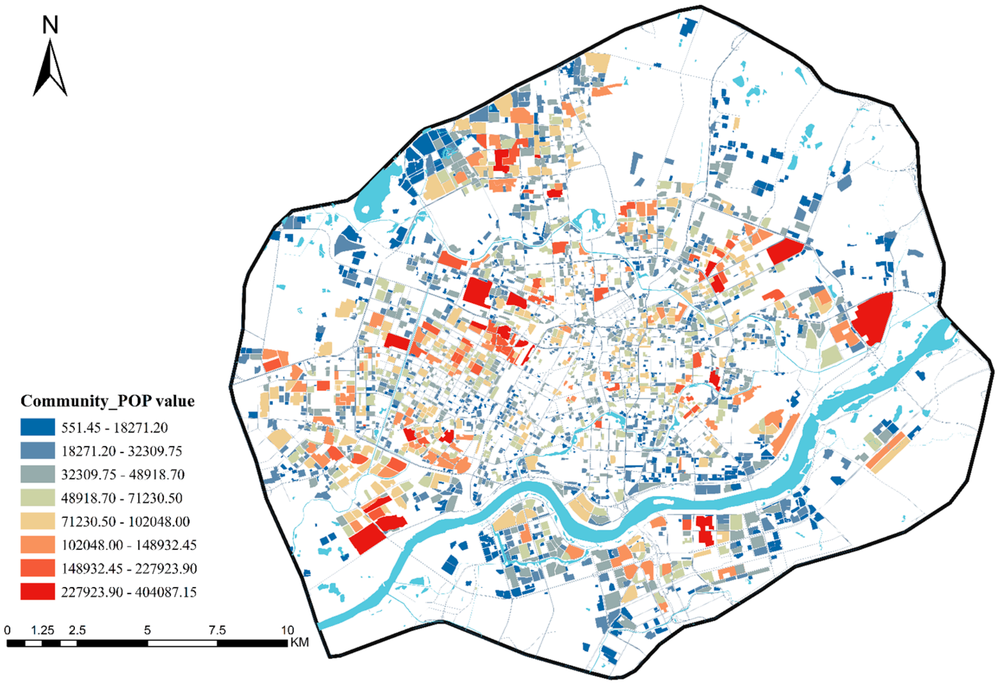

Figure 3. POP values for the total population of each community.

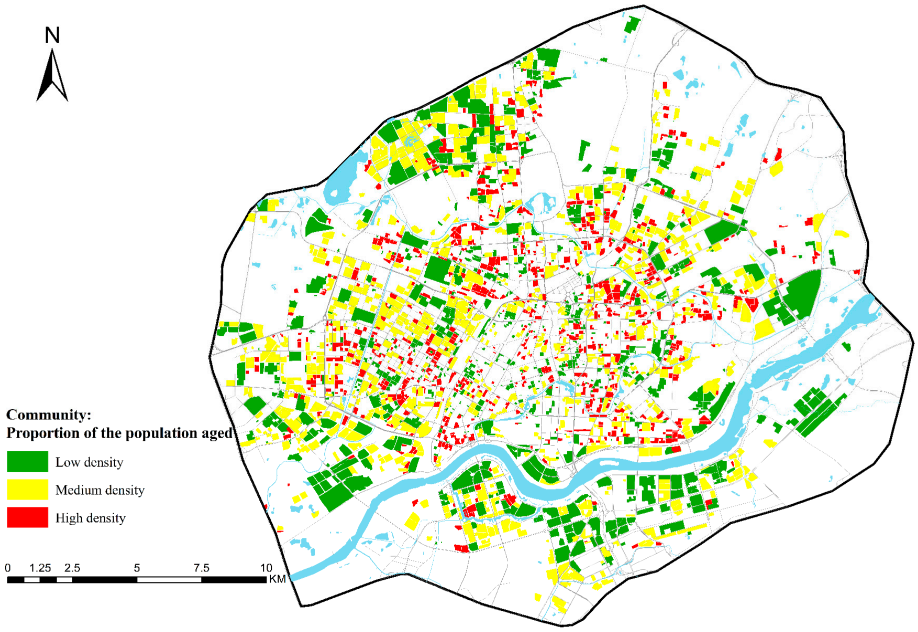

Figure 4. Distribution of the elderly population by community.

2.2.2. Urban Green Space Data

This study refers to the classification and grading standards for urban parks in multiple cities in China, as well as the "Classification Standards for Urban Green Spaces" published by the Ministry of Housing and Urban-Rural Development. It accounts for the specific characteristics of green spaces in Shenyang and their current service capacity. The parks and green spaces within the study area are divided into four levels, namely, Level 1 (city scale), Level 2 (district scale), Level 3 (block scale), and Level 4 (node scale), corresponding to service radii of 5000 m, 2000 m, 1000 m, and 500 m, respectively. The Baidu Maps application programming interface (API) is utilized to obtain the geographic information of communities and park entrances/exits, as well as route planning and distance costs for multiple transportation modes, to construct an origin-destination (OD) cost matrix. By integrating the spatial distribution data of parks at different levels, population distribution data, and transportation cost data and using the GIS spatial analysis method, the deprivation index for green spaces in each street (Figure 5a) and the service range of parks at different levels can be determined (Figure 5b).

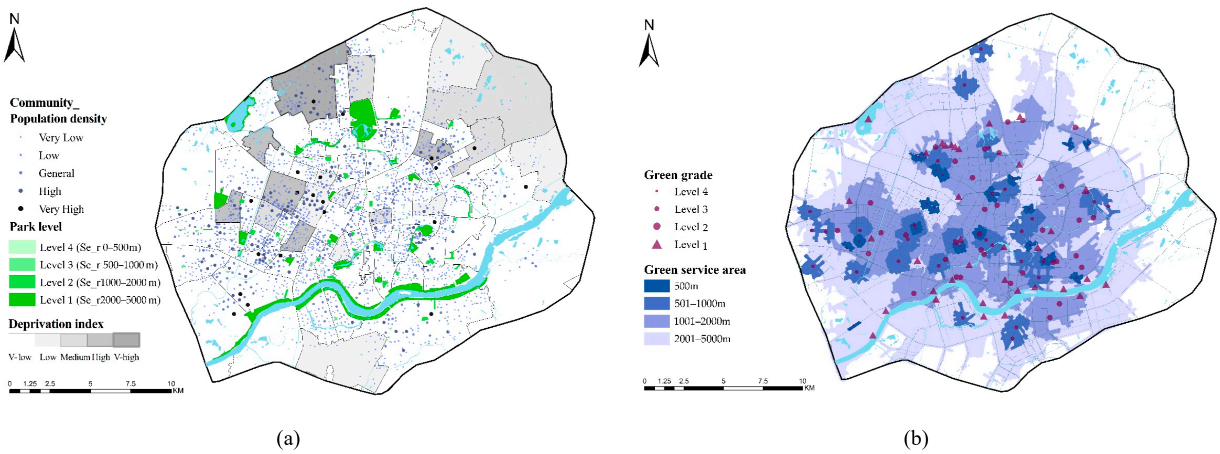

Figure 5. Street green space deprivation index and green space service scope.

2.3. Supply and Demand Evaluation Indicators and Calculation Methods

2.3.1. Selection of Green Space Supply and Demand Indicators

The supply side is evaluated and analyzed in terms of service volume and release degree. The service volume includes the quantity and quality of green space supply. The quantity indicators for green space include the number of parks in each street, park area, per capita green space area, and the proportion of green space. The analysis of green space supply quality is based on the impact of landscape composition unit scale, diversity, heterogeneity, and other factors on the effectiveness of green space ecosystem services. This approach utilizes selected landscape pattern indices from landscape ecology to analyze the morphology and distribution characteristics of green patches. Specific indices include the patch density (PD), the largest patch index (LPI), the landscape shape index (LSI), the landscape division index (DIVISION), the effective mesh size (MESH), the splitting index (SPLIT), and the aggregation index (AI). The release degree of services is represented by spatial resistance, which includes transportation distance costs and the green space service radius.

On the demand side, the demand intensity is represented by the 1:00–5:00 resident population values in each community, which are adjusted based on static population distribution data. This data granularity effectively corresponds to the community scale and improves the accuracy compared to traditional population statistics. The specific supply-demand analysis path is shown in Figure 6.

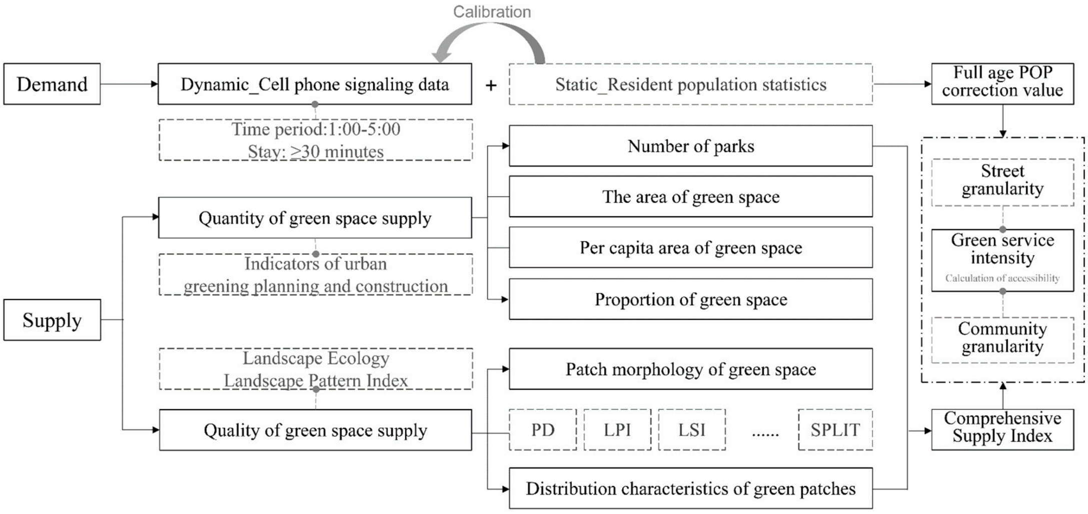

Figure 6. Diagram of green space supply and demand index selection.

2.3.2. Calculation of the Quantity of Green Space Supply

The number of park green space supply analysis indicators, m indicators, and statistical objects are drawn from the streets in the study area, i.e., n objects. The raw data matrix is composed as shown in Equation (1):

$$X = \left\{x_{ij}, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n\right\} \tag{1}$$

The normalized matrix of polar differences after translation is shown in Equation (2):

$$Y = \left\{y_{ij} + 0.001, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n\right\} \tag{2}$$

The entropy value and entropy weight are calculated according to the entropy evaluation method (EEM) based on each quantitative index after normalization of the translation; the specific calculation formulas are shown in Equations (3) and (4):

$$\begin{gathered} H_i = -k\sum_{j=1}^{n} P_{ij}\ln\left(P_{ij}\right) \\ P_{ij} = y_{ij}/\sum_{j=1}^{n} P_{ij} \end{gathered} \tag{3}$$

$$W_i = 1 - H_i/m - \sum H_i \tag{4}$$

In Equation (3), k is a constant, i.e., $k = 1/\ln(n)$. The comprehensive evaluation index of the number of green areas is calculated based on entropy weighting.

2.3.3. Calculation of Green Space Supply Quality

Based on the area of interest (AOI) vector data of green space parks in the research area, rasterization processing is performed. The landscape granularity, which is the pixel size, is set at 10 m, with a minimum patch granularity of 0.01 hectares. The raster elements are reclassified, where green patches are assigned a value of 1, while the rest are assigned a value of 0. The green patches are then segmented based on their respective street affiliations. Fragstats 4.2 software is used to calculate landscape pattern indices for the green patches in each street. The positive indices include the aggregation index (AI), the largest patch index (LPI), and the effective mesh size (MESH), while the negative intervention indices include the patch density (PD), the landscape shape index (LSI), the landscape division index (DIVISION), and the splitting index (SPLIT). All indices are standardized, and a comprehensive indicator of green space supply quality is obtained through principal component analysis.

2.3.4. Calculation of Green Space Supply and Demand

Using the results of population data, the Ga2SFCA model is applied to calculate the supply-demand ratio and obtain the potential green space per capita value. The community accessibility value calculation is performed within the multilevel search. The first step calculates the supply-demand ratio using Equation (5):

$$R_j = \frac{S_j}{\sum_{i\in\{d_{ij}\le d_0\}}^{k} P_i G\left(d_{ij}\right)} \tag{5}$$

where i is the demand point, i.e., community; S_j is the supply point service volume, i.e., the comprehensive green space supply index (green space quantity index and green space quality index); Pi is the demand of a single demand point i in k partitions, i.e., the community population; d_{ij} is the travel distance between i and j, i.e., the multimodal arrival distance cost obtained by the API; d0 is the travel distance threshold, i.e., the corresponding green space of different levels of park service radius; and k is the number of communities within the travel distance threshold.

G(dij) is the distance decay function considering the spatial friction factor and is defined as shown in Equation (6):

$$G\left(d_{ij}\right) = \begin{cases} e^{-(d_{ij})^{2/k}, d_{ij}\le d_0} \\ 0, d_{ij} > d_0 \end{cases} \tag{6}$$

In the second step, the accessibility is calculated as shown in Equation (7):

$$A_i = \sum_{j\in\{d_{ij}\le d_0\}} \frac{S_j\left(d_{ij}\right)}{\sum_{k\in\{d_{kj}\le d_0\}} P_k G\left(d_{kj}\right)} \tag{7}$$

The accessible value of each community is calculated; thus, the proportion of the composite index of supply and demand for each street is evaluated. The supply and demand composite index is the sum of the green accessibility indices of each community in the street. The Gini coefficient of the study area is calculated by combining the population share of each street using the following equation:

$$\mathrm{Gini_i} = 1 - \sum\nolimits_{k=1}^{n} (P_{ik} - P_{ik-1})(P_{ik} + P_{ik-1}) \tag{8}$$

The streets in study area i were ranked from lowest to highest by the combined green space supply and demand index, where P_{ik} is the cumulative percentage of population from street 1 to street k in study area i, and R_{ik} is the cumulative percentage of green space accessibility from street 1 to street k in study area i. The smaller the Gini coefficient is, the more balanced the supply and demand of green space is among residents; i.e., there is a higher social equity of green space. In this study, the Gini coefficient of 0.4 is used as the critical value of equity level for the assessment of street green space equity in the study area.

Afterwards, the entropy calculation of each street district is carried out based on the comprehensive index of supply and demand, as shown in Equation (9):

$$Q_{ij} = (G_{ij}/G_j)/(G_j/G) \tag{9}$$

where Q_{ij} is the entropy of the green space supply and demand location of street I in administrative district j, G_{ij} is the green accessibility index of street i in administrative district j, G_j is the summary of the green accessibility index of administrative district j, and G is the summary of the green accessibility index of all administrative districts. Streets with location entropy values >1 are set as supply and demand balance areas, streets with location entropy values in the range of 0.3–1 are set as supply and demand imbalance areas, and streets with location entropy values in the range of 0–0.3 are set as supply and demand serious imbalance areas.

2.4. Supply Priority Establishment Method

Based on the experimental results from the previous step, priority analysis is conducted based on the street-community pairs that exhibit a severe imbalance in the supply-demand relationship of green space. Within this set of pairs, the green accessibility index of each community serves as a reference indicator for supply at this stage, while the proportion of the population aged 60 and above in each community serves as a reference indicator for demand. The analysis pathway is depicted in Figure 7.

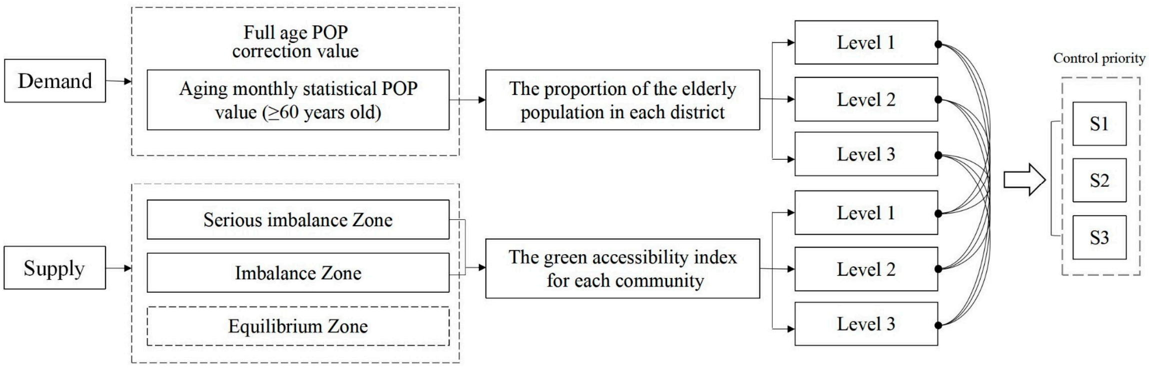

Figure 7. Analysis path diagram of the priority of green space allocation and regulation in each community.

Based on the comprehensive supply level of each street (excluding balanced areas) and the proportion of the elderly population data, the "important-urgent" priority is determined using the Eisenhower matrix. The X-axis represents the green space accessibility indicators in severely imbalanced and imbalanced street-community pairs, while the Y-axis represents the proportion of the elderly population in each community. The accessibility indicators and elderly population proportion data are standardized, and outliers are removed. Using the natural break method, a 1–3 scale is established to identify the priority levels as follows: accessibility indicators and elderly population proportions at Level 3 are classified as Priority Level 1 (S1), indicating an important and urgent priority; accessibility indicators and elderly population proportions at Level 2 or 3 are classified as Priority Level 2 (S2), indicating a relatively important or relatively urgent priority; and accessibility indicators and elderly population proportions at Level 1 or 2 are classified as Priority Level 3 (S3), indicating a relatively less important or relatively less urgent priority. The accessible value is represented by a, and the elderly population proportion is represented by b. The priority classification criteria are shown in Equation (10):

$$\begin{cases} S_1 = [a = 3, b = 3] \\ S_2 = [a = 3, b = 2; a = 2, b = 3; a = 2, b = 2] \\ S_3 = [a = 1, b = 1; a = 1, b = 2; a = 2, b = 1] \end{cases} \tag{10}$$

3. Results

3.1. Comprehensive Supply Analysis of Green Space

3.1.1. Analysis of the Quantity of Green Space Supply

Applying the entropy weight method, calculations are performed for both entropy value H_i and entropy weight W_i of the green space quantity-related indicators across the 91 streets within the study area. The constant "k" is assigned a value of −0.2219. Among these, Indicator 1 pertains to the number of parks; Indicator 2 pertains to the area of park green space; Indicator 3 pertains to the area of green space per capita; and Indicator 4 pertains to the proportion of green space. A partial summary of the comprehensive indicators representing the green space quantity for each street is presented in Table 2.

Table 2. The entropy value H_i, entropy weight W_i, and composite indicator of green space quantity.

Street Name	H_1	H_2	H_3	H_4	W_1	W_2	W_3	W_4	Index
Lingxi	0.0267	0.0561	0.0385	0.0515	1.0273	1.0591	1.0396	1.0540	2.7640
Zaohua	0.0119	0.0520	0.0777	0.0385	1.0119	1.0545	1.0837	1.0399	2.5981
Nanyanghu	0.0161	0.0193	0.0214	0.0080	1.0163	1.0194	1.0214	1.0078	0.6970
Changbai	0.0069	0.0183	0.0198	0.0161	1.0068	1.0183	1.0197	1.0161	0.5215
Yuhong	0.0069	0.0018	0.0020	0.0007	1.0068	1.0015	1.0015	1.0005	0.1430

There are significant variations in the distribution of park quantity among the streets (Figure 8a). Using the natural break point classification method, the supply level is divided into five grades, with an average value of 0.4486. A considerable number of streets exhibit a moderate to low level of park supply (15% moderate, 35% low, and 41% very low), while fewer streets demonstrate a high level of park supply (0.3% very high, 0.5% high). This indicates that the overall park supply quantity in the central urban area is relatively low. However, some streets with large comprehensive parks and a moderate population distribution show a coordinated or surplus supply. For instance, North Tomb Park is located on Liaohe Street, and Lilac Lake Park is situated on Zaohe Street. Additionally, the streets of Wusi, Nanhu, Nanta, and Fengle are traversed by belt-shaped parks along the Hun River. Moreover, these streets have a moderate to low population density, resulting in a relatively good level of park supply.

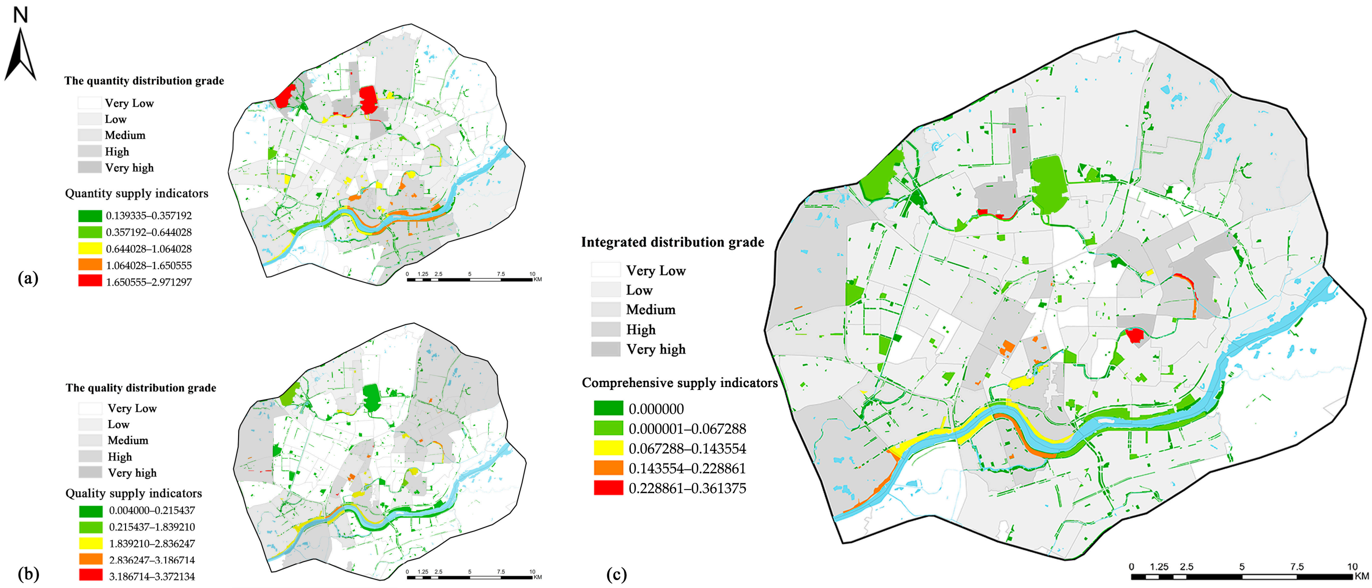

Figure 8. Spatial distribution of green space supply index by street.

3.1.2. Green Space Supply Quality Analysis

Based on the seven landscape pattern index indicators described above and the results of the calculations conducted in Fragstats software, the collection results are standardized for negative and positive indicators. The following table shows the collection results of some of the street indicators (Table 3).

Table 3. Standardized treatment of the landscape pattern index of certain street parks.

Street Name	Standardization_Positive Indicators			Standardization_Negative Indicators			
	LPI	MESH	AI	PD	LSI	DIVISION	SPLIT
Lingxi	0.9009	0.3889	0.0187	0.0072	0.4608	0.8671	0.9317
Zaohua	0.2557	0.3584	0.0167	0.0009	0.4284	0.2503	0.4113
Nanyanghu	0.7971	0.9781	0.0106	0.0009	0.6309	0.7363	0.8539
Changbai	0.7872	0.3633	0.0160	0.0024	0.6355	0.7296	0.8495
Yuhong	0.9836	1.0000	0.0028	0.0007	0.8656	0.9776	0.9892

Descriptive statistics are performed on the factor analysis, and the Kaiser-Meyer-Olkin (KMO) and Bartlett's sphericity tests are used to assess the correlation matrix. The component matrix, coefficient matrix, and explained total variance are obtained through computation (Tables 4–6). Two principal components, namely, C1 and C2, are extracted with corresponding weights of 3.304 and 2.376, respectively. The component indicators and their respective coefficient values are used to calculate the park supply quality indicators for each street. Using the natural break point classification method, the supply level is divided into five grades, with an average value of 1.0393. The proportion of streets with a low level of park supply quality is 58%, while those with a relatively high level of park supply quality account for 31%, indicating a certain level of representativeness. However, there is a scarcity of streets with an extremely high or moderate-level supply, resulting in a fragmented distribution pattern overall (Figure 8b).

Table 4. Component matrix.

Standardization	Component 1	Component 2
PD	0.058	0.975
LPI	0.987	0.097
LSI	0.631	−0.558
DIVISION	0.987	0.103
MESH	0.019	−0.353
SPLIT	0.977	0.086
AI	0.021	0.981

Note: The extraction method is principal component analysis.

Table 5. Component score coefficient matrix.

Standardization	Component 1	Component 2
PD	0.018	0.41
LPI	0.299	0.041
LSI	0.191	−0.235
DIVISION	0.299	0.043
MESH	0.006	−0.149
SPLIT	0.296	0.036
AI	0.006	0.413

Table 6. Total variance explained.

Component	Initial Eigenvalue			Extraction of the Sum of Squares of Loads		
	Total	Variance %	Accumulation %	Total	Variance %	Accumulation %
1	3.304	47.197	47.197	3.304	47.197	47.197
2	2.376	33.941	81.138	2.376	33.941	81.138
3	0.935	13.357	94.495			
4	0.359	5.123	99.618			
5	0.025	0.353	99.97			
6	0.002	0.023	99.993			
7	0	0.007	100			

By integrating the park quantity supply indicators and park quality supply indicators, the comprehensive park supply indicators for each street in the central urban area of Shenyang are obtained. There are 25 streets with an extremely low comprehensive park supply, 44 streets with a low park supply, eight streets with a moderate park supply, 11 streets with a high park supply, and three streets with an extremely high park supply (Figure 8c). The overall park supply level is relatively low. The streets with a high park supply are predominantly located along rivers, including the Hun River, Nanyun River, and Xinkai River.

3.2. Green Space Supply and Demand Analysis

First, the green space service population-to-supply ratio is calculated based on the Ga2SFCA model. Accounting for the different levels of green space service capacity, the multilevel service range of green space is determined through service area analysis. This approach provides the comprehensive supply index for each green space, represented as Sj. By combining the obtained distance cost matrix, the population within the service area of each community is calculated to complete the ratio calculation.

On this basis, multilevel reachable ranges are set for the communities, and decay coefficients for parks at distances of 500 m, 1000 m, 2000 m, and 5000 m are calculated. Each decay coefficient corresponding to a service level outside the reachable range is gradually eliminated. Finally, the green accessibility index for each community is obtained in ArcGIS (Figure 9).

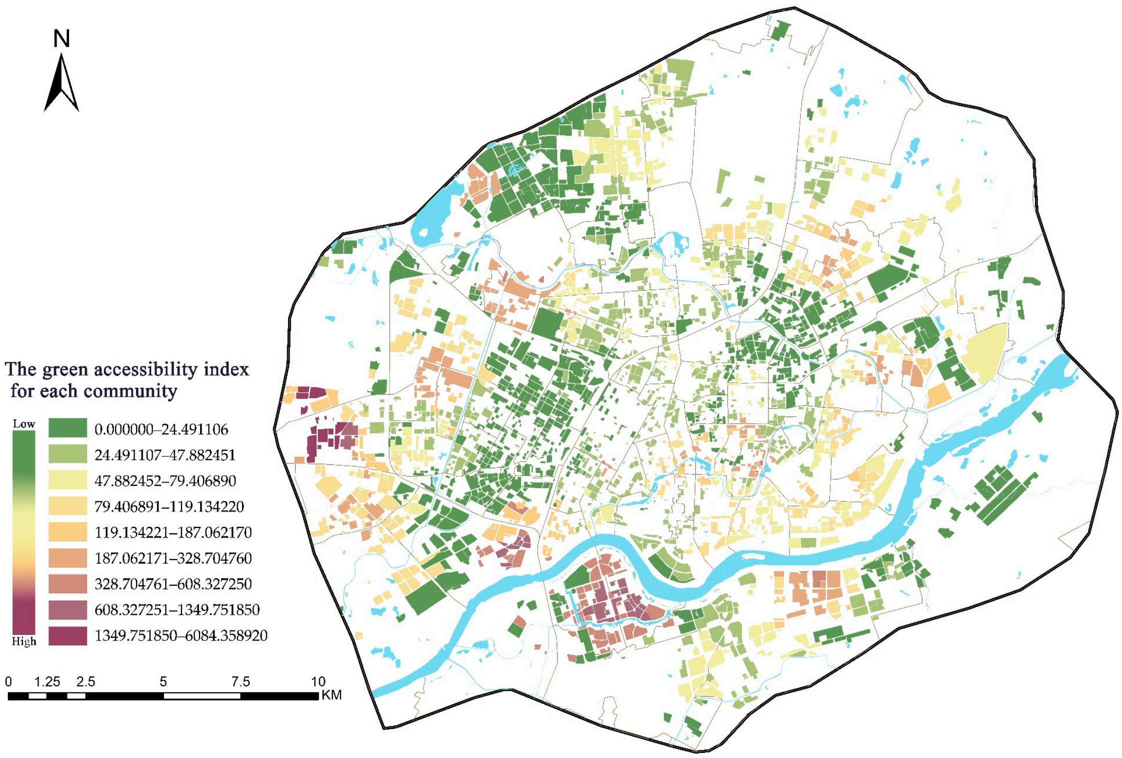

Figure 9. Community accessible green space distribution.

The Gini coefficient for the study area is calculated based on the comprehensive supply index of the streets, resulting in a coefficient of approximately 0.58 (Figure 10). Based on this, the overall administrative district reachable levels are determined according to the average green accessibility index of the streets. The locational entropy within each administrative district is calculated (Figure 11), and the distribution of locational entropy values for the streets is analyzed. Balanced area streets account for 21.98% of the total streets, while imbalanced area streets account for 26.37%, and severely imbalanced area streets account for 51.65%.

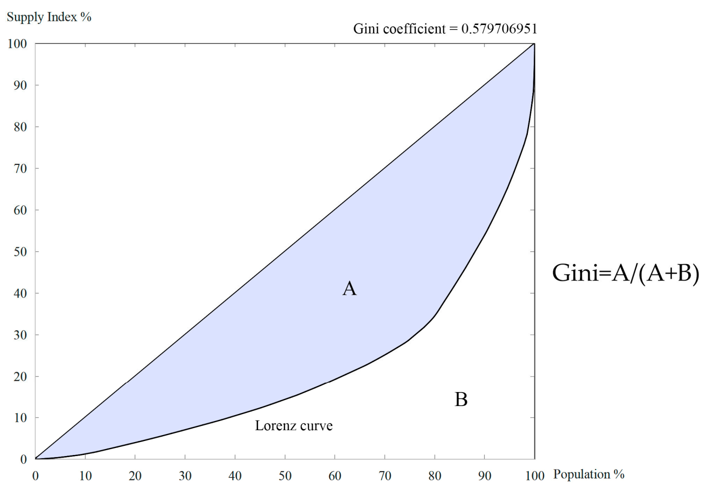

Figure 10. Gini coefficient of street green space supply and Loren meter curve distribution.

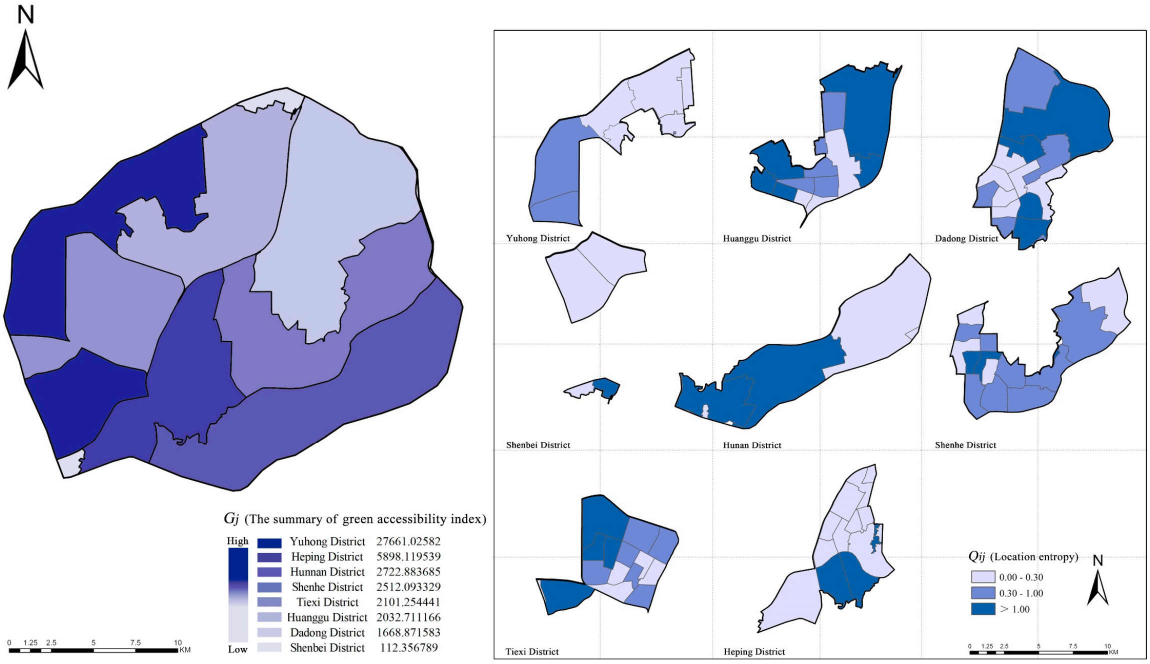

Figure 11. Street green space supply-level analysis.

3.3. Community Supply Priority Analysis

The communities within the streets classified as imbalanced and severely imbalanced are divided into three intervals based on their green accessibility index, following the green accessibility index classification criteria shown in Figure 8. Each interval represents three levels. Furthermore, utilizing statistical data on the proportion of the elderly population in each community, the communities are categorized into three ageing levels using the natural break method. The three supply levels correspond to the three ageing levels. The prioritization of interventions in the four quadrants is determined based on the methods described earlier (Figure 12), and the spatial distribution of each priority level is obtained based on the spatial coordinates of the communities in ArcGIS (Figure 13). Among them, S1 priority level communities account for 7.45%, S2 priority level communities account for 60.86%, and S3 priority level communities account for 31.69%. Notably, S1 priority level communities are mainly concentrated in XinHua Street, Lingxi Street, Dongta Street, and Nanshichang Street.

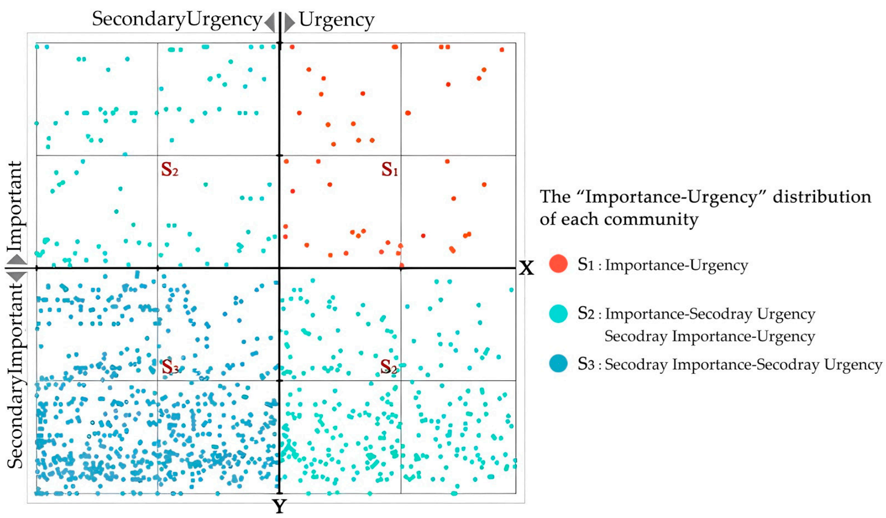

Figure 12. Supply priority four-quadrant scatter plot.

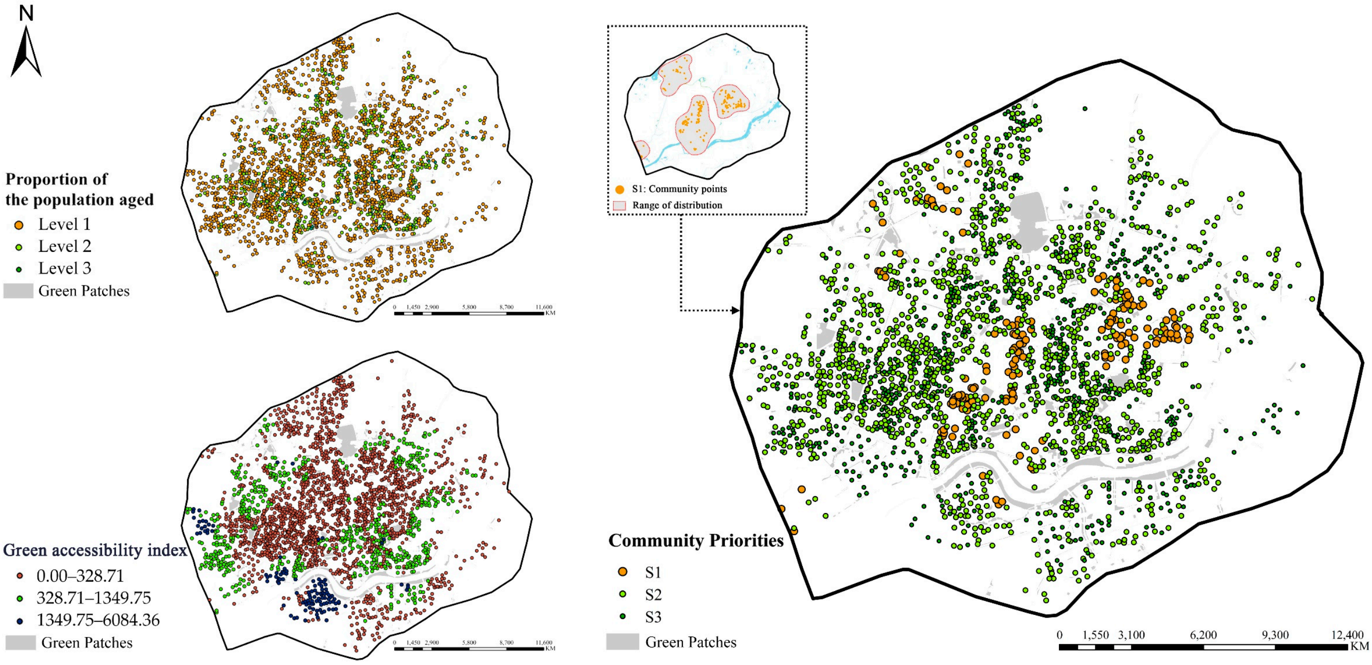

Figure 13. Spatial distribution of priorities by community.

4. Discussion

4.1. Presentation of Findings

There are more studies on the evaluation of supply and demand of urban green space, and the selection of evaluation indexes tends to be diversified, but the discussion of green space supply is relatively rare. Population data tends to be static statistics, and such data are weak in terms of timeliness; it is not easy to extract the proportion of the distribution of the ageing population, which is important to better conduct research related to the distribution of green space resources in an ageing city.

This study sought a more scientific and easier to quantitatively analyze method that not only provides a means of balance in green space supply for underserved areas, but also prioritizes the allocation of resources for the elderly population. This approach aims to establish a hierarchical framework for regulation, thus furnishing the central urban area with innovative strategies for the development and allocation of green resources.

The results of this study showed that the overall accessibility of green spaces in the communities located within the Third Ring Road of Shenyang is relatively low, and the accessibility within the Second Ring Road is generally lower than that between the Second and Third Ring Roads. At the administrative district level, there is a considerable disparity in the level of green space supply, with a trend of fewer park supplies in the north and east and greater park supplies in the south and west. Specifically, the green space supply-demand relationships in Shenbei District, Dadong District, and Huanggu District are severely imbalanced and require urgent planning and adjustment.

At the street level, the spatial distribution of severely imbalanced supply-demand areas exhibits a pattern of central aggregation and peripheral diffusion, indicating the poor equalization of green space resources within the First Ring Road and along the boundary of the Third Ring Road. In some communities located within the First Ring Road, there is a severe lack of green spaces within a 500–1000 m service radius, highlighting the need to supplement micro green spaces to achieve a balance in green space supply and demand at the micro scale. The imbalanced areas are mainly distributed between the Second and Third Ring Roads, and the green space supply-demand relationship is more complex along the boundary of the Third Ring Road.

At the community level, the overall level of green space supply-demand matching is relatively low. The accessibility of green spaces in communities shows a certain distribution pattern along the city's water systems. Communities located along the Hun River and the Nan Yunhe River generally exhibit a moderate to high level of green space accessibility, while communities located along the Xin Kai River show an intermittent distribution of high and low green space accessibility. The green space accessibility is lower along the First and Third Ring Road sections, while it is generally higher between the Second and Third Ring Roads. Communities located along the Weigong Mingqu River show a distribution pattern of higher accessibility in the west and lower accessibility in the east. This finding has some guidance implications for the optimization of green spaces in waterfront areas. The central area located along the Xin Kai River and the boundary area located along the Third Ring Road require renovation and improvement to enhance the quality of green space supply. On the eastern bank of the Weigong Mingqu River, efforts should be made to strengthen green space ecological restoration projects and the development of waterfront parks.

In the prioritization analysis results, there are a total of 103 communities in the S1 category, which are characterized by their urgent demand. In urban revitalization efforts, these communities should be precisely targeted to enhance the overall supply-demand homogeneity at a relatively lower cost while significantly improving the needs of the elderly population. Subsequent green space redevelopment initiatives aimed at creating age-friendly cities can be carried out in stages based on the priority of community transformation. This includes identifying suitable locations for green space expansion, the ecological restoration of existing green areas, and enhancing the vibrancy of parks, among other revitalization efforts.

4.2. Comparative Analysis of Methods

In the determination of supply-demand ratios in related studies, the service volume of supply points is often quantified through area-based statistics [44,45]. However, such an approach fails to adequately reflect the actual perception of urban residents regarding the accessibility of green spaces and overlooks the variations in ecological service benefits provided by the green spaces themselves. This study intended to incorporate both the quantity and quality indicators of green space supply to derive a comprehensive supply indicator that could replace the traditional reliance on green space area in characterizing the service volume of supply points.

In traditional evaluations of urban green space resources, street- or community-level statistical data obtained from population censuses are used as a basis for identifying the spatial distribution characteristics of the total population and various age groups [46,47]. However, there is a timeliness issue associated with this approach. Most countries conduct population censuses every ten years, and while population growth estimates can be used to approximate annual changes, the local-level accuracy is insufficient to support the spatial analysis of specific areas within cities. In this study, the population data are derived from dynamic spatiotemporal distribution data obtained by calibrating static statistical data, thus achieving a comprehensive population distribution that combines static and dynamic elements. This approach aims to better address supply-demand issues at the community scale within high-density areas of the urban population.

5. Conclusions

This study conducted an analysis of the green space supply-demand relationship in the central urban area located within the Third Ring Road of Shenyang using the Gaussian two-step floating catchment area (Ga2SFCA) method. Compared to traditional approaches, this study made improvements in data collection and analysis methods on the demand side by utilizing "dynamic-static" spatiotemporal population data. Additionally, the representation of supply point service volume was enhanced by proposing a comprehensive supply index.

The analysis of the results encompassed a comprehensive evaluation across various strata: administrative district, street, and community levels. The overarching goal was to pinpoint regions beset by acute supply-demand dissonance and establish equilibrium within each tier. Furthermore, an in-depth exploration was conducted into the intrinsic mechanisms underpinning the supply-demand disparity within each echelon. Identifying unfavorable factors in resource distribution was achievable through a meticulous examination of substantial disparities in green space supply and demand across various scales. This study can be used for the development of a comprehensive strategy that draws upon multiple intervention points and diverse resource origins.

Moreover, the multidimensional evaluation of green space supply and demand can be synergistically integrated with research centered on the impacts of diverse urban ecological services. This encompasses a range of investigations, such as the multitier modeling and appraisal of urban thermal and wind environments. By harmonizing the alignment between ecological and social service provision across multiple scales, integrating distinct ecological service indicators within a meaningful "ecological-social" dual-tier synthesis, delimited within an appropriate research scope, can be achieved.

Addressing the prerequisites for an age-friendly urban environment demands strategic adaptations. At the street level, regions that have attained equilibrium were excluded from the dataset, with the remaining street-level data pertaining to community accessibility values integrated with the percentage of elderly residents. This fusion determined the priority for supply optimization. In the zones earmarked for optimization, both green space accessibility and the distribution patterns of the elderly population were taken into account. This culminated in the formulation of a meticulously sequenced green space replenishment strategy within the optimization domain. Such an approach provides a more empirically grounded foundation for municipal authorities engaged in green space development and enhancement initiatives.

In future research, further optimization of green space quality indicators can be explored, accounting for the dimensions of social service benefits. Building upon the identification of supply priorities, intelligent algorithms can be utilized to determine specific locations for green space expansion and the form of green space boundaries, thereby providing more precise recommendations for the update and construction process.

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