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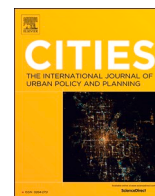
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The green space availability paradox in high-density cities: Evidence from Shenzhen, China

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ABSTRACT

In high-density contexts, the Urban Green Spaces (UGS) availability often fails to benefit from the theoretical advantages of compact developments, but rather is negatively affected. There are existing studies have applied GIS-based analysis to examine such phenomenon in terms of accessibility, provision, and equity. However, these studies are struggling to identify the dilemmas in spatial design that contribute to this issue and consequently hinder the proposal of practical solutions for UGS design in high-density environments. This article aims to fill this gap by conducting a case study on the availability of UGS systems in Shenzhen for different travel modes and social groups. In this process, the study explores the spatial patterns of UGS availability more accurately by combining navigation mapping API data with population spatial distribution data. It also incorporates an urban design perspective into the urban analysis to investigate the challenges in spatial design and corresponding practical solutions. The study results indicate that high-density development is challenging to benefit UGS availability without careful consideration of urban design, including optimizing the design framework, rational UGS layouts, effective pedestrian and cycling systems, and sophisticated spatial design on the local scale. Therefore, the study not only strives to apply an urban study method but also holds broader significance for future high-density urban design practices or research.

1. Introduction

In high-density urban environments, the social well-being is highly dependent on the recreational opportunities and other ecosystem services provided by urban green spaces (UGS) (Kabisch, 2019; Kabisch et al., 2015). These added values and services offered by UGS are closely related to having access to nearby parks for recreational activities and being close to nature (Ekkel & de Vries, 2017), especially in a highly urbanized landscape (Lachowycz & Jones, 2013). Therefore, the availability of UGS has been the focus of urban design, planning and research (Baycan-Levent & Nijkamp, 2009). In many studies, availability often appears as a synonym for accessibility (Gupta et al., 2016; Morar et al., 2014; Oh & Jeong, 2007a). The possibility for residents to access an appropriately sized UGS within a reasonable distance is considered to be a key factor. However, several studies and reports also emphasize that sustainable urban planning should provide equal access to UGS that is sufficient to meet the demands of all residents, including different social groups in terms of age or incomes (Rigolon, 2016; World Health Organization, 2007). It can be seen that the availability of UGS involves three

basic aspects, the presence of sufficient area of UGS, the accessibility of residents to these UGS at appropriate distances, and the equitable access to these UGS by different social groups. In addition, there are also studies that have been conducted on these three topics through other perspectives, such as psychological accessibility, advantages of biodiversity, and facilities (Kaczynski et al., 2016; Kimpton, 2017; Park, 2017).

Theoretically, the mobility and land-use advantages of high-density development will benefit the UGS availability. It is believed that compact developments can enhance the accessibility of UGS, provide more opportunities for walking, and more space to enhance the quality of the UGS system (Don & Tomalty, 2002). However, the reality seems cannot be a solid argument for this view. High-density development poses challenges to all three dimensions of UGS availability. Some studies have shown that the proximity that comes with high density development is not trusted, which in turn is detrimental to the availability of public open space (De Roo & Miller, 2019). Insufficient UGS provision is a common issue in high-density areas (Haaland & van den Bosch, 2015), and despite theoretical advantages, UGS accessibility in

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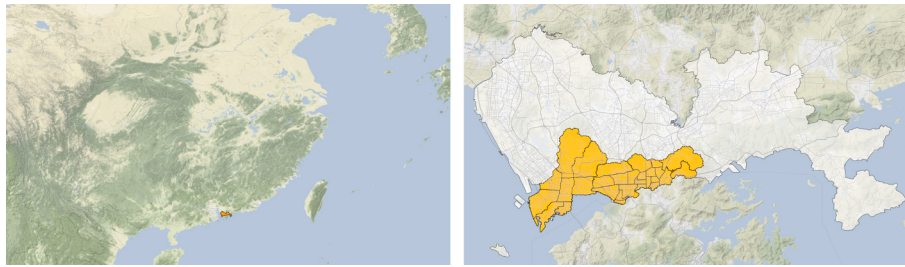


Fig. 1. The study areas in Shenzhen, China.

many high-density cities is often not as favorable as expected (Tian et al., 2017). On the other hand, the provision of UGS in many cities is also not equal for different social groups (Sun et al., 2022). Even though measures such as setting UGS supply standards and defining catchment areas for different UGS types have been widely adopted in urban design and planning process (Oh & Jeong, 2007b; Van Herzele & Wiedemann, 2003), such issue remains prevalent in high-density cities. This reveals a critical disconnect between the theoretical spatial advantages of high-density development and the actual UGS availability experienced by residents. A core challenge is that the very features of high-density—concentrated infrastructure, high land values, and intense human activity—can create unforeseen barriers that counteract the benefits of simple geographic closeness.

In this regard, existing studies have devoted efforts to researching the UGS availability in high-density contexts through applying GIS-based methods. The two-step floating catchment area (2SFCA) approach is a commonly used method. For instance, Liu applied this method in his study to examine the equity of UGS accessibility among different ethnic and income groups in Chicago (Liu et al., 2021). Similarly, Xing used the same approach to analyze the accessibility of UGS for teenagers of different age groups in Wuhan (Xing et al., 2020). They have effectively demonstrated this issue through spatial analyses from perspectives such as accessibility, provisioning, and equity. However, these studies often struggle to identify the dilemmas in spatial design that contribute to this problem and consequently hinder the proposal of practical solutions for UGS design in high-density urban environments. This is a typical limitation of studies that apply the 2SFCA approach. This limitation is largely related to several factors. Firstly, many studies use population data at the community level, which typically has a lower resolution than the service range of small UGS (300–500 m) (e.g. the above-mentioned studies by Liu (Liu et al., 2021) and Xing (Xing et al., 2020), and Ma's study on the accessibility of UGS in Guangzhou (Ma et al., 2023), etc.). As a result, these studies lack the precision to reflect the spatial patterns of UGS availability across different scales. They can only highlight issues in UGS distribution and provision at a macro level but fail to provide practical insights for urban design solutions. Some studies have attempted to address this issue by using more precise population data. For example, Zhang's study on UGS accessibility in Shenzhen utilized mobile user data from telecom operators (Zhang et al., 2022). Chen's study on UGS accessibility in the central urban area of Hefei also applied a similar method (Chen et al., 2022). However, the primary focus of these studies is more on optimizing the research methodology and corresponding mathematical models. Due to the lack of engagement with urban design perspectives during the research process, such studies similarly suffer from the same limitations.

This article aims to fill this gap by conducting a case study on the UGS system availability in Shenzhen, a quintessential high-density city. To move beyond the limitations of previous work, this study integrates more accurate, real-world travel data from a navigation mapping API with high-resolution population spatial distribution data. Through this process, the study investigates the three core dimensions of UGS availability, framed through the lens of urban design principles as follows:

- 1) **UGS Accessibility:** Proper network connectivity and walkability are among the core principles of sustainable high-density urban design. This study explores how UGS service areas cover urban space and population across travel modes.
- 2) **UGS Provision:** How many urban residents can actually access adequate UGS provision is a core issue of land use planning and urban morphology in high-density contexts, where design decisions directly determine the allocation of public space.
- 3) **UGS Equity:** Investigated as a matter of inclusive design and environmental justice, questioning whether UGS resources are friendly distributed and designed among sensitive social groups.

By exploring these dimensions, this study seeks to deconstruct the challenges of UGS availability in dense environments and identify practical, design-oriented solutions. This approach not only provides a more nuanced urban analysis but also holds broader significance for future high-density urban design and planning practices.

2. Research methods and materials

2.1. Overview of the study area

The study conducted a case study in Shenzhen, China (see Fig. 1). Shenzhen is located in the south of China, close to Hong Kong and Guangzhou, and is one of the central cities in the “Greater Bay Area”. It is also a main economic and tech hub in the south of China. According to the National Bureau of Statistics of China (National Bureau of Statistics of China, 2020), Shenzhen's population has reached 17.56 million in 2020, with an overall population density of 8625/km². The population density of Futian and Luohu districts in the downtown area even exceeds 20,000/km². A growing population and limited areas suitable for urban development make Shenzhen one of the most densely populated cities in China. For this reason, it is an appropriate case for this study.

The local government of Shenzhen has consistently seen the UGS system as a highly important part of its urban developments. The “Shenzhen Green Space System Planning 2004–2020” has set some key criteria for the UGS system development in Shenzhen. The urban planning expects to provide a minimum of 10m² of public green space for each resident in the central areas and to allow all residents to access these UGS within a 500 m walking distance. These UGS mainly composed of parks systems, which are divided into two main types according to their size: urban parks and community parks. These UGS play different roles in the city, but Shenzhen does not set a different catchment area for them. As a result of urban planning, the public UGS area per capita in the three districts of central Shenzhen (Luohu, Futian, and Nanshan) has reached 11.4m² per person without taking into account the natural parks around the city, and the coverage of the UGS service area has exceeded 80 % (Li et al., 2019). In order to explore the availability of UGS in a high-density environment, this study will be conducted in these three districts.

2.2. Research methods

The accessibility is the foundation of UGS availability. There are multiple methods have been applied to estimate UGS accessibility in related studies. One of the methods is to use a fixed distance buffer to define the service area and in this way evaluate the population and urban areas that can be covered, or conversely to calculate the amount of green space within the buffer area of a community (McPhearson et al., 2013; Richardson et al., 2010). Another approach is to calculate the shortest route to the UGS by estimating the Euclidean distance or performing network analysis on the road system (Comber et al., 2008; Coombes et al., 2010). This approach optimizes the accuracy of the first method, but it still has two limitations. The first is that the above approach fails to take into account the resistance that residents will encounter in traveling, such as hard-to-cross streets, waiting times at busy intersections, fences, etc. The second is that they do not take into account the population stress on UGS use (i.e., demand for use within the service area), which often leads to unequal provision of UGS. Addressing these two issues requires finding ways to more accurately reflect the travel time of residents and a accessibility model that takes into account supply and demand and their interactions.

2.2.1. Estimating travel time by navigation mapping API

Application Programming Interfaces (API) for navigation mapping have been widely used by researchers as a geo-information database with enhanced spatial analysis capacity (Chen & Nguyen, 2017; Kobayashi et al., 2010). Its backend high-performance platform and precise geographic information can take into account the time resistance of residents during their commuting, thus directly and accurately acquiring travel time in relation to distance and routes (García-Albertos et al., 2019; Socharoentum & Karimi, 2015; Wang & Xu, 2011). In addition, navigation mapping APIs can integrate multiple modes of transportation to estimate travel times, such as residents often need to walk to a nearby stop to take public transportation to a particular UGS. These two advantages offered by the navigation mapping API can effectively alleviate the first problem mentioned above. This study will use the AMAP API to estimate the travel time for residents to travel to UGS by no transportation mode. This map database is widely used in China, and its accuracy and navigation capabilities have been recognized by public and relevant studies over a long period of operation.

2.2.2. The two-step floating catchment area (2SFCA) approach

As a widely studied topic in urban design and planning, multiple methodological systems have been applied in the research of UGS accessibility. Commonly used methods include the minimum distance method (Apparicio et al., 2008), simple buffer analysis (Mallick & Routray, 2001), network analysis (Li & Liu, 2009), the gravity-based model (Wu et al., 2017), and the two-step floating catchment area (2SFCA) approach (Liu et al., 2021). Both the minimum distance method and simple buffer analysis are based on Euclidean distance, which does not consider the actual commuting routes of residents (Nicholls, 2001). Network analysis improves this by incorporating the road network, yet it does not account for the supply-demand relationship (Liu et al., 2010). The gravity-based model, while factoring in the interaction between UGS service capacity and resident demand, introduces uncertainty due to the choice of its decay coefficient (Lee et al., 2018). Overall, these methods face inherent limitations that are difficult to overcome.

The 2SFCA approach is developed based on the gravity model, utilizing the road network to determine accessibility between supply and demand through two floating catchment area searches. In this approach, public facilities serve as supply points, while residents are considered demand points. The advantage of this method lies in its ability to account for the supply scale of urban public facilities, the demand scale, and the distance relationship between supply and demand, making its interpretation more intuitive (Luo & Wang, 2003). Subsequently, some studies have extended and improved upon this method. On one hand,

some studies introduced different distance decay functions. For example, the enhanced 2SFCA (E2SFCA) (Luo & Qi, 2009) and the approaches applied different decay functions like Gaussian 2SFCA (Ga2SFCA) (Dai, 2010; Dai & Wang, 2011). On the other hand, some studies incorporated dynamic population distribution data, such as dynamic 2SFCA (D2SFCA) (Li & Liu, 2009). To enhance the analytical depth and better reflect that the attractiveness of a park declines with increasing travel time, this study adopts an enhanced model incorporating a Gaussian distance decay function. The Gaussian function provides a continuous, smooth decay, assigning higher weights to closer locations and lower weights to those at the edge of the service area. However, since this study aims to explore the general conditions of the study area over an extended period, dynamic population distribution data are not suitable. In this case, static population distribution data will be utilized in this study.

The weighting function G is defined as:

$$G(d_{kj}, d_0) = \begin{cases} e^{-\frac{1}{2} \times \left(\frac{d_{kj}}{d_0}\right)^2} & \text{if } d_{kj} \leq d_0 \\ 0 & \text{if } d_{kj} > d_0 \end{cases}$$

In this formula, $G(d_{kj}, d_0)$ represents the weight of the Gaussian decay, d_{kj} is the commuting time between population sampling point k and park j , d_0 is the preset service threshold or travel time limit, and e is the base of the natural logarithm.

Then, the Ga2SFCA method involves two steps, both incorporating this Gaussian weight:

- 1) Select the location of any park j as the centroid, take the service threshold d_0 of the park (including all possible travel modes) as the search radius, search for all population sampling points k that fall within the service threshold, and calculate the intra-domain provision and demand ratio weighted by the Gaussian function G , which is calculated as follows:

$$R_j = \frac{S_j}{\sum_{k \in \{d_{kj} \leq d_0\}} D_k \times G(d_{kj}, d_0)}$$

In the formula, R_j denotes the ratio of provision to demand of green space area at park j , S_j is the service capacity at point j (area of the park), D_k denotes the number of populations in demand for UGS provision in the search area, and d_{kj} denotes the commuting time between park j and population sampling point k .

- 2) Select the location of population sampling point i as the centroid, search all parks j that fall within the search radius, add up the provision and demand ratio R_j of all parks, and obtain the UGS provision score for the population sampling point i :

$$A_i^F = \sum_{j \in \{d_{ij} \leq d_0\}} R_j \times G(d_{ij}, d_0) \\ = \sum_{j \in \{d_{ij} \leq d_0\}} \frac{S_j}{\sum_{k \in \{d_{kj} \leq d_0\}} D_k \times G(d_{kj}, d_0)}$$

where A_i^F denotes the UGS provision (park area per capita) at population sampling point i , and d_{ij} is the time cost of accessing park j from the population sampling point i .

For the Ga2SFCA approach, the service threshold d_0 of the UGS is a key parameter. As mentioned above, the local government in Shenzhen has set this value at 500 m, which is estimated to be about 6 min of walking time according to the average human walking speed. WHO, instead, recommends a 5-minute walking distance (about 300 m) to evaluate the health benefits of UGS (World Health Organization, 2016). In addition, Fields In Trust (FIT) suggests that residents need to access UGS within a 10-minute walking distance (about 800 m) (Fields in Trust,

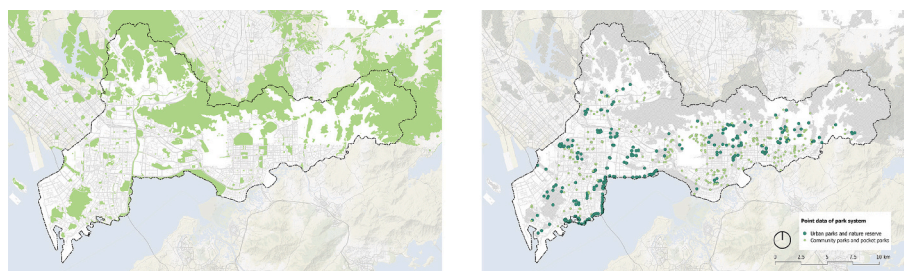


Fig. 2. The park system in study areas and the point data of park entrances.

2020). These different service distances will all be considered in this study, however, it is assumed that residents within a 10-minute walking distance have basic walkable accessibility. For bicycle, public transportation, and self-driving, some studies suggested that the threshold of travel time for residents is between 15 and 30 min. The study follows this argument by setting the travel time threshold at 15 min for cycling and 30 min for public transportation. In the Ga2SFCA model, d0 represents the travel time at which the park's influence becomes negligible, creating a “soft” service boundary.

2.2.3. Assessing equity through population distribution data

For the equity of UGS provision, the study will focus on two aspects: the equity of UGS provision for population distribution and the equity for different social groups. The population in cities is often not evenly distributed, which often results in a portion of residents living within the UGS service areas but not receiving an adequate UGS provision for the size of the population. This study incorporates population distribution data into the 2SFCA approach to investigate the supply-demand ratio between UGS provisioning and population distribution in Shenzhen. Regarding the relationship between UGS supply and different social groups, this study will examine the equity of UGS supply and accessibility for specific age groups (elderly and children) based on the population spatial distribution data in different age ranges in the study area. Such social groups exhibit different usage patterns for parks compared to the general population, necessitating special attention in UGS design and planning process.

2.3. Data sources and processing

The UGS data in the study will be obtained from multiple sources. At first, the “Shenzhen Park Directory 2020” contains all 1206 parks in Shenzhen, including their names, addresses, and categories. In addition, the Open Street Map (OSM) provides geometric data, but they are incomplete, with only 836 parks included. Therefore, this study will revise and supplement the data based on the “Shenzhen Park Directory

2020”. The study will transform the UGS polygon data into point data to facilitate the computation. For urban parks, the study will calculate through their entrances, while community parks will be processed through their centres of mass. Park data from the surrounding areas were not included in this study due to the volume of calculations. Since the study area is of a certain scale and covers the central areas of Shenzhen with dense population, the impact on the overall validity of the data is considered minimal. The figure below shows the UGS data used for this study (Fig. 2).

This study will obtain the travel time of residents to UGS by accessing AMAP's API data. AMAP is one of the most popular web maps in mainland China, and the accuracy of its database has been recognized by the market during its years of operation. The urban space is transformed into a matrix composed of many starting points at a 100 m spatial resolution, and AMAP's API data is able to calculate the time for residents to visit the aforementioned UGS data points from these starting points through different travel modes. The time to obtain the data through the API needs to be more accurate when it is not a holiday and there are no serious traffic accidents. Therefore the time to obtain the data is from 9:00 am to 11:00 am on Wednesday, October 25, 2023 and Thursday, October 26, 2023. This study obtained a total of 21,133 * 579 * 3 data based on walking, cycling, and public transportation travel by accessing the AMAP's API.

In this study, applying accurate and high-resolution population distribution data in the 2SFCA approach is a key focus. Given the aim of reflecting the general state of the urban environment over a long period, this research prioritizes the use of static population distribution data. “WorldPop” serves as a representative open-access database for such purposes. WorldPop integrates a variety of data sources, including census data, land cover information, MODIS NPP data, elevation, and slope, utilizing a random forest model to estimate population density (Stevens et al., 2015). This database has been widely used across multiple disciplines, and has proven to be effective in Chinese urban areas (Gaughan et al., 2016; Liu et al., 2020; Zhao et al., 2024). The database illustrates the distribution of the population within cities at a resolution

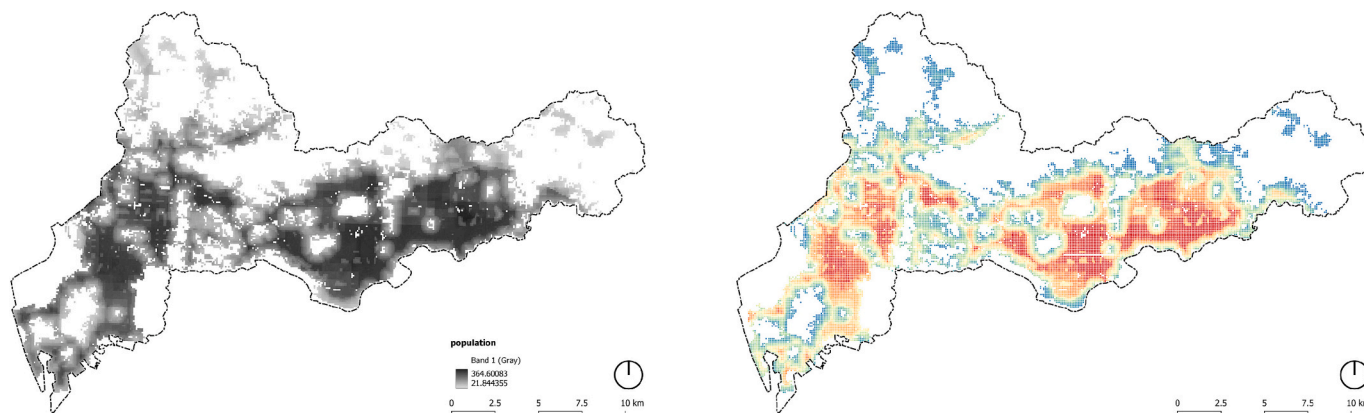


Fig. 3. Population spatial distribution data and sampling points based on it.

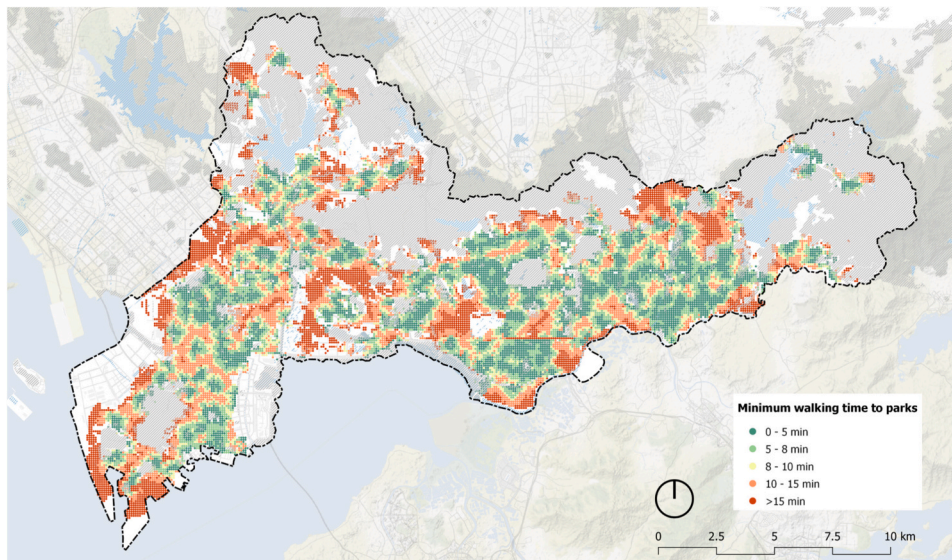
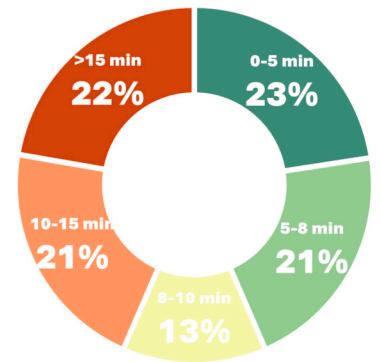


Fig. 4. The pattern of walking accessibility in the study area.

WALKING ACCESSIBILITY PATTERN



Within the walking service areas **57%**

Outside the walking service areas **43%**

of 100 m (Fig. 3). Such resolution is much less than the maximum walkable distance to the parks (500 m), so it is valid for this study. The WorldPop data were extracted by municipal districts and fitted based on the “Shenzhen Seventh National Population Census Bulletin (No. 1)” to obtain static population distribution data. In addition, the database includes the spatial distribution of the population across different age groups, and this data is also incorporated into the dataset of sampling points to investigate the equity of UGS accessibility and supply for various social groups.

For this analysis, the study utilizes static population distribution data. This choice is deliberate, aiming to establish a crucial baseline understanding of the fundamental, structural inequities in UGS availability within the existing urban form. We acknowledge that high-density environments are inherently dynamic, with shifting population distributions and land-use patterns. However, a “static snapshot” is essential for diagnosing these persistent structural issues before considering temporal variations. The implications of this methodological choice and directions for future dynamic analysis will be further explored in the conclusion.

3. Results

3.1. The patterns of UGS accessibility in different travel modes

Walking accessibility can be seen as the foundation of participation in society for urban residents and contributes to social well-being and public health in many ways (Lättman et al., 2016). Walking accessibility is critical for residents to travel to the nearest UGS (including both community parks and urban parks) for daily recreational activities, and children and seniors are more reliant on this commuting mode. The Fig. 4 below illustrates the pattern for walking accessibility in the study area. In urban areas with valid population data, residents in 23 % of urban areas are able to reach the nearest UGS within the walking time recommended by WHO (5 min), 45 % of urban areas are able to reach it within 8 min, and 58 % are able to reach it within the walking time advocated by FIT (10 min). Such urban areas can be considered as being within the walking service area of the UGS system. However, there are still 42 % of urban areas where residents are unable to access a UGS by walking in a reasonable time, with 22 % of urban areas taking 10–15 min to reach the nearest UGS and the remaining 20 % of urban areas

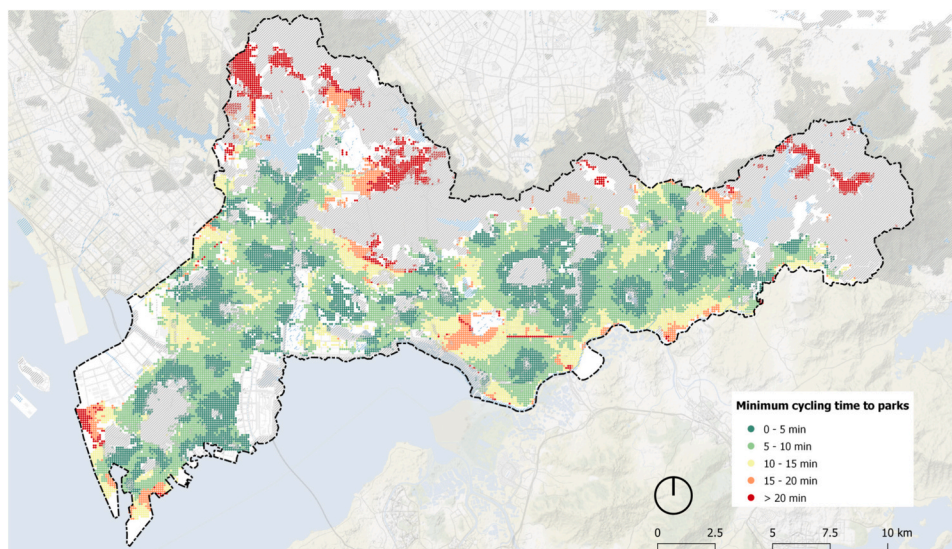
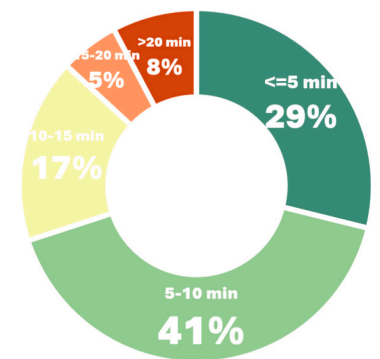


Fig. 5. The pattern of cycling accessibility in the study area.

CYCLING ACCESSIBILITY PATTERN



Within the cycling service areas **87%**

Outside the cycling service areas **13%**

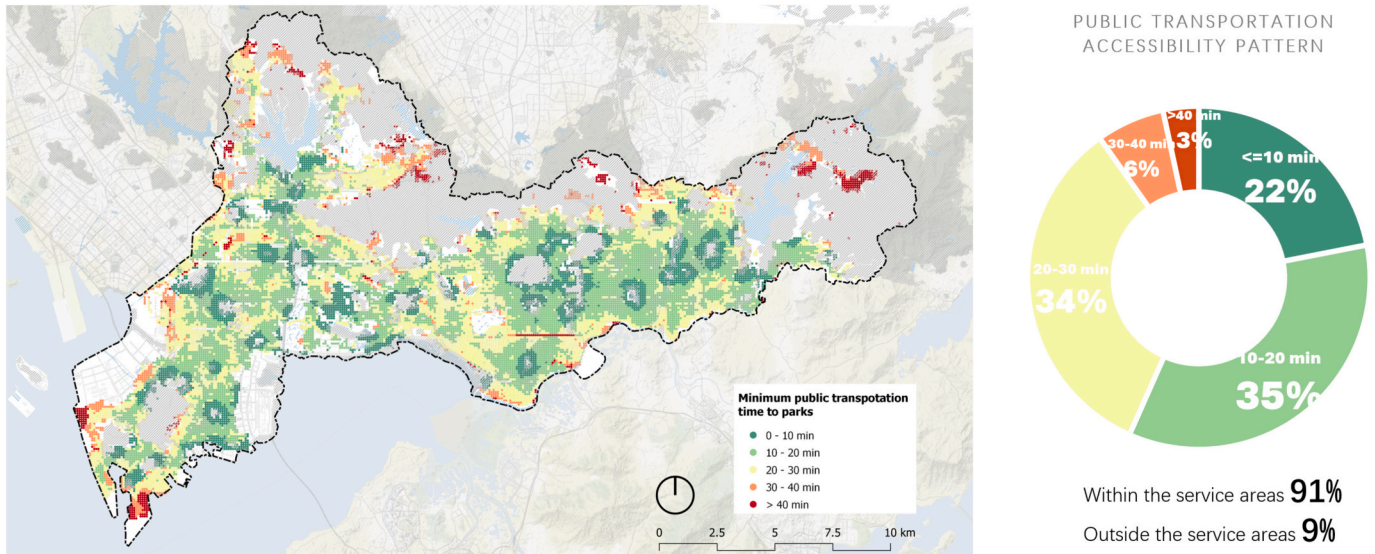


Fig. 6. The pattern of public transportation accessibility in the study area.

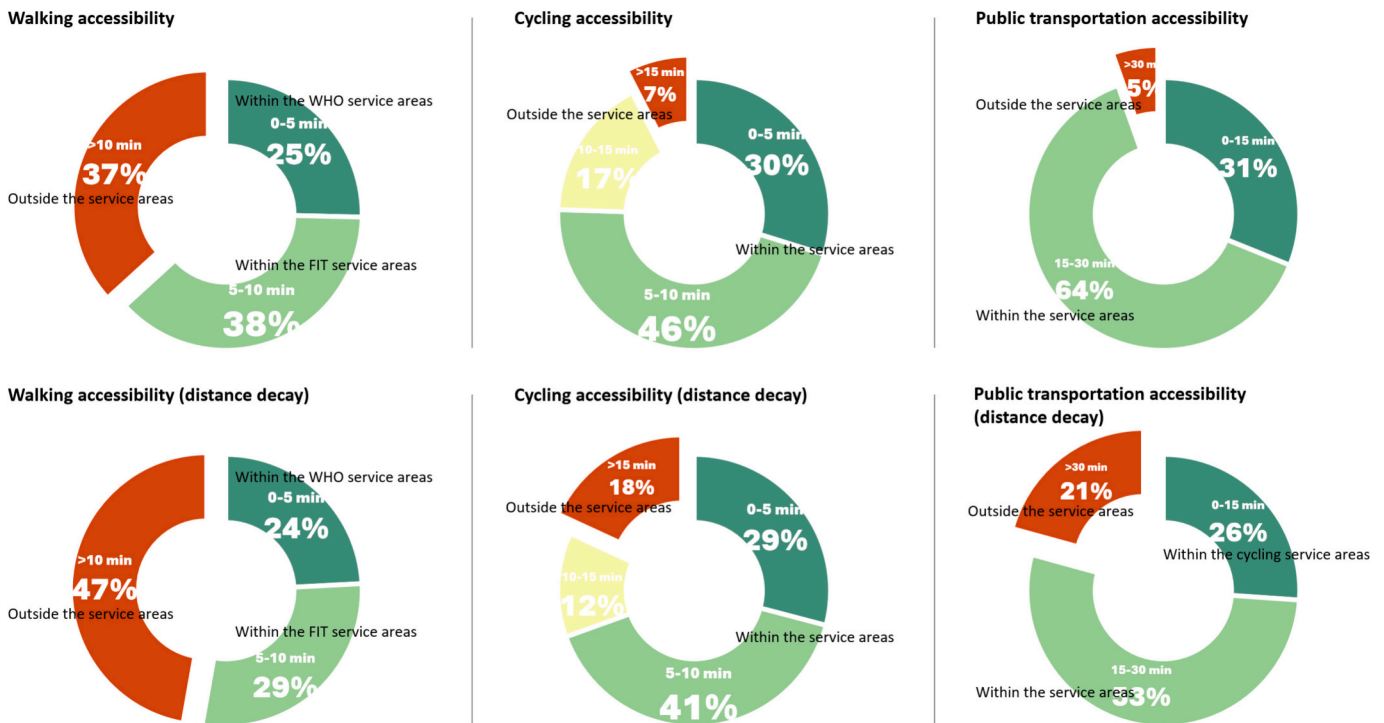


Fig. 7. The population covered by the service areas of the park system under different travel modes.

taking more than 15 min. The results show that walking accessibility pattern within the study area is not a positive picture, with nearly half of the urban area's residents struggling to get to UGSs for recreational activities by walking.

Cycling is widely advocated as a feasible alternative to vehicle mobility for its sustainability, affordability and equity, ability to avoid traffic congestion, and promote social health (Handy et al., 2014; Pucher et al., 2010). Therefore, this study regards cycling as a commuting mode in which residents travel to larger urban parks and spend a longer time on formal recreational activities. Fig. 5 below illustrates the pattern of cycling accessibility in the study area. The state of cycling accessibility is considerably better compared to walking accessibility. Residents in 29 % of urban areas are able to access the nearest city park by cycling within

5 min, and 70 % of urban areas are able to do so within 10 min. Within the 15-minute ride time threshold, the service area of the UGS system is able to cover 87 % of the urban areas. Therefore, residents in most of the urban areas are able to access nearby urban parks for formal recreational activities by riding within a reasonable amount of time.

A well-functioning public transport system is an alternative to private vehicles for urban mobility that offers better sustainability, equity, and systematic mobility. Public transport systems also play an important role in the accessibility of UGS. Many related plans or reports, such as the London Plan, regard it as the main commuting mode for residents traveling to larger urban parks for formal recreational activities on weekends. This study also follows this to examine the public transport system in the study area (considering the accessibility of urban parks

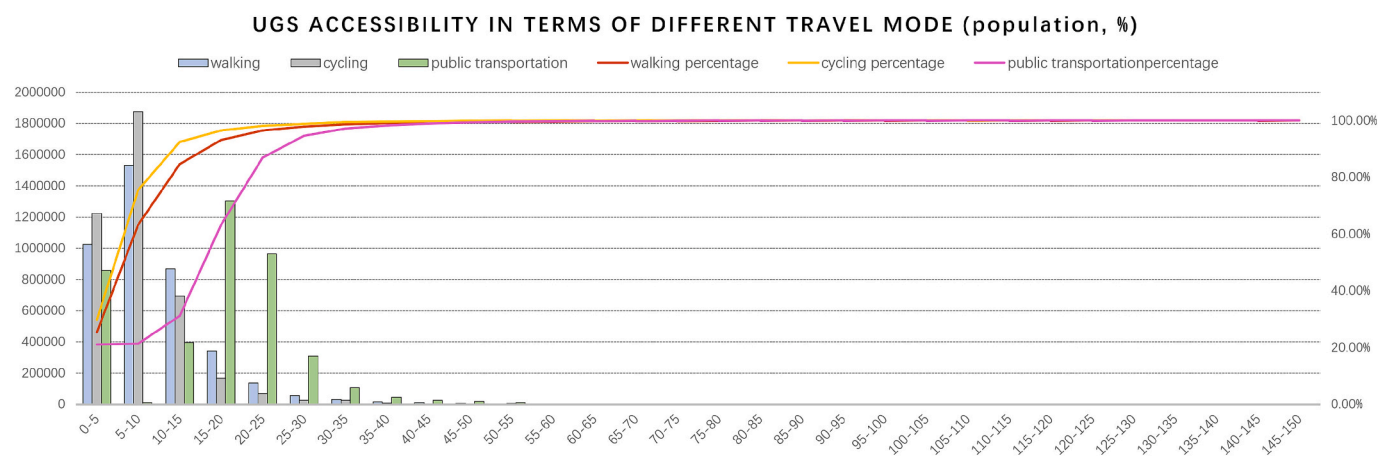


Fig. 8. The distribution of the population served by the park system under different travel modes along the commuting time axis.

only). As shown in Fig. 6 below, residents in 91 % of the urban areas are able to reach the nearest urban park within the 30-minute public transport commuting time threshold, which covers the vast majority of the study area. However, only 57 % of these urban areas can be reached within 20 min and 22 % within 10 min, which means that even though most of these areas are within the service area, a significant proportion of residents still need to spend more than 20 min on public transport to get to a urban park.

3.2. The equity of UGS availability in terms of population distribution

The population distribution in urban areas is often uneven. In such cases, the spatial accessibility of UGS may not accurately reflect the proportion of residents who have the opportunity to use these parks. Fig. 7 below illustrates the coverage of the UGS service areas under different commuting modes for the population in the study area. Similar to the spatial accessibility situation, the majority of the population within the study area can reach the nearest urban park within reasonable commuting times through cycling or public transportation (93 % for cycling and 95 % for public transportation). However, a considerable portion of residents (37 %) are unable to reach the nearest park within a reasonable walking time. In terms of population distribution, disparities in UGS accessibility persist across different commuting modes and usage patterns, posing disadvantages for social groups such as the elderly and children who rely more on short-distance walking.

When distance decay is taken into account, the accessibility of each mode of commuting deteriorates to varying degrees. This suggests that a significant portion of the population resides near threshold zones, where the reduced perceived accessibility can suppress their willingness to travel to UGS. Under these conditions, 47 % of the population cannot reach a nearby park within walking distance, 18 % face the same issue when cycling, and 21 % when using public transportation. Notably, when accounting for distance decay (reflecting travel willingness) cycling emerges as the most effective mode of commuting to access UGS.

Fig. 8 below elaborates on the distribution of the population proportion served by the UGS system within the study area under various travel modes along the commuting time axis. This also reflects the differences in the availability of different travel modes in the distribution of the population, as mentioned earlier. The case is similar for walking and cycling, the population within the service areas mostly concentrates within the 10-minute timeframe, with 5–10 min being the most prevalent. Compared to walking, a larger proportion of residents can access nearby parks within a 10-minute through cycling. However, it is essential to note that the corresponding recreational activity demands for these two modes are different. Public transportation, on the other hand, exhibits significant differences, with the majority of the service population distributed within the 15–25 min time range. Since the API

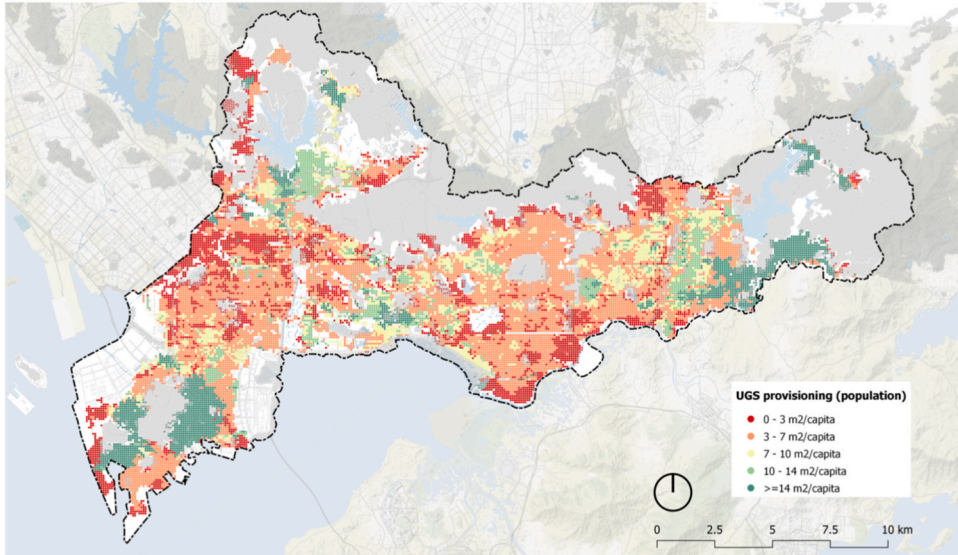
data counts the paths taken by residents near urban parks that are directly accessible by walking as part of the public transportation paths, it is appropriate to exclude the population distribution in the less-than-5-minute timeframe. Thus, from the data, it appears that there is a minimum travel time threshold of approximately 10 min for the accessibility of UGS under public transportation.

UGS availability by definition encompasses more than just UGS accessibility; it must also consider whether residents have an adequate provision of park area. In traditional standard approaches, the park area per capita is often calculated roughly within a larger region (the ratio of the population to the park area within the region). Under this approach, the UGS provision in the study area is approximately 8m² per capita. It is lower than the standards of 10m² in Shenzhen and data from other studies. However, it exceeds the value of 7m² per capita in the Chinese urban greening standards. Taking into account the differences in population counting methods, this discrepancy can be considered within a normal range. However, this standard approach, by neglecting the complexity arising from the uneven distribution of population and UGS accessibility, often fails to accurately reflect the true picture of UGS provisioning.

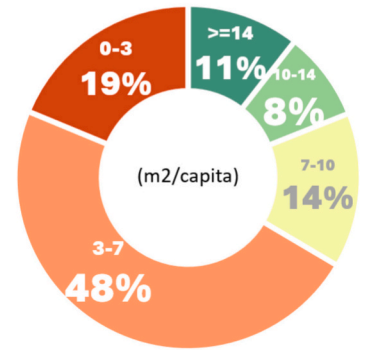
Fig. 9 below illustrates the spatial distribution of UGS supply within the study area. It reflects the park area supply available to each resident within each statistical unit during reasonable commuting times for walking, cycling, and public transportation. As can be seen from the figure, even though the overall park area per capita is higher than the China urban greening standard, in reality 67 % of the residents in the study area still have less than 7m² of available park area per person, and 19 % of the population has less than 3m² per person. If the standard set by the local government in Shenzhen (10m² per capita) is followed, only 19 % of the population has sufficient park area supply. When incorporating the decay function into the analysis, the situation becomes even more concerning: 75 % of residents do not have access to an adequate standard of UGS supply, and as much as 43 % of the population have less than 3 m² of accessible UGS per capita. This indicates a rather unsatisfactory state of UGS provision in Shenzhen's central areas. Moreover, a significant portion of residents—although technically within a reasonable distance to parks—are located near threshold limits, which can suppress their actual willingness to travel to these spaces in practice.

As evident from the data distribution in Fig. 10 below (according to the Ga2SFCA approach), the main reason for this issue is the inequality in UGS provision across the spatial and population distribution. From the perspective of population distribution, the park area per capita for the majority of the population in the study area is below the average of 8m²/p, which is also lower than the Shenzhen standard of 10m²/p. The distribution of the data for each statistical cell shows that the median is 5.3m²/p, indicating a significant difference from the average (8.4m²/p). The average in the data distribution is close to the upper quartile of the

UGS Provisioning



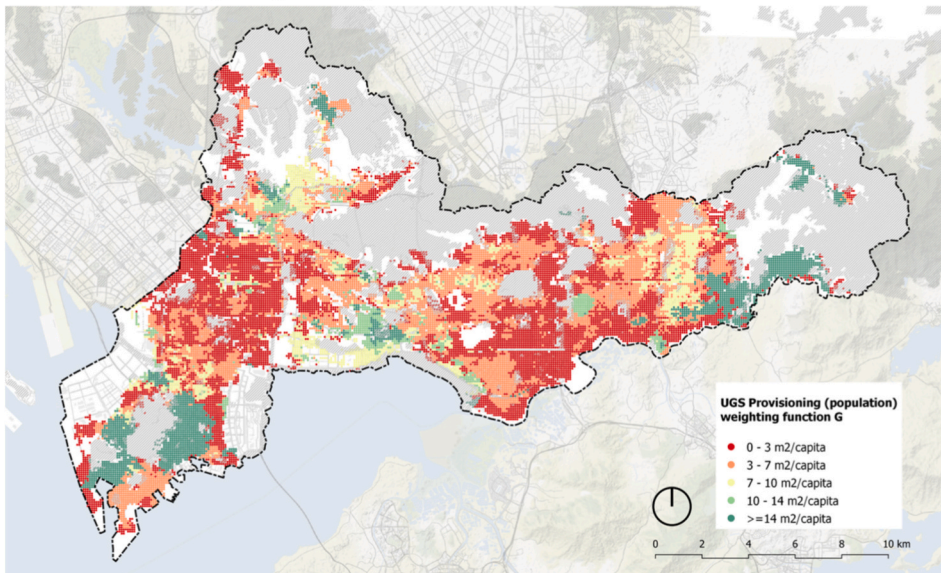
PARKS PROVISIONING IN TERMS OF POPULATION



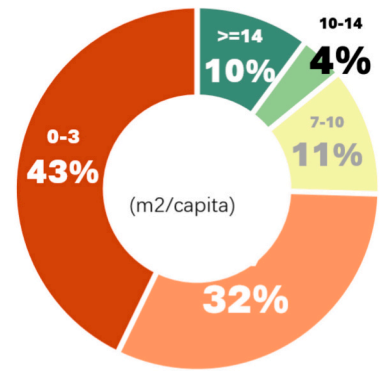
Have sufficient available park area **33%**

No sufficient available park area **67%**

UGS Provisioning weighted by the Gaussian function



PARKS PROVISIONING IN TERMS OF POPULATION

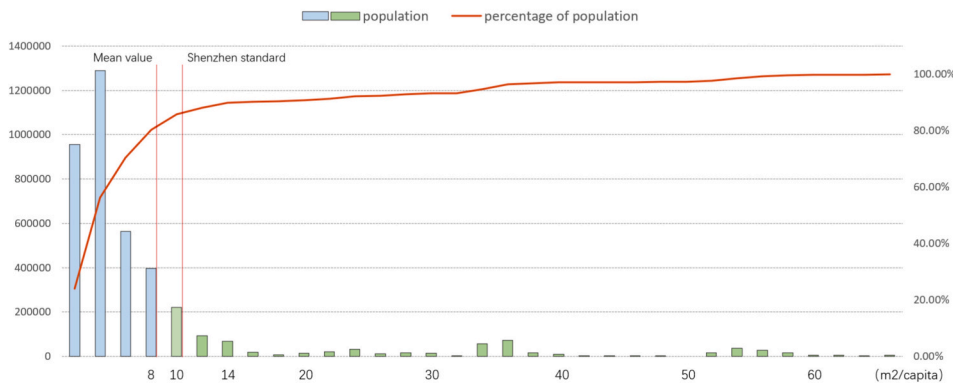


Have sufficient available park area **25%**

No sufficient available park area **75%**

Fig. 9. The pattern of UGS provision (park area per capita) in the study area.

THE DISTRIBUTION OF UGS PROVISION ACROSS THE POPULATION (population, %)



DATA DISTRIBUTION OF PARK AREA PROVISION

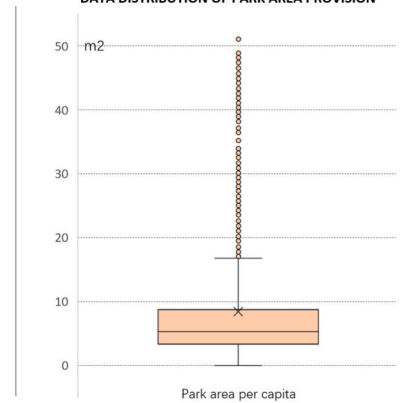


Fig. 10. The data distribution of UGS provision (weighting function G) in the study area.

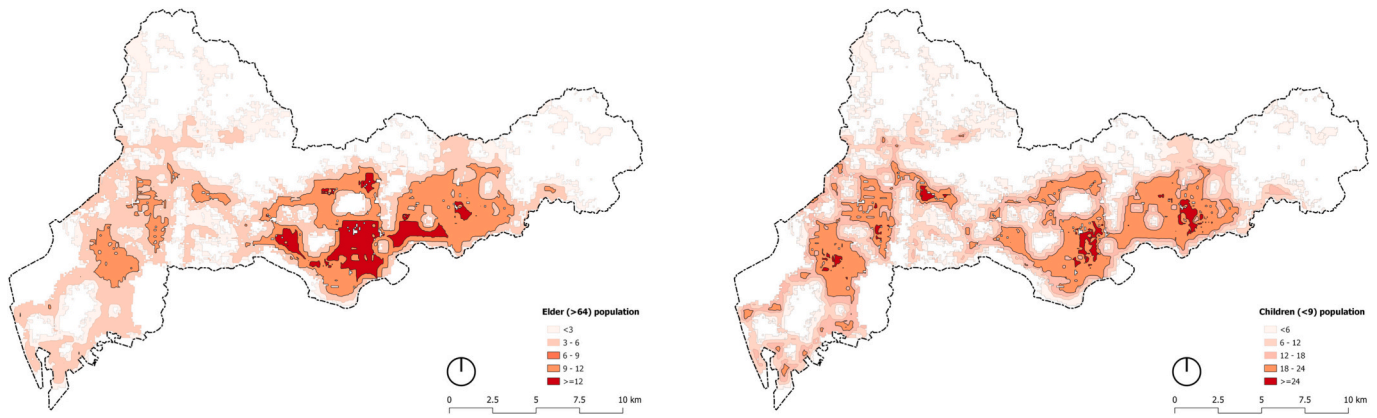


Fig. 11. Urban areas with a high concentration of elderly and children.

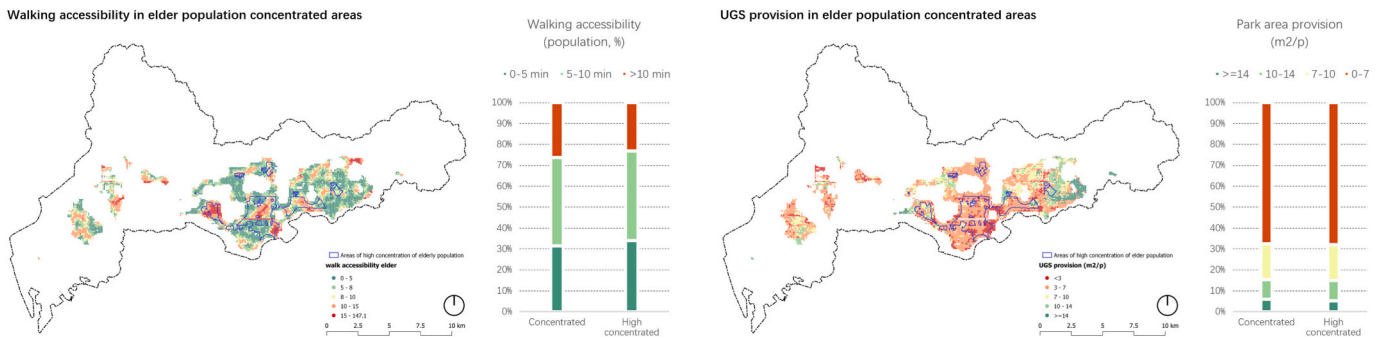


Fig. 12. Spatial patterns of UGS walking accessibility and provision in urban areas with high concentrations of elderly populations.

overall data sample, and the data overall is quite dispersed, with some statistical units reaching $20m^2/p$ or even exceeding $40m^2/p$. This suggests that while most residents do not have sufficient UGS provision on average, a small percentage of residents have abundant UGS resources. This aligns with the spatial distribution of UGS provision, where there is an overflow of UGS resources on the east and southwest of the study area but not supplied to the wider population.

3.3. The equity of UGS accessibility in terms of social groups

The equity in UGS availability also includes whether different social groups have equal access to the park and the provision of UGS. It covers a wide range of topics from different genders, ethnic groups, income levels and age ranges in society. Among them, The elderly and children

are two social groups that are representative for the UGS availability. On one hand, UGS provision is crucial for the health and well-being of these two social groups; on the other hand, their reliance on walking accessibility is higher due to physical reasons. Fig. 11 below illustrates the spatial distribution of the elderly (>64) and children (<10) populations within the study area. The distribution of the elderly population is relatively concentrated, with the majority located in the central part of the study area (Luohu District and Nanshan District), which is also the earliest area in Shenzhen to undergo urban developments. In comparison, the distribution of the child population is relatively even. Therefore, this study explored the equity of park accessibility and supply through the distribution of the elderly population.

Fig. 12 below elaborates the distribution of park walking accessibility and provision in areas with a high concentration of elder

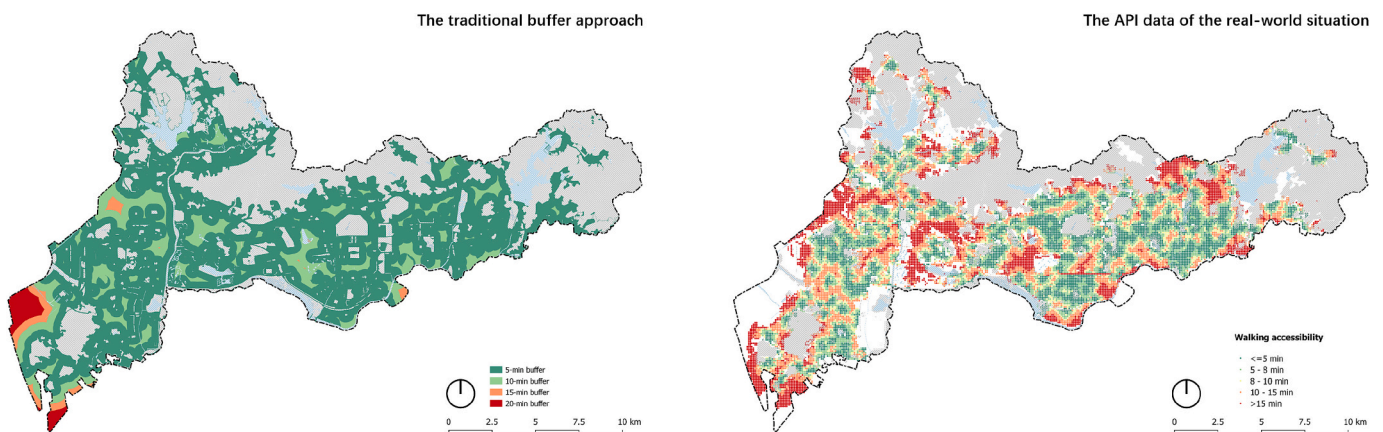


Fig. 13. Comparison of differences in UGS walkability calculated by different approaches.

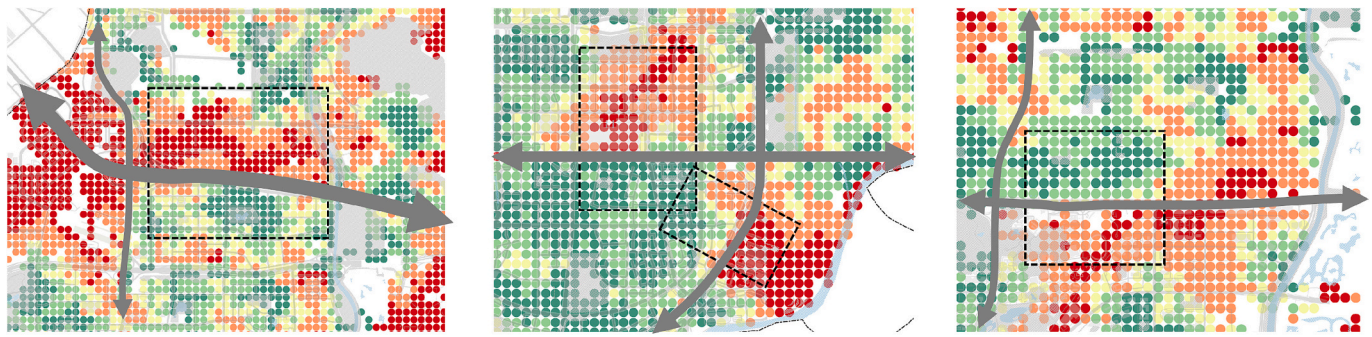


Fig. 14. The impact of highways and primary roads on the walking accessibility patterns in the study area.

populations. In terms of walking accessibility, the situation in such areas is similar to the overall situation of the study area, with one-third of the elder population still having difficulty getting to the nearest park on foot. On the other hand, the UGS provision in these areas is also generally consistent with the whole study area, with close to 70 % of the population not having sufficient park provision. In addition, the areas with the highest concentrations of elder populations fall within the areas of lowest UGS provision in the study area. Although the data distribution does not show a significant difference from the general situation in the study area, the specificities of this social group should also be taken into account. The elderly population is more dependent on walking accessibility than the prime age population due to physical factors, and the threshold for maximum walking distance is shorter accordingly. These factors require that the UGS planning and design process be biased in favour of these social groups, which suggests that the equity of UGS availability in the study area is not optimised.

4. Discussion: from systemic challenges to strategic solutions

4.1. The systemic challenges of high-density developments for UGS availability

4.1.1. A high-density illusion: overestimated accessibility and provision

The importance of accessibility is widely recognized in the UGS design and planning process. Related plans normally set a certain service area for each type of park or travel mode, and require that the vast majority of the population and urban area (usually greater than 80 %) be covered by the service area. In this process, service areas are often defined using fixed-distance buffers or network analysis as mentioned earlier. However, as shown in Fig. 13 below, these methods tend to overestimate the accessibility of the UGS system compared to the actual situation, especially for walking accessibility. According to the buffer approach, nearly all the population within the study area can be covered by service areas. However, in reality, over one-third of the population still cannot access nearby parks by walking. This inconsistency between proximity and accessibility needs to receive adequate attention in UGS design and planning in high density contexts.

On the other hand, the UGS provision is also an essential topic in the UGS design and planning process. Most cities have set an overall standard for park area per capita, or furthermore a specific standard for the city centre. However, for high-density cities, the central areas are often vast and characterized by uneven population distribution, similar to the research area in this article. In such cases, the overall value of park area per capita in the urban areas may not accurately reflect the UGS provision because residents cannot access all the parks in the city. Additionally, the inadequacy in this provision should also be considered with respect to the specific needs of different social groups, such as the dependence of the elderly and children on walking accessibility. In these circumstances, the gap in UGS provision may be further exacerbated.

4.1.2. Layout deficiencies: the green space “vacuums”

One of the key factors contributing to the above issues is the improper layout of the UGS system, which directly reflects the spatial logic of high-density urban development. From the perspective of walkability, small-scale community parks and pocket parks are just as important as large urban parks, as they form the foundation of a fine-grained green network. However, in the central areas of this study—particularly in some high-density blocks of Futian District—there is a severe shortage of such small parks, which is a major cause of poor walking accessibility.

In terms of UGS provision, large urban parks and nature reserves play a more prominent role, but their uneven distribution also leads to inequities. In the study area, major parks are mostly located in the northern, eastern, and western parts, creating large “service voids” in the southern Futian District and central Nanshan District. These areas were developed earlier and are now among the most densely populated. The combination of high population concentration and long distances to major parks exacerbates the problem of insufficient provision. In these core zones where both population and capital are highly concentrated, soaring land values make public green space economically uncompetitive. As a result, large parks are pushed to the urban periphery, leaving the areas with the highest demand in a state of UGS scarcity.

For vulnerable groups such as the elderly and children—who rely more heavily on nearby recreational opportunities and have shorter walking ranges—small-scale green spaces are especially vital. In this study, these social groups are also highly concentrated in densely populated, early-developed areas. Given their dependence on walkable UGS, the inadequacy of supply becomes even more pronounced. The current layout of UGS does not adequately account for the needs of these sensitive groups.

4.1.3. Imbalanced mobility: the loss of walkability and the irreplaceability of travel modes

As can be seen in Sections 3.1 and 3.2, UGS accessibility under different travel modes varies significantly within the study area. While both cycling and public transport achieve over 90 % coverage, walking accessibility falls short of two-thirds. Crucially, different modes of travel correspond to different recreational needs and are not interchangeable. Residents may be willing to spend 20 min on the subway to visit a large urban park on weekends, but they are unlikely to make such a trip for everyday leisure after dinner. This means that over one-third of residents lack access to nearby spaces for daily recreation. Such disparity also poses a serious challenge to the equity of the UGS system, particularly for vulnerable groups like the elderly and children, who rely more heavily on walking and may have no access to recreation at all under these conditions.

Walking is not only fundamental to residents' participation in social life but is also considered a core issue in high-density urban development. The deficiency of walking accessibility in the study area highlights its critical role within the green space system. Although adding community parks or pocket parks is an effective solution, the large gap between results from buffer analysis and API-based travel times suggests

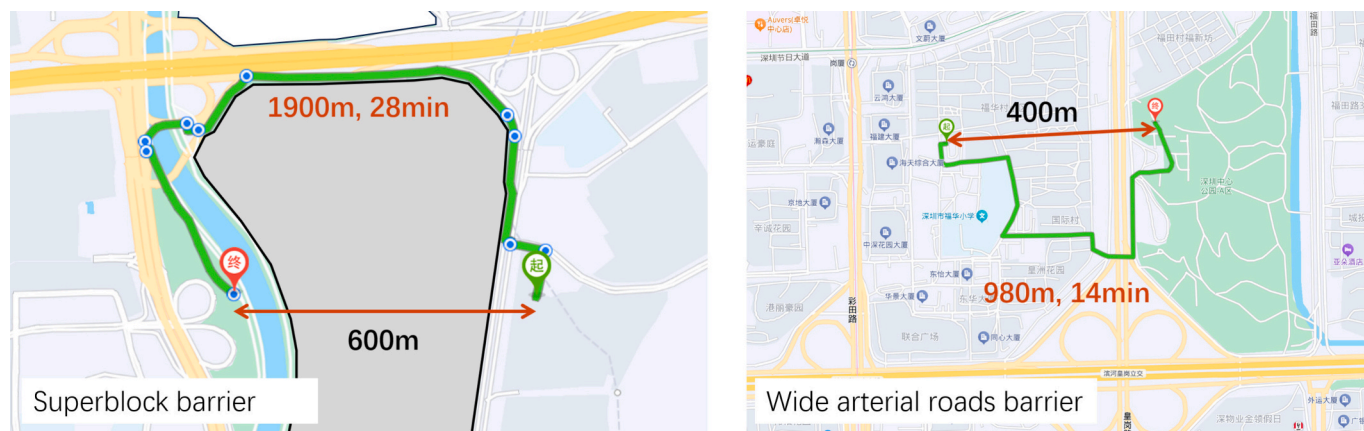


Fig. 15. The additional effort and difficulty required for pedestrians to cross superblock and arterial road barriers.

that the absence of small parks is not the sole cause. In order to accommodate high traffic volumes, urban form in high-density areas is often dominated by wide arterial roads and superblocks designed for vehicle efficiency. While these elements serve traffic flow, they also form physical barriers to pedestrians, fragmenting neighborhoods and rendering nearby parks functionally inaccessible. From an equity perspective, elderly and child pedestrians face greater difficulty crossing these roads and may be exposed to higher travel risks. As shown in Fig. 14, high-density traffic demands lead to wider roads, which themselves become major obstacles to walkability.

Fig. 15 below illustrates, at the local scale, the additional effort and difficulty required for pedestrians to cross these large blocks and wide roads.

4.1.4. Suppressed potential: cycling under risk

Although both cycling and public transportation demonstrate high service coverage, their spatial distribution patterns differ significantly. Within the 15-minute travel threshold, cycling covers 87 % of the built-up area and 93 % of the population, while public transport covers only about 30 %. Considering factors such as waiting times, transfers, and traffic congestion in high-density areas, cycling is undoubtedly the most efficient travel mode within short to medium distances. Coupled with its benefits for energy conservation, emissions reduction, and public health, cycling holds significant untapped potential in high-density urban development.

However, API data may not fully capture the actual conditions of cycling accessibility, which still faces numerous real-world challenges in high-density environments. According to the *Shenzhen Bicycle Transportation Development Plan (2021–2035)*, as of 2020, bicycle lanes accounted for only 13.7 % of the city's total road length, with most lacking physical separation from motor vehicle traffic. This means that many of the cycling routes assessed in this study are situated in high-risk, mixed-traffic environments. Busy roads and wide intersections in dense urban areas also pose substantial safety hazards for cyclists. Due to

inadequate design, cyclists are often forced to make dangerous left turns at wide crossings shared with vehicles. Additional issues such as a lack of clear signage, poor nighttime lighting, and insufficient parking infrastructure further undermine the cycling experience. As a result, the actual cycling accessibility to green spaces in the study area is far less favorable than what API data suggests.

4.2. The importance of spatial design on local scale for UGS availability in high-density contexts

To address the systemic challenges arising in high-density urban contexts, urban design must move beyond macro-level planning toward more targeted, human-scaled spatial interventions. In environments characterized by intense construction and infrastructure concentration, refined spatial design becomes an essential tool for achieving both efficiency and sustainability. The following strategies offer specific design responses to the issues diagnosed earlier:

4.2.1. Beware of overestimating supply and accessibility

High-density urban design must first acknowledge and address the widespread overestimation of UGS accessibility and supply. Planners and designers can no longer rely on Euclidean distance or simple buffer analyses. This study clearly demonstrates that in high-density environments, the existence of physical and perceptual barriers such as major roads and large residential complexes often renders “proximity” meaningless in terms of actual accessibility. Therefore, the starting point for design interventions should be grounded in more realistic assessment methods—such as the navigation API data analysis used in this study—to accurately identify areas that appear well-served but in fact suffer from serious accessibility barriers. Only then can subsequent design interventions effectively target real problems.

4.2.2. Building a “green network” to counter spatial fragmentation

To address uneven green space distribution and fragmented

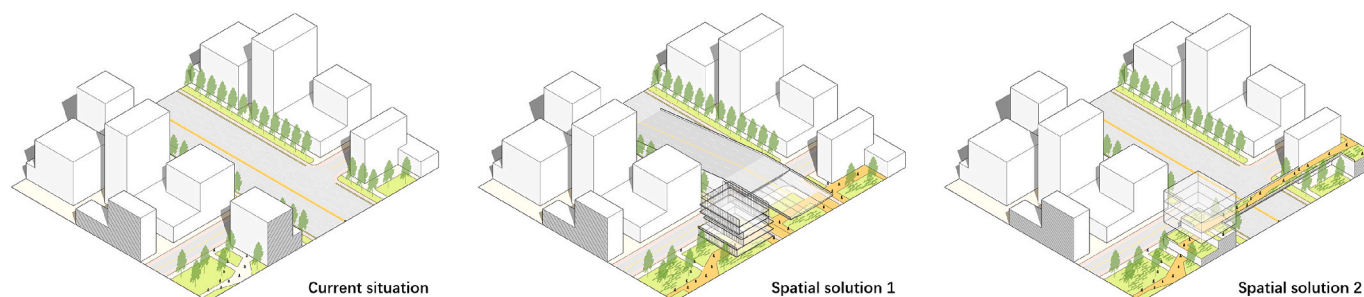


Fig. 16. An example of enhancing the walking accessibility of a community park through spatial design on the local scale.

networks, design strategies should focus on constructing a systematic green infrastructure network. In densely populated built-up areas, urban renewal initiatives should make efficient use of underutilized land, ground floors of buildings, rooftops, and other available spaces to embed pocket parks and other small-scale green spaces. Linear parks along streets or waterways can also be introduced. This “infill” approach weaves a fine-grained green network into the coarse urban fabric of high-density developments, countering spatial homogenization and isolation caused by large-scale construction. To promote equity, these small green spaces should be prioritized in areas with high concentrations of elderly and children—especially in aging urban districts—and be equipped with age-appropriate and child-friendly facilities to meet their essential need for safe and convenient recreational spaces close to home.

4.2.3. Multi-scale walkability strategies

Beyond repairing the built environment, high-density urban design must proactively shape urban form to prevent accessibility issues from emerging. A more human-centered block scale should be promoted. Breaking up superblocks can significantly increase road network density and the range of walking routes, while also helping to moderate street widths. For existing physical barriers such as wide arterial roads, local-scale spatial design solutions are needed. For example, partial elevation of main roads, clearly guided pedestrian overpasses, or underpasses can ensure the continuity and safety of the pedestrian system (see Fig. 16). These design measures are especially important to safeguard the independent mobility of vulnerable populations such as children and the elderly.

4.2.4. Developing safe and dedicated bicycle infrastructure

To fully unlock the potential of bicycles in high-density cities, safe and continuous dedicated infrastructure is essential. This includes: (1) physically separated bike lanes on major urban roads; (2) clear bicycle signage, dedicated traffic signals, and waiting zones at intersections; and (3) ample bicycle parking facilities at park entrances. These measures aim to rebalance the motor vehicle-dominated transportation system and make it better suited to the compact and dense urban form.

5. Conclusion and outlook

This article investigates the typical conditions of Urban Green Space (UGS) availability in high-density urban environments, using the central areas of Shenzhen as a case study. By combining navigation mapping API data, high-resolution population data, and the 2SFCA approach, this study reveals a fundamental paradox: the physical proximity promised by high-density development does not automatically translate into functional UGS availability for residents. Our findings demonstrate how specific characteristics of high-density urbanism—such as car-centric infrastructure, land-use patterns driven by intense economic pressure, and a coarse-grained urban fabric—systematically create barriers that undermine accessibility, produce severe inadequate in UGS provision, and disproportionately affect vulnerable groups like the elderly.

The significance of this study lies in its argument that overcoming these challenges requires moving beyond macro-level planning metrics toward a deliberate, multi-scalar urban design approach. High-density urban environments demand more systematic and meticulous design considerations, ranging from the rational layout of a hierarchical green network to human-scale interventions that reclaim street space, enhance pedestrian and cycling connectivity, and ensure that design benefits are equitably distributed among all social groups.

The study has some limitations that also point to directions for future research. The analysis focused exclusively on the formal park system; future work could include the role of informal green spaces in residents' recreational activities. Additionally, this study utilizes static population data, which provides a critical baseline but does not capture urban dynamics. Therefore, future research should leverage dynamic or

longitudinal data to analyze how UGS demand and accessibility evolve over time. Finally, this study did not fully capture park quality and attractiveness, which are essential factors influencing residents' willingness to visit. Future studies should incorporate these aspects, integrating interdisciplinary perspectives like environmental psychology to better understand user preferences and perceptions in complex urban environments.

CRedit authorship contribution statement

Shile Zhou: Writing – original draft, Visualization, Formal analysis, Conceptualization. **Yingying Gan:** Writing – review & editing, Software, Methodology, Data curation.

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.

Data availability

The data that has been used is confidential.

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