Heliyon 9 (2023) e21671

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Constructing a multi-functional small urban green space network for green space equity in urban built-up areas: A case study of Harbin, China

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ARTICLE INFO

Keywords:
Green space equity
Ecosystem services
Urban green planning
Green infrastructure
Environmental justice

ABSTRACT

Ensuring equitable access to green spaces in urban built-up areas is not only vital for fostering environmental justice but also aligns with the United Nations Sustainable Development Goals (SDGs). However, there is a noticeable gap in the current body of research regarding the role of small urban green spaces, especially their multifunctionality from an ecosystem services perspective. Taking the urban built-up area of Harbin as an example, this study first applied the Analytic Hierarchy Process to classify the supply and demand of green space into three types. Then, the article further analyzes the potential functional positioning of the newly added green spaces, including ecological and social functions, using Minimum Cumulative Resistance and Point of Interest. Finally, multi-criteria decision models are used to explore the priority and functional positioning of green space and construct a multi-functional and highly-efficient small urban green space network. The results indicate a significant imbalance in green space supply and demand, with severe and medium mismatch areas accounting for 30.17 % and 48.50 %, respectively. By assessing the multifunctionality of small green spaces, we propose guidelines that include five types of areas: Concentrated Development (85.85 km^2, 16.94 %), Backup Development (70.74 km^2, 14.31 %), Maintenance (304.49 km^2, 61.51 %), Protection (14.94 km^2, 3.02 %), and Optimization (20.89 km^2, 4.22 %). Finally, the article proposes a 277.60 km multi-functional small urban green space network. By examining small urban green spaces, this study crafts a pivotal framework for enhancing green space equity in urban built-up environments, providing valuable insights for policymakers and urban planners. The approach has significant implications for developing multifunctional green networks in varied urban contexts and offers a model for wider application, serving as a reference for achieving green space equity in developing countries globally.

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https://doi.org/10.1016/j.heliyon.2023.e21671
Received 22 May 2023; Received in revised form 16 October 2023; Accepted 25 October 2023
Available online 28 October 2023

1. Introduction

The rapid urbanization process has led to the disordered growth and expansion of buildings within cities [1]. Urban built-up areas, as the population concentration zones, face an imbalance in resource supply and demand, and a decline in the residential quality of the living environment [2]. In 2015, the United Nations proposed Sustainable Development Goals (SDGs) for 2030, emphasizing the balanced and coordinated development of economic, environmental, and social goals [3], and the provision of short-term benefits to residents while protecting long-term interests [4]. Due to the limited availability of land in urban built-up areas, small urban green spaces enable addressing the shortage of green space resources in densely built areas [5]. Through the synergetic effect on existing green spaces, small urban green spaces contribute to urban sustainable development, including protecting the ecological environment and providing spaces for residents' leisure activities [6]. Previous studies on urban small green spaces have mainly started from a single functional perspective, such as alleviating the urban heat island effect [7], or providing a place to respondents for the scarce land resources [8]. As the land area gradually reduces, improving land use efficiency is becoming increasingly critical [9]. Green space with a single function cannot meet the multi-functional needs of residents. Therefore, comprehensively analyzing the small green space system from multiple perspectives of ecological and socio-cultural functions has become an urgent issue to address.

Environmental justice is a decisive factor in achieving sustainable development [10]. As an essential part of environmental justice, green space equity has recently become a research focus. Related studies have studied the environmental justice of underrepresented groups considering race, gender, and education level [11–13]. Current research mainly analyzes green space equity in quantities. For example, Tang Yuhan et al. used the spatial distribution of the population and spatial reachability to analyze the equitable allocation of green space [14]. Xu Xin et al. evaluated the spatial equity of green spaces from three dimensions: quantity, quality, and accessibility [15]. Little research considered green space equity from the ecosystem services and functions perspective. Therefore, it needs to propose green space layout and optimization strategies based on the urgency of green space construction and the importance of ecosystem service functions. Furthermore, small urban green space has the characteristics of a small area and flexible layout, which is suitable for built-up urban areas. However, previous studies on green space equity did not consider the role of small urban green spaces within built-up areas.

The green space network is an important spatial component for balancing cities' natural and social attributes and addressing the contradictions between the environment and urban development [16]. Previous studies on green-space networks mainly focused on building corridors and matrices for biodiversity conservation, while there is less attention on patches, especially considering the multifunctionality of green spaces. For example, the extraction of habitats and corridors used the least-cost path for species migration [17]; the study extracted ecological networks based on habitat suitability [18]; and constructed green networks based on existing ecological resources [19]. As an important part of the urban green space system, previous studies rarely presented a scientific approach to building a small urban green space network [20]. The small urban green space network in this study refers to connecting small urban green spaces along pedestrian spaces to construct green space corridors, making them part of the urban green-space networks [21]. A green space network comprises corridors and patches and connects scattered habitats, providing connectivity throughout the landscape. To develop harmoniously with nature, considering small urban green spaces in green spaces and constructing urban built-up area green-space networks has become an urgent issue to address.

In this article, urban small green spaces refer to public urban green spaces with an area of fewer than 1 ha. This paper takes the built-up area of Harbin as an example and aims to construct a small green space network with multiple functions for green space equity. The study aims to address the following research questions: 1. What is the current supply-demand situation of green spaces in the built-up area? 2. What is the potential functional positioning of the newly added green spaces? 3. What can achieve a balance between green-space supply and demand to ensure environmental equity? By focusing on small urban green spaces, this study develops a foundational framework for enhancing green space equity in urban built-up environments, thereby offering invaluable insights for policymakers and urban planners. This methodology has far-reaching implications for the creation of multifunctional green networks across diverse urban landscapes and presents a versatile model for broader application. It stands as a valuable reference for attaining green space equity in developing nations worldwide, contributing significantly to the global discourse on urban green space development and equity.

2. Literature review

2.1. Chronological evolution of green space multifunctionality for environmental equity

The evolution of green space equity has witnessed a multifaceted development since Mcallister's foundational work in 1976, which introduced equity and efficiency principles to urban public facility siting [22]. The progression of green space equity research has undergone several distinctive stages. Initially, during the Quantitative Equity Stage, the emphasis was on government-led construction of urban green spaces, focusing on achieving equal per capita green space. Subsequently, the field evolved into the Spatial Equity Stage, where the goal shifted towards achieving a spatial balance in green space resources, ensuring equal access to ecosystem services and improving residents' well-being [23]. Recently, the focus has shifted to the User Group Equity of green space Phase, which hones in on addressing the specific and varied needs of diverse social demographics, with a particular emphasis on catering to disadvantaged groups [24,25]. Additionally, the Green Space Efficiency Equity stage is also a rising research focus [26,27]. This stage centers around community-level interventions, aiming to provide a spectrum of ecosystem services with the ultimate goal of amplifying the efficiency of ecological resource services. The journey of this research evolution encapsulates transitions from quantitative and spatial equity, moving towards group equity, and subsequently to equity in the utilization of green space. Each transition signifies a shift in focus—from ensuring equal green space per capita, to maintaining spatial balance, addressing the diverse needs of varied social groups, and finally, to enhancing the efficiency of ecological services. However, the current landscape of research predominantly concentrates on aspects of quantity and spatial equity. A minority of studies have begun exploring environmental equity under the social and economic conditions in developed countries, particularly focusing on racial disparities. Nevertheless, research addressing efficiency equity remains notably scarce and underexplored.

Recently, there has been a gradual increase in quantitative research focusing on the spatial equity of green spaces. Traditional methods, such as interviews and questionnaires, are employed to investigate park stakeholders and analyze the equity of existing green spaces. However, these methods are high in cost and challenging to scale up for broader research on the fairness of green spaces. Subsequently, there has been a rising interest in analyzing green space equity based on supply and demand using GIS. Scholars choose different indicators and weights of the influence of green space supply and urban demand according to the research object [23,24]. Therefore, the indicator system has not formed a unified standard. The two step Gaussian mixture model (2FSCA) proposes the concept of "spatial thresholds" based on the traditional green space accessibility analysis, and measures accessibility by accumulating the opportunity value of green space resources in each space [28]. Dony, C. et al. Proposed A Variable-width Floating Catchment Area (VFCA) method to avoid errors in the results when the study distance thresholds were determined manually [29]. The method only considers the straight distance between the green space and the residents it serves when analyzing the spatial accessibility of the green space within the buffer zone but does not take into account the road network and land use in the study area, resulting in inaccurate findings. User research is widely used in various fields and is a research method with the ability to analyze the fairness of green spaces based on user perceptio [30]. User interviews and questionnaires are used to research park stakeholders and analyze the equity of existing green spaces. However, the lack of range of responses to their question answers makes the imprecise responses of the research participants and obtaining imprecise research results. Despite the surge in studies exploring the multifunctionality of green spaces, a research gap persists in establishing a definitive methodology for developing green space networks in densely built-up urban areas.

In recent times, a discernible shift has been noted from focusing primarily on large urban green spaces to acknowledging the importance of smaller ones. Traditionally, urban green space research and planning have predominantly centered around larger parks and green areas. However, the constraints and unique challenges posed by densely built-up urban regions often make the development of such expansive green zones impractical. As a result, small urban green spaces have emerged as essential elements in the urban green ecosystem, gaining increasing attention and recognition. Despite their limited size, these spaces offer a myriad of benefits: they necessitate less area, provide flexible layout options, and can fulfill diverse functions, thereby playing a pivotal role in enhancing the environmental quality of urban built-up areas [31,32]. The field has witnessed a surge in the study of the spatial layout of these urban green spaces. Researchers have been incorporating graph theory into landscape ecology [33], conceptualizing ecological source sites as nodes and the connecting trajectories as pathways for species or energy migration, thereby forming a theoretical green space network. This approach facilitates quantitative analysis aimed at optimizing the network. Advanced methodologies, such as GIS, have significantly enriched this area of study. The Minimum Cumulative Resistance (MCR) model, based on GIS, forms ecological networks by identifying the least resistance paths species use to migrate between ecological source sites, aiding in the creation of urban green space networks [34]. Another innovative approach is the Spatial Planning for Multifunctional Green Infrastructure (GISP), a GIS-based multi-criteria strategy that integrates six essential ecosystem services: stormwater management, social vulnerability assessment, green space distribution, air quality improvement, mitigation of the urban heat island effect, and landscape connectivity [35]. The green space layout developed through this methodology significantly enhances the social and ecological resilience of urban areas. However, despite these advancements, the research and application of micro-green spaces remain notably limited. This gap underscores the need for further exploration and understanding of the multifunctional potential and efficiency of such spaces in addressing environmental equity in urban settings.

2.2. Geographical historical overview of green space equity

Green space equity research within developed nations, particularly in Europe and the United States, primarily focuses on specific populations, racial disparities, and socio-economic conditions. Race and income disparities have led to inequities in both the quantity and quality of green spaces, notably in the United States. The expansion of green space areas can inadvertently trigger an "environmental justice trap," whereby vulnerable groups, unable to afford increased rents, are forced to relocate from their original living environments. Studies by researchers such as Comber Alexis et al. and Rigolon Alessandro et al. have highlighted how factors like race, religion, and income level significantly affect access to quality green space [36,37]. Furthermore, MellIan et al. have identified that neighborhoods characterized by high racial diversity, low incomes, and residents with poor physical health tend to have less access to green space services, especially evident during the Covid-19 pandemics [38]. Europe, grappling with an aging population, places a heightened emphasis on ensuring equal access to green spaces for the elderly and those with limited mobility. Research by Wen Chen et al. has underscored how age impacts access to high-quality green spaces, with mobility emerging as a crucial factor [39]. While the extensive research in these developed regions offers significant insights, the distinct dynamics and nuances of green space equity in rapidly urbanizing and populous cities in developing countries remain challenging to parallel directly and warrant nuanced examination.

In developing countries, exemplified by China, a unique confluence of rapid urbanization and diverse regional cultural influences shapes green space equity. Urban centers in these countries embody multifaceted challenges. Notable studies by Wang et al. and Kuang Wei et al. have evaluated urban green space equity from various dimensions including geographical equality, social equity, and social justice, and proposed methods to enhance the efficiency of green space utilization [40–42]. Despite concerted efforts to augment urban green spaces through macro-regulations, cities in these regions grapple with pressing constraints such as land scarcity and high population density. A few cities like Macau underline the importance of strategic green space planning, transitioning from large parks to small-scale green areas. Macau, with a 100 % urbanization rate, has adopted innovative approaches such as "plug and play" to increase green space and optimize road greening to mitigate the issues associated with insufficient green space [43]. The significance of small-scale or 'small urban green spaces' in fostering environmental equity remains underrepresented in the existing literature. Moreover, current research predominantly emphasizes achieving equity through increasing the quantity of urban green spaces, with limited studies considering the multifunctionality and efficiency of green spaces as pivotal elements in realizing environmental equity.

3. Materials and methods

The research mainly consists of three stages (Fig. 1): analysis of green-space supply and demand from a spatial perspective, evaluation of the importance of ecosystem services in built-up areas, and construction of multi-functional green-space networks. In the first stage, based on the approach of AHP and GIS spatial analysis, the paper combines the provisions of green space and the needs of residents and obtains the supply-demand relationship of existing urban green spaces. Next, the paper adopts MCR and GIS Spatial Join to analyze the ecological and social functional positioning of the newly added green spaces. Finally, the paper derives the priority and functional positioning of green space by Multi-criteria Decision Models, determined by the green-space spatial and functional requirements of different areas, and constructs a multi-functional small urban green space network.

3.1. Area study

Harbin, serving as the economic, political, and cultural hub of the capital city of Heilongjiang province, has experienced a substantial influx of population due to urbanization, reaching 9.885 million in 2020. The urban built-up area of the city is characterized by a high density of population and construction, frequent dust storms, haze, and other extreme weather events, which underscore its representativeness and typicality. On the economic and social front, Harbin is grappling with a significant aging population, leading to a marked increase in the demand for community green spaces. The effective provision of green spaces in Harbin's built-up area is palpable and crucial, addressing both environmental protection needs and improving living conditions for its residents. In 2021, with the implementation of territorial spatial planning and the renovation plan for old industrial cities, Harbin proposed the Harbin Territorial Spatial Master Plan (2020–2035). This proposal aims to further promote the city's renewal, providing a significant opportunity for our research.

3.2. Land use profile

The built-up area of Harbin houses 78.13 % of the city's population (as of 2021) and is situated in the western part of the city, spanning approximately 495.02 square kilometers and accounting for 0.93 % of Harbin's total area. According to the Harbin Yearbook 2018, the urban green coverage rate in Harbin is 33.7 %, falling short of the 43 % mandated by the National Land Greening Plan Outline (2022–2030). Moreover, green spaces are predominantly located in the areas north of the Songhua River, the Qunli area, and parts of the Xiangfang district. In contrast, residential land is densely concentrated in the central area of the built-up area, characterized by an extensive road network (Fig. 2a). This distribution results in a significant misalignment between the availability of green spaces and residential needs (Fig. 2b). The high-intensity development in the current built-up area leaves little to no large expanses of land available for development. Consequently, there is an urgent need to optimize the supply and demand of urban green space

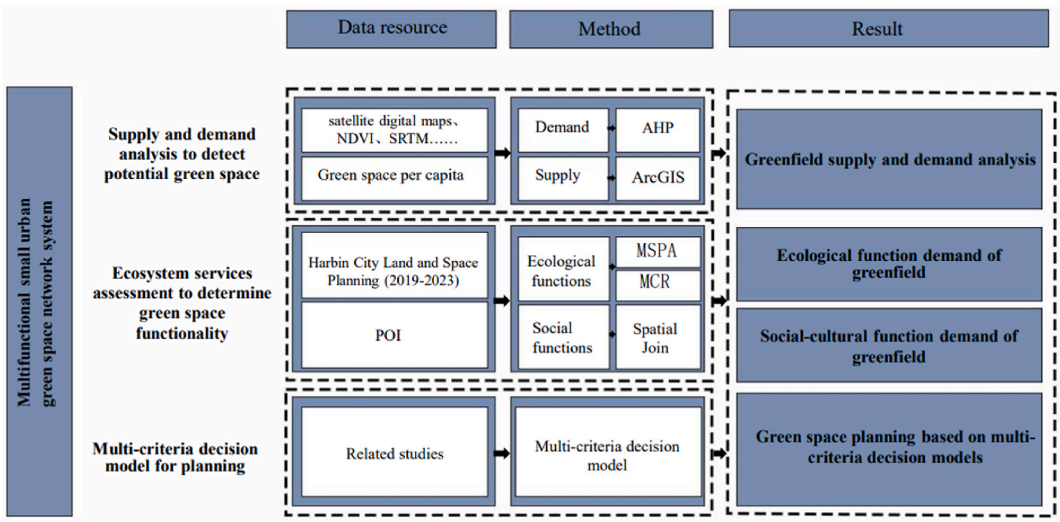

Fig. 1. The analyzed framework of small urban green space network construction.

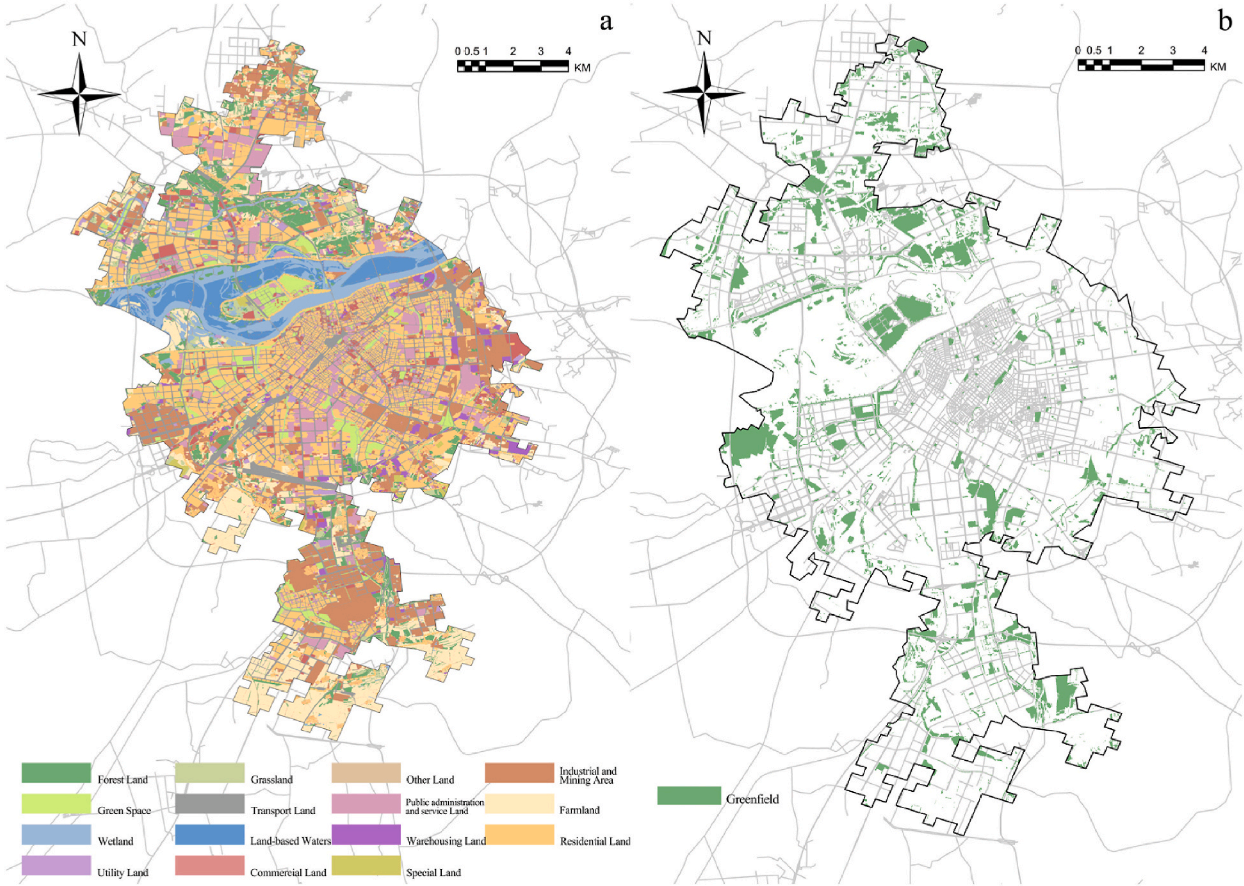

Fig. 2. (A) Land use status (b) status of spatial distribution of green spaces.

through the integration of micro-green spaces, with the aim of achieving environmental justice.

3.3. Date sources

The study uses the following data sources: (1) 2020 Landsat8 OLI_TIRS satellite digital maps, 2020 road network maps, 2020 standardized vegetation index (NDVI) data at 250 $m \times 250$ m resolution, and 30 $m \times 30$ m resolution Spaceborne Radar Topography Mission (SRTM) data were obtained from the Chinese Academy of Sciences Resources and Environmental Science Data Center (https://www.gscloud.cn). (2) 2020 nighttime light data imagery (NPP-VIIRS) was obtained from (https://www.mines.edu). (3) The 2020 1km × 1 km resolution World POP population density distribution map data was sourced from (https://hub.worldpop.org), calculated and drawn by the University of Southampton. (4) The complete version of the Point of Interest (POI) interest point data has not been officially released. To analyze these data, location coordinates were obtained by batch querying the Gaode map using Python, and spatial coordinate system correction was performed using the geographic coordinate system transformation tool.

3.4. Methods

3.4.1. Green space equity analysis based on supply-demand relationship

The study evaluates the green space demand based on the Analytic Hierarchy Process (AHP) method, considering habitat suitability, residents' demand, and accessibility. To model the level of Residents' demand for green space, the study builds a demand system that uses three sets of variables: natural conditions, residents' demand, and spatial accessibility [44–46]. "habitat suitability" reflects the ecological resistance of green space construction, "residents' demand" mainly represents leisure and recreational needs, and "spatial accessibility" reflects the ease of reaching the space. Twenty experts in landscape architecture and urban planning are invited to score the weight matrices of the criteria layer and indicator layer. Using this information, we can determine the importance of all the elements. The study used the Yaaph software to obtain the weight of the elements of the indicator layer. Then, the requirement is classified into four grades using the quantile classification method, with corresponding values of 1, 2, 3, and 4. The study obtained the green space demand distribution map by integrating the above research data using the Weighted Sum in ArcGIS 10.8 Spatial Analyst.

Then, the study evaluates the green space supply based on per capita green areas, considering existing green spaces and their service range. The green space supply in the urban built-up area is based on existing green spaces and their service range. The service radius of street-side green spaces is 200 m [47]. The Multiple Ring Buffer tool in ArcGIS 10.8 analyzes the green space service distribution.

Finally, the study analyzes the supply-demand relationship of green spaces concerning green space demand and supply. Compared with the per capita green area using the Weighted Sums method, The supply and demand results are divided into the green space supply and demand analysis diagram. The study selects the Weighted Sums method to integrate the supply and demand of green space and analyses the urgency of constructing green spaces in the study area. According to the Sixth Census Data and the Harbin City Land and Space Planning (2019–2023) - Central City Land and Space Use and Sea Current Status Map, we calculate the per capita green area at the street level. The study analyzes the supply-demand relationship of green spaces in urban built-up areas using the AHP combined with GIS Spatial Analysis methods and evaluates the rationality of green space re-source distribution. The supply and demand results are compared with the per capita green area using the Weighted Sums method, dividing the green space supply and demand analysis diagram. The Global Ecological Environment Remote Sensing Monitoring 2020 Annual Report shows that the world's urban per capita green area is 18.32 square meters, while the 2021 China Land Greening Status Bulletin indicates that China's urban per capita green area is 14.87 square meters. The date is a spatial reference to classify the urgency of green space construction in the built-up area of Harbin city. The study area is divided into three scores, which are defined as extremely mismatched, mildly mismatched, and balanced with corresponding values of 0–10,10–16 and 16 or more.

3.4.2. Green space ecological function analysis based on the least-cost resistance model

The study obtains ecological patches through Morphological Spatial Pattern Analysis (MSPA), constructs ecological corridors through Minimum Cumulative Resistance (MCR), and integrates them to analyze the potential ecological network [34]. This method is suitable for urban scales, which can extract sources and corridors by analyzing the connectivity of patches and the resistance to species migration between patches to construct ecological networks [48].

First, the study uses the MSPA method to obtain the landscape patches and subsequently calculate the connectivity probability (PC). Based on the results of the PC analysis, we evaluate the landscape connectivity and determine the patches' degree of importance.

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} p_{ij}^{*} \bullet a_i \bullet a_j}{A_L^2}$$

In the formula, n represents the total number of patches in the landscape, ai and aj represent the areas of patches i and j, respectively, and p_{ij}^{*} represents the maximum likelihood of species directly spreading between patches i and j.

Secondly, since different landscape elements may influence the resistance surface of species migration [34], the paper establishes an indicator system considering the resistance values of different landscape types (Table 1). Finally, based on the generated ecological source and resistance surface, the Cost Connectivity tool in ArcGIS 10.8 calculates the least-cost paths between each pair of ecological sources to obtain the urban built-up area ecological network. According to the previous study, the corridor width is 50 *m* for the migration and spread of birds, small mammals, and amphibians in the urban built-up area [49]. The study chooses a 50 *m* area around the corridors as an ecologically functional important area of the newly added green spaces.

3.4.3. Green space social function analysis based on GIS

POI data in cities are used for spatial functional analysis [50]. The study analyzes the examining POI density and attributes to get the urgency and type of social function demand for green spaces. ArcGIS processes POI data and, using the Spatial Join in ArcGIS 10.8, presents the POI density in the smallest land use units, and then the study employs the natural breaks method to divide the urgency of

Table 1
Resistance value indicator system.

Landscape type	Description	Area proportion (%)	Resistance factor
Source	Ecologically important values in ecological networks	1.91 %	1
Core	It provides larger habitats for species and is important for biological conservation	5.21 %	10
Islet	Small patches independent of each other, with low connectivity between patches	0.38 %	30
Bridge	A narrow area linking the core area is essential for biological migration and landscape connectivity	0.39 %	15
Branch	Areas where only one end is connected to a boundary zone, bridging zone, ringway zone, or aperture	0.70 %	25
Loop	Corridor linking the same core area, a shortcut for species migration within the core area	0.16 %	30
Edge	Transition areas between core areas and non-green landscape areas	2.60 %	60
Perforation	Marginal areas of the internal edge	0.10 %	50
Grassland	Growing herbs and scrub, providing food or habitat for animals	1.65 %	40
Farmland	Agricultural production land, including arable land and agricultural parks, etc.	8.39 %	40
Construction area	Land for the construction of buildings and structures. Including land for public utilities, storage, commercial services, residential land, etc.	70.04 %	200
Water	Areas covered by water. Includes wetlands and terrestrial waters	8.48 %	200
Other	The use is not yet known	0.01 %	150

providing social functions in green spaces in the study area into “important areas,” “moderately important areas,” and “non-important areas.”. According to the different attributes of urban points of interest, green spaces providing social functions are divided into three categories: social relation, physical and mental recovery, and recreation.

3.4.4. Green space planning based on multi-criteria decision models

The study uses Multi-Criteria Decision Models, considering supply-demand relationships and functional analysis to determine the potential functional positioning of the newly added green spaces, guiding the construction of small urban green spaces.

Summarizing the results based on existing literature on spaces with conflicting ecological and social functions, this study constructs important ecological functions in green spaces. The first step is to integrate the ecological importance and social function importance of green spaces, obtaining an analysis of the functional importance of green spaces. The second step is to integrate the classification of green space functional importance with spatial supply-demand relationships, classifying the direction of green space planning into five types.

After obtaining guidance for the construction of small urban green spaces, this research selects two standards to design the green space system: (1) spaces with conflicting ecological and social functions, the study plans importantly ecological function green spaces; (2) the constructed small urban green space network should connect with existing green spaces. In this way, we constructed a multi-functional small urban green space network.

4. Results

4.1. Analysis of the supply and demand relationship for small urban green spaces

From the perspective of demand, population spatial distribution plays a dominant role in green space demand, and high-demand areas are concentrated in the central and eastern parts of urban built-up areas. The green space demand assessment framework (Table 2) shows that the first category of elements (habitat suitability) accounts for only 9.36 % of the total, and factors such as slope, elevation, and NDVI have proportions below 5 %, indicating their relatively small impact on suitability evaluation; the second category of elements (human impact) accounts for 62.67 % of the total, becoming the dominant variable for suitability distribution, with the spatial distribution of the population accounting for 35.72 %, far exceeding other sub-elements; the third category of elements (spatial accessibility) accounts for 27.97 % of the total, with the proximity to bus stops accounting for about 10 % more than the total proportion of the first category of elements. High-demand areas are mainly distributed in the central part of the city, especially in old towns with high building and population densities. Medium-demand areas form a ring surrounding high-demand areas. Low-demand areas are located in the Songhua River Basin, where the population density is low.

From the perspective of green space supply, the spatial distribution of green space resources is relatively scattered, and the size of green space patches is small. In green space resources, forestland accounts for 56.33 % of the total area, becoming the main source of supply. Green space services are mainly concentrated in the northern, southern, and Qunli areas of the built-up area, where forestland, green spaces, and open spaces are densely distributed. In the central area, the green space supply shows a scattered distribution.

The supply and demand relationship of current green space in the built-up area of Harbin is inequity, with 60.3 % of the area having a per capita green space area of less than 12 square meters. Severe mismatch is distributed in the central and eastern parts of the city, especially in the old urban areas. The analysis of green space construction urgency (Fig. 3) shows that the green space resources are abundant in the northern and southwestern areas, and there isn’t a severe mismatch in space in the region. The central and eastern parts of the built-up area have a shortage of green space resources, and severely mismatched areas account for more than 75 % of the

Table 2
Green space demand assessment framework.

Target Layer	Criteria Layer	Indicator Layer	Standard				Weight
			1	2	3	4	
The demand for small urban green space	Spatial Accessibility	The distance to the bus stop(m)	≥500	[350,500)	[200,350)	< 200	0.1921
		The distance to the main road of the city(m)	≥800	[600,800)	[400,600)	< 400	0.0522
		The distance to pavement (m)	≥400	[300,400)	[200,300)	< 200	0.0354
	Human Impact	Spatial distribution of residential (person)	<3479.5	[3479.5,6782)	[6782 , 10084.5)	≥10084.5	0.3572
		The distance to Urban green space(m)	< 300	[300,450)	[450,600)	≥600	0.1182
		The distance to urban infrastructure(m)	≥200	[150,200)	[100,150)	< 100	0.0436
		The distance to the residential district(m)	≥500	[350,500)	[200,350)	< 200	0.1077
	Habitat Suitability	DEM (m)	[187.5226]	[149,187.5)	[110.5149)	[72,110.5)	0.0106
		Slope (%)	≥25°	[15°,25°)	[5°,15°)	<5°	0.0398
		The distance to the water area (m)	≥1200	[900,1200)	[600,900)	< 600	0.0119
		NDVI(%)	[0,50)	[50,100)	[101,150)	[150,201]	0.0313

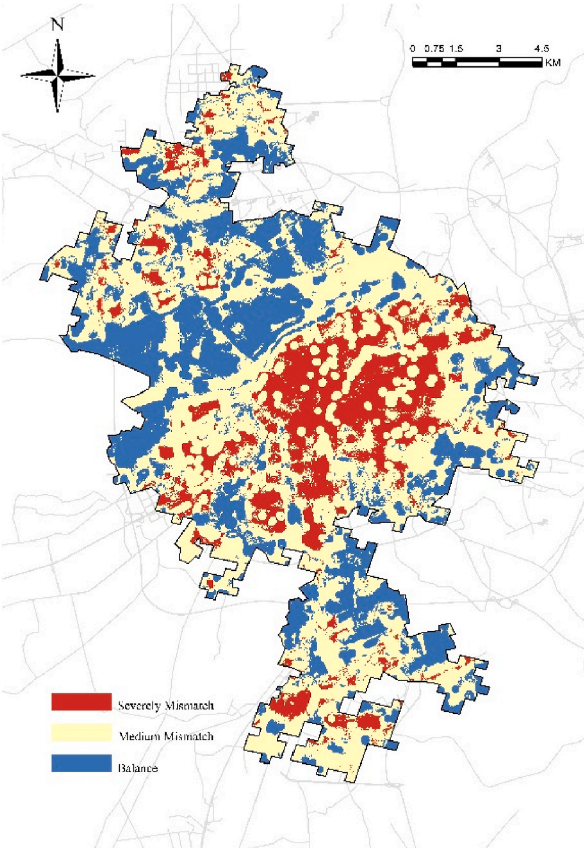

Fig. 3. Green space supply and demand analysis.

total area. Balanced areas are mainly distributed in the outside of the city center and the Songhua River region.

4.2. Evaluation of ecological and social function

Based on MSPA, our study found the distribution of landscape patches is uneven and relatively scattered, with a spatial pattern of more resources in the west and less in the east. Human production and development activities affect the area of green space. Extensive landscape patches are distributed in the northern part of the Songhua River. These regions depicted a lower resistance value and better ecological security status than other spaces, which can be used as ecological sources. Among the study area, the area of the urban center accounts for 25 % of the total area, but its ecological resources percentage is less than 7 %.

Based on MCR, we found that there are 221 green space corridors in Harbin city's built-up with a total length of 387.37 km, distributed in the plenty of green space resources. The northern and western parts of the city have multiple interconnected corridors with an endless flow of ecological materials, energy, and other resources. The central and western regions have fewer corridors and poor connectivity. Green space patches are independent of each other and have not become potentially important green space resources.

Based on MSPA and MCR, the green space network (Fig. 4) shows that existing green space resources are concentrated in the northeastern and southern parts, coinciding with existing wetland landscapes and scenic spots. Spatially, there are three high-density areas: the northern part of the Songhua River, the Qunli New District, and parts of the Xiangfang District, with large internal patch areas and dense ecological networks. In the central and western regions, patches are small, mostly distributed independently of each other, and lack ecologically high-value areas. It is worth mentioning that human interference leads to the fractured distribution of important ecological sources in the city center area and depicts the lowest ecological security status.

In general, the social functions of green spaces are densely distributed within the central part of the urban built-up area, and their position highly coincides with residents' living and active areas (Fig. 5). Extremely important areas of social and cultural function are mainly distributed in the central part of the built-up area. Extremely important areas on the north and south sides are point-distributed, overlapping with government institutions and commercial centers. In extremely important areas, the proportions of transportation, commerce public facilities, and residential land greatly exceeded other types of land-use types, and the cumulative contribution rate of the three types reached 77 %. The social function non-critical areas are located around extremely important areas in the city's periphery and the Songhua River area.

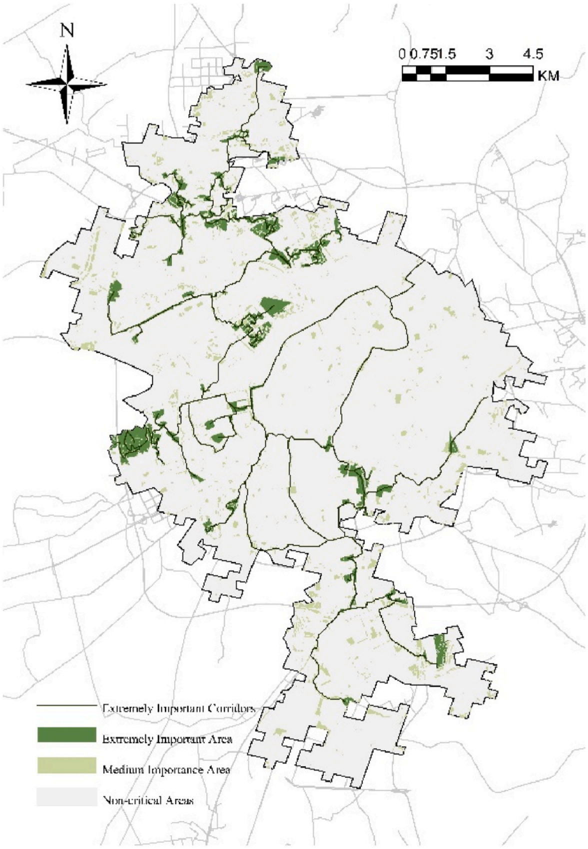

Fig. 4. Ecological function assessment.

The analysis of the potential functional positioning of the newly added green spaces reveals spatial dislocation between ecological functions and social functions, but ecological green spaces and social green spaces overlap in the partial area (Fig. 6). Ecologically important areas are concentrated in the northern, southern, and western parts of the city, with abundant ecological resources and strong connectivity between patches. Social functionally important areas are concentrated in the central part of the city, where the population and building density are high. In this area, the green space function is relevant to the work and life of residents, and small urban green spaces can solve the problem of lack of space in built-up areas of the city. Ecological green spaces and social green spaces are overlapping in the central city. Moreover, the ecological functional green space network integrated the ecological sources in the central city into the overall ecological network, which ensured the movement of various species. Therefore, we should build ecological green space, which not only prevents the spread of ecological risks of human activities but also covers the shortage of green space sources.

4.3. Evaluation of ecological and social function

According to the multi-criteria analysis model [51,52], the paper divides the study area into five planning types, integrating the supply-demand relationship of green space with the spatial ecosystem service functions [53](Table 3). The concentrated development areas are located in the central part of the city, where green space resources are scarce, population and building density are high, and residents have a high demand for social functions. The backup development areas are mainly distributed around the concentrated development areas, where greenspace can be improved. Maintenance areas are mainly distributed in the northern part of the Songhua River and the urban fringe, with abundant green space resources and an excellent ecological environment. Protection areas coincide with the green space network, and some ecological spaces can be further improved, as these areas have high ecological value and provide essential ecosystem services for the urban area.

The results show (Fig. 7) that areas with concentrated development areas account for 16.94 % of the urban total area, reserve development areas account for 14.31 %, and these are mainly distributed in the old urban areas, urgently requiring green space improvements. Protection areas and construction areas account for 3.02 % and 4.22 %, respectively, including large wetland parks and natural green spaces. The concentrated development areas are distributed in both planar and scattered patterns, where they can build a small urban green space network around existing green spaces. The backup development areas should focus on green space improvements, such as encouraging residents to build gardens and reuse abandoned gardens. Protection and optimization areas are

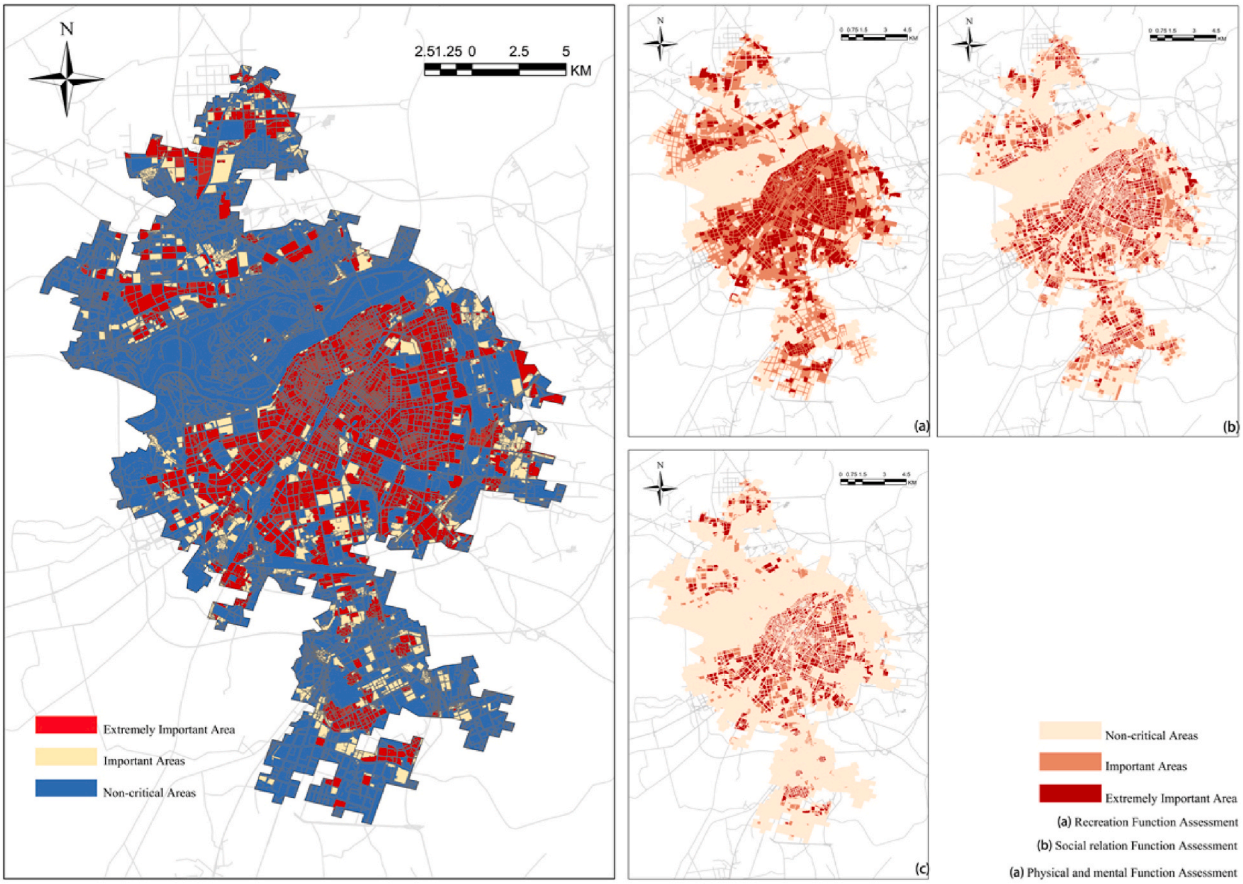

Fig. 5. Social service function assessment.

essential for sustainable urban development. Existing protection areas with gaps need further improvement, so small urban green spaces should be added to ensure species migration. In protected areas with good existing green space resources and high ecological value, the area should be protected. Maintenance areas cover a large proportion of space, and since the supply and demand are balanced, the area should maintain the existing land-use types.

Constructing a small urban green space network (Fig. 8) not only improves the green space ecosystem service capacity but also ensures the equitable supply and demand of urban green spaces. Concentrated development areas are mainly located in the central areas of the city, so small urban green spaces with a focus on social functions are constructed in the region to build a small urban green space network [54]. The northern, southern, and western sides have good existing ecological resources, and the planning types of this region are maintenance areas and protected areas; thus, by relying on the existing green spaces, small urban green space corridors can be added locally [55,56]. Long green corridors can be added between regions to enhance the hierarchy of the green space network. This method not only compensates for the demand for social functions in the city center but also connects green spaces through the construction of a green space network.

5. Discussion

This study takes Harbin's urban built-up area as an example, aiming to construct a network of multifunctional small urban green spaces that addresses green space equity. Our approach goes beyond the conventional analysis of supply-demand relationships, encompassing the spatial ecology and societal function of these green spaces, as well as their efficiency. The objective is to forge an intricate system that continuously delivers essential ecosystem services. This innovative strategy, with its emphasis on achieving spatial fairness, has the potential to generate efficient and precise planning solutions for green space distribution. Consequently, it plays a pivotal role in addressing the noted spatial disparities in urban planning and management. Furthermore, this methodology can serve as a reference for achieving green space equity in the urban built-up areas of other developing countries globally, thus providing a valuable model for widespread application.

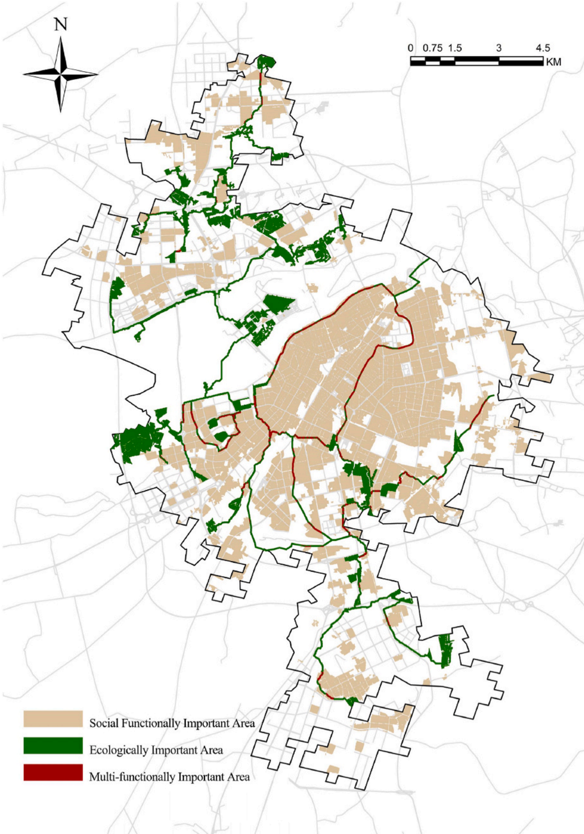

Fig. 6. Ecosystem services analysis.

Table 3
Multi-criteria decision models.

		Spatial supply and demand		
		Severely mismatch areas	Medium mismatch areas	Barely coordinate areas
Ecosystem service function analysis	Integrated important areas	concentrated development areas	backup development areas	maintenance areas
	Ecological functionally important areas	protection and optimization areas	protection and optimization areas	protected areas
	Social functionally important areas	concentrated development areas	backup development areas	maintenance areas
	Non-critical areas	concentrated development areas	maintenance areas	maintenance areas

5.1. Spatial inequities in urban green space distribution

The results of this study highlight the importance of spatial inequities in green space distribution, which bear significant ramifications for environmental sustainability and societal well-being. This study contributes to the existing body of research on spatial inequities in green space distribution, substantiating the previous findings of seminal works [57,58]. These investigations delineated the proclivity of densely populated urban areas to manifest unequal access to green spaces, a phenomenon corroborated by the observations made in Harbin City. The data reveals a pronounced scarcity of green space in concentrated development areas and mature urban regions, wherein approximately 75 % of the land exhibits a critical need for green space resources. A comparative analysis across multiple global cities elucidated the multifaceted challenges and risks intrinsic to unequal green space distribution, encompassing diminished biodiversity and compromised human health and well-being [57]. The disparities discerned in this study accentuate the exigency of addressing such inequalities, advocating for initiatives that promote both ecological equilibrium and social justice.

Innovatively, this study employs small urban green spaces as a focal point to scrutinize green space equity. Modern urban settings frequently demonstrate a diminished collective responsibility for equitable green space resource distribution, engendering

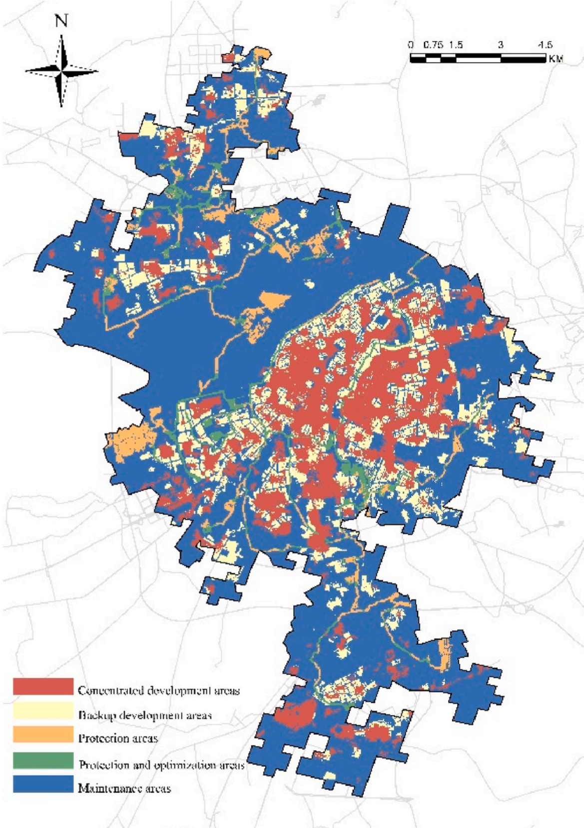

Fig. 7. Guidance of small urban green space construction.

individualism and a deprioritization of communal benefits [57]. The process of urbanization often witnesses the conversion of green spaces into constructed lands for economic gains, engendering a subsequent shift in resident priorities towards quality of life [59]. The inherent characteristics of urban built-up areas—high population density, elevated building concentration, and limited spatial availability—foment the inequitable distribution of green space. Previous research has primarily focused on large green spaces, for instance, urban parks, often neglecting the feasibility of introducing large and medium-sized green spaces in built-up urban locales [59]. The spatial and regulatory constraints in these regions render the development of expansive green spaces logistically challenging. Recent studies, however, establish a positive association between the proportion of small urban green spaces and the augmentation of ecological services [58]. With their compact and multifunctional nature, small urban green spaces emerge as pivotal for mental and physical well-being [31]. In the future, by analyzing the relationship between small green spaces in urban built-up areas and urban residents and biodiversity, the study will make more suggestions and recommendations for the construction of small green spaces. The city of Harbin exemplifies the incongruity between the supply and demand for varied green spaces, necessitating a reevaluation of urban planning strategies [59]. By strategically incorporating green spaces in proximity to residences and workplaces, a flexible and integrative urban layout is achievable [60]. The infusion of high-density small urban green spaces within city confines offers a remedial approach to the prevailing issues of green space inequity and functional monotony [58]. The interconnection of these green spaces heralds a paradigm shift in urban green space planning, proffering ecological services and a refreshed perspective on urban development.

5.2. Utilizing the environmental-societal multifunction of small green space for environmental justice

In addressing spatial inequities and fostering environmental justice, recognizing the multifunctional potential of small green spaces is paramount. This study illuminates the integral role of such spaces, showcasing their capability to harmonize environmental conservation with societal development, particularly in central urban areas like Harbin City. By integrating ecological and social functions, small green spaces contribute to mitigating spatial disparities and advancing the overarching aims of environmental justice and urban sustainability. This aligns with the previous findings [61,62], which have underscored the transformative capacity of multifunctional green spaces in bolstering social cohesion, ecological resilience, and inclusive urban growth. The insights derived from this research enrich the existing discourse, offering practical avenues and strategic approaches for optimizing the multifunctionality of green spaces in urban planning and development.

Proffering a novel methodology, this study advocates for achieving green space equity both quantitatively and functionally through

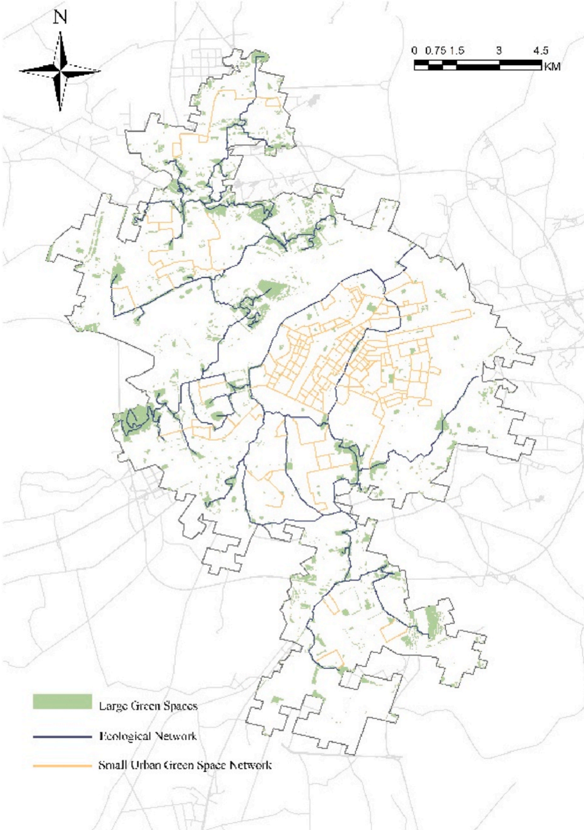

Fig. 8. Small urban green space network system.

an ecosystem services perspective. It is established that green space networks, by connecting existing patches, not only furnish residents with ecosystem services and benefits but also safeguard urban biodiversity [63,64]. They significantly alleviate the challenges posed by rapid urbanization in built-up areas [65,66]. Through enhancements in research systems and spatial planning, green space networks contribute to refining the existing green space systems and pinpointing apt locations for future development, thereby promoting green space fairness. The study also accounts for residents' varying preferences, influenced by socioeconomic backgrounds and familiarity with green spaces [67], and integrates these considerations in planning, thereby ensuring the construction of green spaces aligns with the functional needs of the populace. This methodology, encompassing POI data statistics for urban commerce, medical care, and office space, provides a blueprint for other cities, facilitating equitable access to public resources for residents through tailored green space planning.

Further delving into the ecosystem services of small urban green spaces, this article proposes the construction of a green space network in urban built-up areas designed along pedestrian routes. Such a design fosters a natural and socially conducive environment, offering continuous avenues for relaxation and appreciation [68]. Prior research using birds as indicator species substantiates the role of green spaces in enhancing biodiversity and the connectivity of urban landscapes [69,70]. The integration of fragmented green spaces is pivotal for both biodiversity conservation [71] and the provision of continuous recreational spaces [72]. By thoroughly considering the ecological and social function needs of space, this study proposes designs that enhance green space utilization, connect with the urban-scale green space network, and bundle different scales and functions. This approach contributes to fostering harmonious human-nature coexistence and propelling urban sustainable development.

5.3. Practical implications and policy recommendations

The meticulous exploration of Harbin's urban built-up area uncovers considerable insights and offers substantive guidance for formulating a resilient small urban green space system. A conspicuous scarcity of these green spaces is particularly evident in Harbin's older urban locales. The multifaceted urban structure and the dynamic interaction between social and ecological necessities make the development of a green infrastructure catering to both human and environmental needs an urgent undertaking.

Addressing this imperative, it is paramount for urban planners to accentuate the establishment of small urban green space networks with a pronounced focus on their social functionalities. These spaces are instrumental in fostering mental well-being and community cohesion, serving not merely as recreational areas but also as focal points for community engagement and social interactions [73]. Strategic development of such spaces, especially in the north, south, and west of the built-up areas, is essential for biodiversity conservation. Incorporating green corridors facilitates biological survival and migration, thereby amplifying urban biodiversity [64]. The central and eastern segments of Harbin's urban built-up area, are marked by a distinct imbalance in green space resources. Integrating small urban green spaces with the prevailing road networks in these areas can fulfill many purposes. This multifunctional strategy addresses pedestrian requirements, diminishes travel expenditures [74], and augments the utilization of outdoor leisure spaces, thereby fostering a harmonious amalgamation of urban domains with green infrastructure.

The insights and recommendations deduced from this study are paramount for urban planners, policymakers, and community stakeholders. They necessitate targeted initiatives to amend the disparities in green space distribution across diverse urban territories. The rejuvenation of underutilized green areas, the promotion of community gardening, and the evolution of cohesive urban green space networks are pivotal strategies that can significantly bolster patial equity and environmental justice. Achieving a nuanced equilibrium between the social functionalities in central locales and the ecological robustness of the peripheral regions mandates a comprehensive and integrative approach. Enhancing green space connectivity by adding longitudinal green corridors can amalgamate social and ecological functions, cultivating a more sustainable and equitable urban milieu.

Moreover, the emphasis on community-driven initiatives, such as community gardens, is especially salient in densely populated urban areas. These endeavors not only fulfill the green space requirements but also catalyze community participation and guardianship [75]. At the policy level, fostering public-private partnerships can expedite the genesis and preservation of green spaces, assuring their enduring influence and sustained benefits. The strategies and interventions proposed herein align with the principles of environmental justice [76], underscoring the imperative for an equitable distribution of green spaces and the promotion of inclusive urban development. Adopting and actualizing these recommendations will enable urban regions to progress towards a harmonious coexistence of ecological preservation and societal prosperity, thereby furthering the overarching goals of sustainable urban development.

6. Conclusions

This research, centered around Harbin's urban built-up area, initiates an intricate endeavor to devise a network of multifunctional small urban green spaces, with a prime objective of addressing issues pertaining to green space equity. The practical implications and policy recommendations extracted from this study provide substantial guidance for urban planners, policymakers, and community stakeholders. The insights offered emphasize the imperative of tailored initiatives to rectify disparities in green space distribution, thereby fostering cohesive urban green space networks and cultivating a more harmonious and sustainable urban environment. Significantly, this research holds value not just for Harbin but also stands as a scalable model for ensuring green space equity in urban built-up areas worldwide, especially in developing countries.

The findings of this study underscore a significant imbalance in the supply and demand of green spaces in Harbin, revealing pronounced spatial inequities with far-reaching implications for environmental sustainability and societal well-being. The envisioned network of multifunctional small urban green spaces, extending over 277.60 km, embodies a transformative approach to urban planning, aimed at alleviating these disparities and pursuing the concurrent goals of environmental justice and urban sustainability.

One of the standout aspects of this research is its innovative emphasis on the multifunctionality of small green spaces, which shines a light on their crucial role in aligning environmental conservation with societal advancement. The study scrutinizes the interplay of social, ecological, and cultural functions within Harbin's built-up area from a spatial standpoint. Through the integration of ecological and social functions, this methodology enhances green space utilization efficiency, alleviates land tension in urban built-up areas, provides leisure spaces for residents, and augments urban biodiversity.

This study refines the traditional concept of green space equity and champions the pursuit of green space equity from both a quantitative standpoint and a functional efficiency perspective. The findings elucidate the pivotal role of functionality and efficiency in discussing green space equity. Research results indicate that after analyzing the supply-demand relationship of green spaces, some spaces are more conducive to ecological functions, while others are better suited for sociocultural development. Moreover, in terms of efficiency, the study proposes varying levels of optimization priorities through multi-temporal planning paths. This comprehensive approach offers strategic solutions for enhancing the multifunctionality of green spaces, consequently mitigating spatial disparities and encouraging inclusive urban development.

However, limitations were encountered during the study, specifically in the analysis of green space supply and demand. The subjectivity of the targets and their weights hindered comparisons with relevant studies. As a result, future research endeavors should strive to formulate unified standards for indicators and proportions of green space supply and demand. Integral areas for future exploration encompass the integration of small urban green spaces with the wider urban infrastructure, the investigation into community engagement in green space development, and the scrutiny of the interconnectedness of social and ecological functions. In alignment with the United Nations Sustainable Development Goals, this study accentuates the necessity of advancing sustainable and inclusive urban development through equitable green space distribution, thereby contributing to the broader ambitions of environmental conservation and societal well-being.

Funding

This research was funded by the National Natural Science Foundation of China (grant number 52078160).

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics statement

Informed consent was not required for this study because this study didn't involve any data related human or animals.

CRediT authorship contribution statement

Mingjie He: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yuanxiang Wu:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Xiaoguang Liu:** Writing – review & editing, Visualization. **Bing Wu:** Writing – review & editing, Formal analysis, Conceptualization. **Hongpeng Fu:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the Ministry of Natural Resources of the People's Republic of China (Grant No. 52078160) and the seniors and students who help to write assistance.

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