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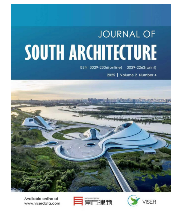

Spatial-temporal Differentiation and Influencing Mechanism of Accessibility of Park Green Spaces: A Case Study Based on Shenzhen City

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ABSTRACT: Park green space is an important part of the urban natural ecosystem and public service facilities. The accessibility index of park green space can characterize the difficulty of using park green space for residents. In addition, it is an important index that reflects the rational layout and fair use of park green spaces. With the rapid development of urbanization, the unrestrained expansion of construction land, and the continuously increasing demands of the population have led to a gradual imbalance between the supply and demand of park green spaces. In this study, the spatial-temporal differentiation characteristics of accessibility of multi-scale park green spaces in Shenzhen under multiple travel modes from 2013 to 2020 were analyzed using the Gaussian two-step floating catchment area (Ga2SFCA) method, which comprehensively considers both supply and demand. The influencing degree of each factor on the accessibility of park green space was studied with a geographical detector from the global scale, through which the dominant factors were screened. The spatial differentiation of the action intensity of each dominant factor on the local scale was investigated using the geographically weighted regression (GWR) model. Results showed that from 2013 to 2020:

1) Within the scope of construction land, the number and area of green parks in Shenzhen increased continuously. The number of community parks increased the greatest amount, and the area of comprehensive parks expanded the greatest amount. There was an imbalanced distribution pattern, which is characteristic of "more in the west and less in the east", "from the inner areas to the outer areas", and expansion from south to north. 2) The demand of residents for park green space was positively correlated with population density. The population density in the western region of Shenzhen was increasing gradually, and the population density in the eastern region was always low. The high-value area of green space demand extended gradually from the inner areas to the outer areas. 3) The accessibility of park green space generally presented a rising trend. The proportion of high-value residential areas was increasing gradually. The accessibility of the outside area became gradually higher than that of the inside area. The average accessibility of community parks achieved the highest growth rate, while the accessibility of comprehensive parks was basically stable. The standard deviation of special parks increased the most, and the spatial differentiation was intensified. 4) In 2013, the p-value of all influencing factors was 0, which passed the 0.01 significance test. In 2020, only the three factors of park area proportion, park entrance and exit density, and road density passed the 0.01 significance test, indicating that the spatial distribution of park accessibility from 2013 to 2020 was closely related to green space factors and road factors. The correlations of park accessibility with location, economy, and natural factors presented a downward trend with the development of science and economy. 5) According to the determination power (q-value) of the dominant factor, the q-values of the proportion of park area, park entrance and exit density, and road density all showed a downward trend on the dynamic level. The factors can be ranked road density > proportion of park area > park entrance and exit density in terms of action intensity. This revealed that road density was a dominant factor in park accessibility, with an explanatory power of as high as 10%, which was much larger than that of other factors. The park entrance and exit density and the proportion of park area were important factors for park accessibility. 6) The influences of different factors on the accessibil-

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ity index of park green space have significant spatial differences. Road density (X4) and proportion of park area (X1) had a greater impact in the eastern study area, while park entrance and exit density (X2) had a greater impact in the western study area. The research enriches perspectives on green space accessibility. The method of exploring the spatial-temporal differentiation characteristics and influencing mechanism of green space accessibility not only can be applied to the layout and planning of urban park green spaces, but also provides a reference to analyze other forms of geographical accessibility.

KEY WORDS: park green space; accessibility analysis; spatial-temporal evolution; gaussian two-step floating catchment area method; influencing mechanism

Introduction

The park green space is an essential part of the urban natural ecosystem and public service facilities. They not only have ecological functions, such as improving the urban environment [1] and reducing the risks of rain and flooding [2], but also social functions, including promoting public health [3] and enhancing real estate value [4]. The Central Committee of the Communist Party of China and the State Council proposed the concept of "Health for All" in the "*Healthy China* 2030" *Plan Outline*. Notably, in the post-pandemic era, the importance of urban green space in promoting public health has become increasingly prominent [3]. However, with the rapid development of urbanization, the disorderly expansion of urban construction land and the surge in population have led to a severe imbalance between supply and demand of urban park green spaces [5]. Furthermore, the current urban park green space assessment in China still primarily uses traditional quota indicators, such as per capita park green space area and green coverage rate, as the main standards, which are difficult to reflect the actual effectiveness of planning implementation and the rationality of spatial distribution [6]. The accessibility of park green spaces typically refers to the difficulty residents face in reaching a park, often due to obstacles such as distance and time. It is an important indicator for measuring the service capacity and spatial configuration of urban park green spaces [7].

A review of research by domestic and foreign scholars on the accessibility of park green spaces encompasses multiple disciplines, including landscape architecture, urban and rural planning, and geographic information. The research focus has gradually shifted from the early exploration of the relationship between physical activity and park accessibility [8] to emerging topics such as public health [9], environmental justice [10], and green space equity [8, 11, 12]. Public health focuses on the relationship between the accessibility of park green spaces and residents' physical health [13] and mental health [14]. Studies have found that the accessibility of park green spaces is directly proportional to the frequency of residents' contact with parks, so that better park accessibility can reduce the risk of physical and mental illnesses [13]. With research on environmental justice and the accessibility of park green spaces focusing on the perspective of "racial differences", many foreign scholars have found that wealthy white communities have higher accessibility of park green spaces and better park facilities than low-income people of color [15]. The study of green space equity has gone through three stages: quantitative equilibrium, spatial equity, and social equity. In the spatial equity stage, green space accessibility was introduced to measure the utilization efficiency and spatial allocation of green space resources [16]. In the social equity stage, the focus was on exploring the relationship between the accessibility of park green spaces and disadvantaged groups, as well as socioeconomic disparities [17, 18]. From the perspective of research time, most existing studies only explore the accessibility of park green spaces in a single year [19], and pay little attention to the dynamic configuration and influencing mechanism of parks in the process of urbanization; in terms of research scale, most studies are conducted at the city and district levels [20, 21], and the differences between subdistricts in the same city cannot be reflected.

There are currently many methods for measuring accessibility both domestically and internationally. For example, the buffer method [22] is simple for calculation, but does not consider the real road network; the network analysis method [23] is based on complete road network data, but requires high accuracy of the data; the gravity model [7] and the two-step floating catchment area method [21] cover more comprehensive factors and take into account the supply and demand relationship. The two-step floating catchment area method incorporates the concept of "spatial threshold" based on the gravity model, and has led to several improved models applicable to different research directions [24, 25]. It is considered the optimal model for measuring green space accessibility [26]. For example, Huang Jiuju et al. used the Gaussian two-step floating catchment area method with multi-radius to study the accessibility of park green spaces for different social groups in Shenzhen [27]; Yang Wenyue et al. combined the application of TIQS to construct a multi-mode two-step floating catchment area model and explored the differences in the accessibility of multi-scale park green spaces and its fairness under three travel modes—walking, public transport and private cars—in Guangzhou [28]; Ren Jiayi et al. used the improved Gaussian two-step floating catchment area method to study the accessibility of park green spaces under high-density urban walking conditions, taking Huangpu District of Shanghai as an example [19].

Previous studies on evaluating the accessibility of park green spaces have primarily employed standard classification methods in GIS, such as the natural breaks method and the quantile method, to assess the level of green space accessibility. The natural breaks method identifies data classification intervals and groups similar values to maximize the differences between classes; quantiles, on the other hand, require each class to contain an equal number of elements, which can be misleading. Therefore, using these classification methods to judge accessibility is biased. The actual meaning of the result calculated by the Gaussian two-step floating catchment area method is the generalized per capita park green space area considering distance decay, which can be compared with the per capita park green space area as the basis for evaluating accessibility levels and conducting horizontal comparisons among different spatial units within the region [21].

There are many methods for studying the influencing mechanism, such as the traditional regression model, the spatial econometric model, the geographic detector, the geographically weighted regression, etc. The geographic detector model focuses on the difference analysis of global-scale influencing factors [29], while the geographically weighted regression model can reflect the spatial heterogeneity of the effect of local-scale influencing factors [30]. Combining the two can make the study of the influencing mechanism more profound and comprehensive. Currently, these two methods are primarily used in studies on the evolution of ecosystem services [31], the characteristics of land use evolution [32], and the spatial distribution of traditional villages and towns [33], but are rarely applied in the field of park green space and accessibility studies. In addition, most studies on influencing factors of green space accessibility focus on green space and the population itself, without considering socio-economic factors. They often use single methods, such as qualitative descriptive analysis and correlation analysis, which cannot quantitatively determine the strength of the influencing factors and the spatial heterogeneity.

Therefore, this paper takes the spatial-temporal differentiation ofthe accessibility of park green spaces as its starting point, and uses Shenzhen, the city with the highest population density and fastest urbanization process in China, as the research object. It employs the Gaussian two-step floating catchment area method that comprehensively considers both supply and demand to analyze the accessibility of multi-scale park green spaces under multiple travel modes in 2013 and 2020. Furthermore, it constructs a composite index system of "green space-transportation-location-economy-nature" and integrates a geographic detector and a geographically weighted regression model to quantitatively express and spatially visualize the influencing mechanism of the spatial-temporal differentiation in the accessibility of park green spaces in Shenzhen. This study more clearly and comprehensively reveals the intensity and spatial differentiation patterns of various driving factors in the urbanization process. The research can provide decision-making suggestions for park policy formulation and green space system planning in similar cities, addressing the shortcomings of current studies that primarily focus on single time segments and travel modes.

1 Research subjects and data

1.1 Overview of the study area

Shenzhen is a national center for finance, science and technology, and innovation. It plays a pivotal role in the development of the Guangdong-Hong Kong-Macao Greater Bay Area, boasting the highest population density and urbanization rate in China. It administers 10 administrative districts and 76 subdistricts. In the early stages of its development, thecity was divided into inner and outer areas, covering a total of 1,997.47 km^2. During the process of urban development, the government places great importance on constructing an ecological environment. It has set forth several strategic goals, such as the "City of a Thousand Parks" and "Park City" initiatives. In 2019, the number of parks reached 1,090, and initial results have been achieved. Green space accessibility is an important indicator of the rationality of urban planning and construction, and it is of great significance for improving the quality of residents' lives and optimizing the allocation of green space resources.

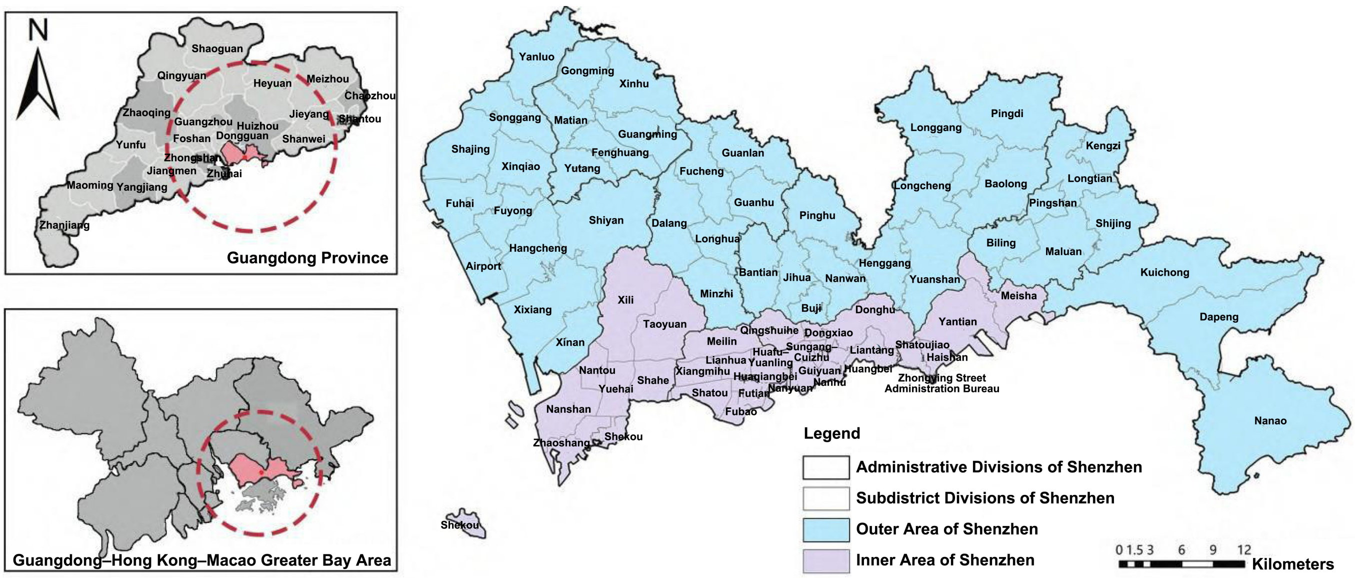


Figure 1 Study areas

1.2 Datasources and processing

In 2012, Shenzhenissued the *Shenzhen Urban Greening Development Plan Outline* (2012-2020), which set a working cycle from 2012 to 2020 and proposed new goals for future urban greening development. The first batch of park directory data was officially released in 2013. Therefore, this paper uses 2013 and 2020 as the research time frames. The park green space data are based on the *Shenzhen Park Directory* and the *Shenzhen Urban Planning Standards and Guidelines* (partially revised in 2019). Park green spaces within the scope of urban construction land are categorized into three types: comprehensive parks, specialized parks, and community parks. The entrances and exits of large parks, as well as the centroids of small parks, are extracted to establish a database of park green spaces. Administrative division data is sourced from the National Administrative Division Information Query Platform; the road network data is sourced from the OpenStreetmap website; data on residential communities, commercial service facilities, government facilities, and bus stops are crawled from Gaode Maps; DEM data comes from the Resources and Environmental Science Data Center of the Chinese Academy of Sciences; population and GDP data were downloaded from the Worldpop website and the Geographic Remote Sensing Ecological Network, respectively, and corrected according to the *Shenzhen Statistical Yearbook* to improve data accuracy.

2 Research framework and methodology

2.1 Research framework

Tomore accurately evaluate the actual construction effectiveness of park green spaces and achieve spatial equity in green space resources, this paper establishes a three-level research framework: spatial-temporal differentiation of supply and demand levels of park green spaces, spatial-temporal differentiation of accessibility, and exploration of the influencing mechanism of accessibility (Figure 2). The spatial-temporal differentiation analysis of supply and demand levels is conducted from both supply and demand perspectives, comparing the changes in the spatial layout, area, quantity, and population density of park green spaces in 2013 and 2020. The spatial-temporal differentiation of accessibility is analyzed using the Gaussian two-step floating catchment area method to calculate the accessibility of multi-scale park green spaces under multiple travel modes in 2013 and 2020, followed by a comparative analysis of its differentiation characteristics. The exploration of the influencing mechanism of accessibility first uses a geographic detector to analyze the relationship between the accessibility index and the factors of "green space-transportation-location-economy-nature", identifies effective influencing factors, and then uses a geographically weighted regression model to explore the spatial heterogeneity of the impact of each effective influencing factor on green space accessibility, aiming to provide differentiated strategies and methodological insights for future urban green space system planning.

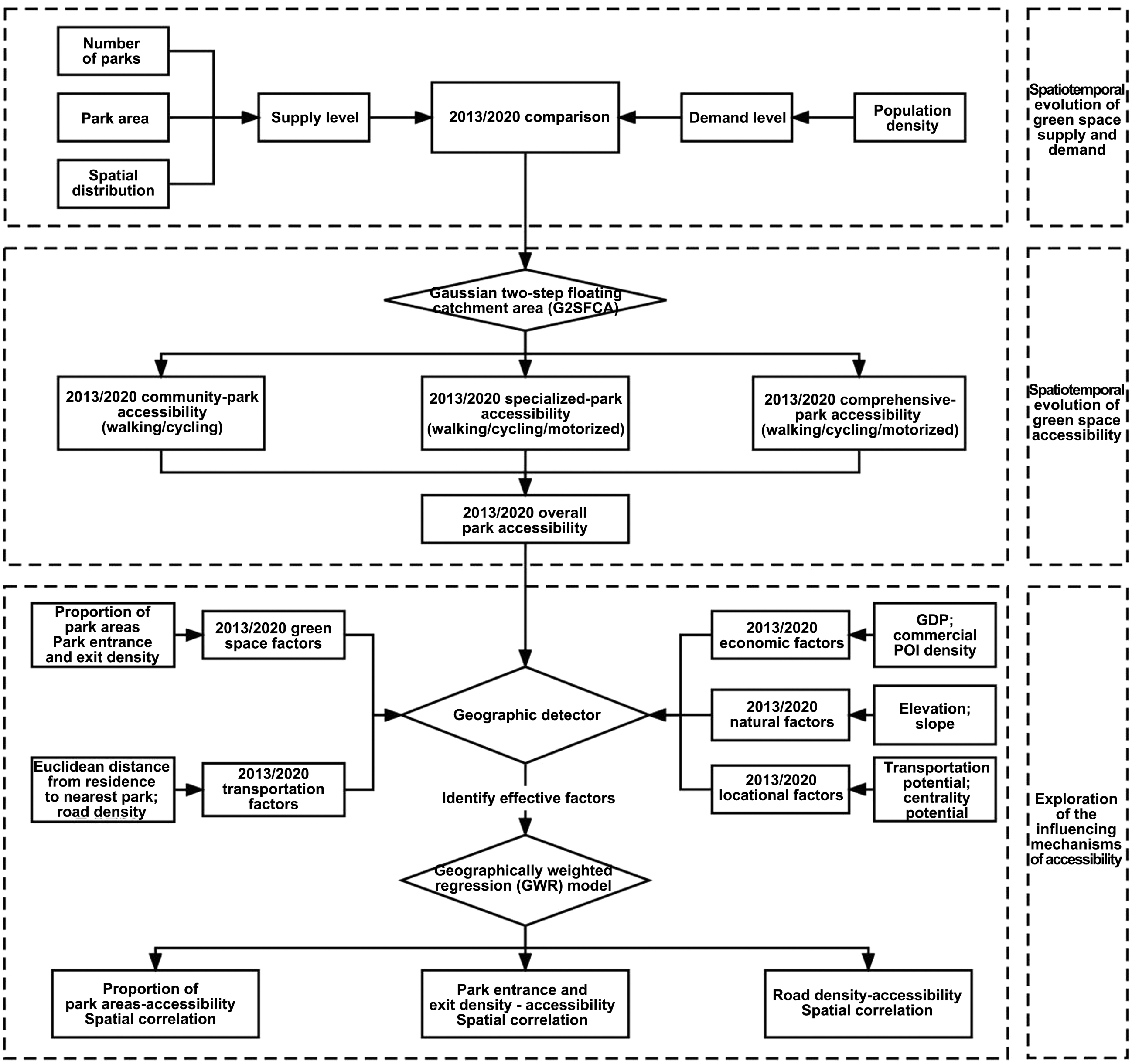


Figure 2 Research Framework

2.2 Gaussian two-step floating catchment area method

The traditional two-step floating catchment area methodadopts a "binary" decay function, meaning that areas within the search radius are completely reachable, while areas outside the radius are entirely inaccessible. This does not reflect the actual travel characteristics of residents. Therefore, this paper employs a Gaussian function, which better reflects the actual travel patterns of residents, to enhance the two-step floating catchment area method. It then explores the accessibility of multi-scale park green spaces under multiple travel modes, thereby improving the reliability and accuracy of the research results. The specific steps are as follows:

Step 1:Use the park entrance or exit as supply point j, and establish a search domain based on the research threshold $d0$ for park green spaces at different levels under multiple travel modes (Tables 1 and 2). Calculate the total population of all demand points k within the search domain of each supply point j, apply a Gaussian function for decay, and calculate the service capacity Rj of each supply point j.

$$Rj = \frac{Sj}{\sum k \in \{djk \leqslant d0\} G(djk,d0)Dk} \quad (1)$$

$$G(djk) = \frac{e^{-1/2 \cdot (djk/d0)2}}{1-e^{-1/2}} (djk < d0) \quad (2)$$

In the formula:Dk is the population (persons) at each demand point k, djk is the distance cost between supply point j and demand point k, $G(djk)$ is the Gaussian decay of the distance cost, and Sj is the supply capacity of supply point j, expressed in park area (m^2).

Table 1 Threshold settings for research on park green spaces at all levels

Mode of travel and speed	Comprehensive parks	Specialized parks	Community parks
Walking at 5km/h	30min	20min	15min
Cycling at 15km/h	20min	15min	10min
Motor vehicles (speed limits based on road grade)	15min	10min	—

Table 2 Speed assignments for roads at all levels

Road grade	Highway	Expressway	Main road	Secondary roads	Branch road
Road speed	80km/h	60km/h	40km/h	30km/h	20km/h

Step 2:Establish a search domain with the residential area as the demand point k and the $d0$ threshold. Find all the park green space supply points j within the search domain and summarize their supply-demand ratio R_j. Use a Gaussian function to decay the ratio and calculate the accessibility index Ai of the residential area k.

$$Aj = G_{(dkj,d0)} * R_j \quad (3)$$

In the formula, $G(dkj)$ is the distance cost after Gaussian decay, and R_j is the sum of the service capabilities of all supply points within the search threshold.

Step 3: Since the accessibility calculated by the Gaussian two-step floating catchment area method represents the generalized per capita green space area, this paper uses the method of "whether the ratio of the accessibility of park green spaces to per capita park green space area is greater than 1" to evaluate the accessibility level and carry out horizontal comparison of different units in the region. Areas with a value greater than 1 are considered to have relatively high accessibility, and areas with a value less than 1 are considered to have relatively low accessibility[21].

2.3 Geographic detector

The geographic detector is a new tool proposed by Wang Jinfeng et al.[29] for exploring driving factors and spatial differentiation. It mainly uses the q value to measure the magnitude of the driving factor's determination power. Its formula is:

$$q_x = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \quad (4)$$

Where q_x is the determination power of the influencing factor x on the accessibility of park green spaces, and its value range is [0, 1], h= 1, 2, ..., L is the number of strata of the driving factor; N_h and N represent the number of samples in the region of stratum h and the number of samples in the whole city, respectively; σ_h^2 and σ^2 are the variances of the dependent variables of stratum h and the whole city, respectively.

2.4 Geographically weighted regression

Geographically weighted regression (GWR) is a geostatistical method developed based on the traditional ordinary least squares (OLS) model, in which spatial characteristics are incorporated into the model through distance-based weighting. It isparticularly effective for evaluating the spatial heterogeneity of influencing factors [34]. The calculation formula is as follows:

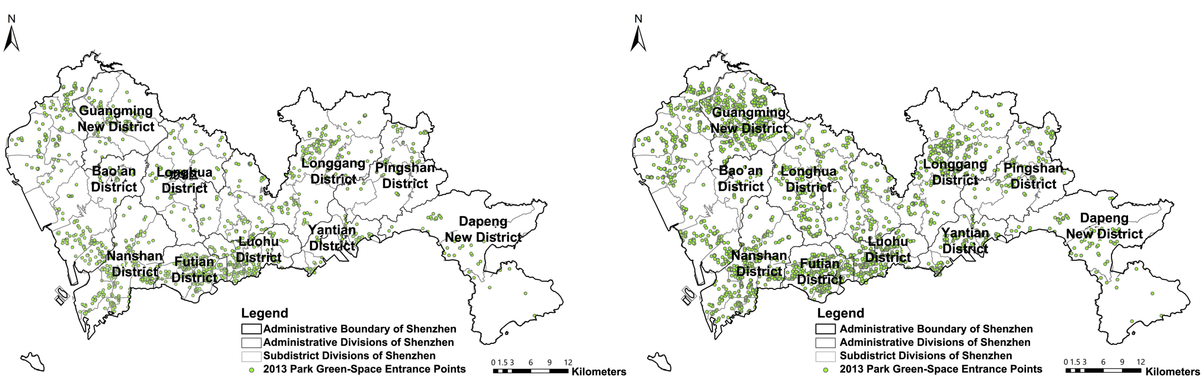
$$y_i = \beta_0(u_i,v_j) + \sum_{j=1}^{k}\beta_j(u_i,v_i)\chi_{ij} + \varepsilon_i \tag{5}$$

Where y_i represents the accessibility of park green spaces on the i-th subdistrict, (u_i, v_i) represents the spatial geographic coordinates of the i-th subdistrict, β0 represents the fixed-effect intercept of (u_i, v_i), X_{ij} represents the j-th influencing factor of accessibility of the i-th subdistrict (j= 1, 2, ..., K), β_j represents the regression coefficient of X_{ij}, and ε_i represents the random error.

3 Results and analysis

3.1 Spatial-temporal comparison of green space supply levels

In terms of spatial layout (Figure 3), the park green space exhibits an uneven distribution pattern with the characteristics of "more in the west and less in the east", "from the inner areas to the outer areas", and expansion from south to north. In terms of the number of parks (Figure 4), the number of parks in Shenzhen increased from 655 in 2013 to 1,169 in 2020, a relative increase of 78.47%, with community parks showing the most significant increase. In terms of park area (Figure 5), the park area in Shenzhen increased from 55.76 km^2 in 2013 to 84.42 km^2 in 2020, representing a relative increase of 51.40%. Comprehensive parks accounted for the most significant proportion of the area. Shenzhen's core development areas are primarily located in the earlier-developedinner areas, such as Futian District, Nanshan District, and Luohu District. These areas serve as hubs for urban functions, including residence, commerce, and administration. The eastern areas, having been developed later, have fewer park green spaces. With the implementation of integrated development between the inner and outer areas of the Shenzhen Special Economic Zone, infrastructure construction in the outer areas has accelerated, and park green spaces have continued to expand. Among them, community parks—characterized by their wide distribution and small size—primarily serve neighborhood residents, resulting in a substantial increase in their numbers. In contrast, comprehensive parks feature larger service coverage and greater scale, thus showing a more significant increase in total area.



a. Layout of park green space entrances in 2013

b. Layout of park green space entrances in 2020

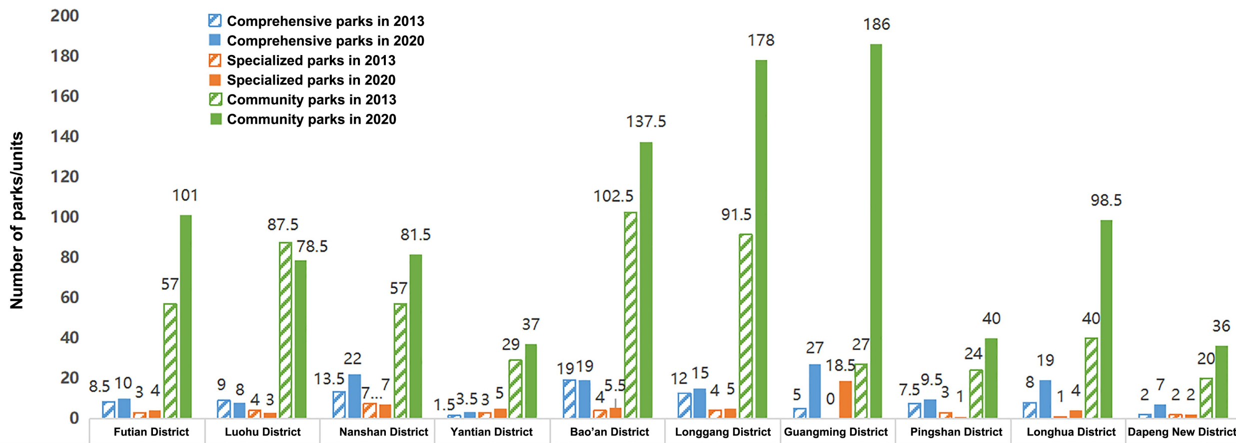
Figure 3 Layout of park green space entrances in 2013 and 2020

3.2 Spatial-temporal comparison of green space demand levels

The demand for park green spaces among residents is positively correlated with population density. From 2013 to 2020, the population of Shenzhen increased by approximately 3.4 million. By calculating the ratio of population to area in each subdistrict, a population density distribution map of Shenzhen was obtained. As shown in Figure 6, from 2013 to 2020, the acceleration of urbanization led to the gradual development of outer areas, with high population density extending from inner to outer areas. Futian, Luohu, and Nanshan are the core development areas of Shenzhen, with high population density and high demand. The population density in Bao'an District, Longhua District, and Guangming District in the west has gradually increased, and the demand level has risen accordingly. The development and construction of Yantian District, Longgang District in the east, and Dapeng District were slower, with lower population density and lower demand.

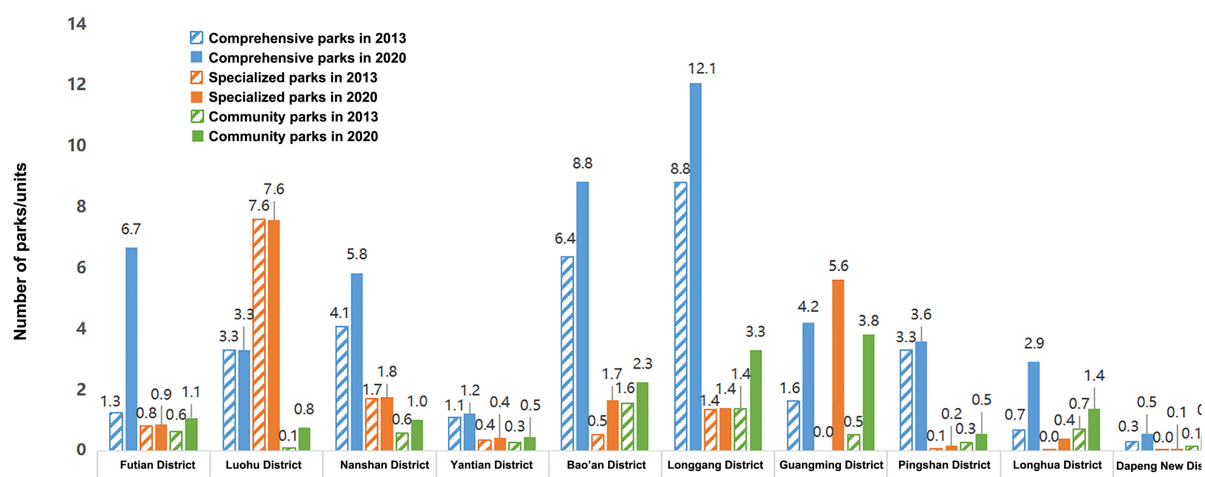
3.3 Spatial-temporal differentiation characteristics of the accessibility of park green spaces

This paper takes the spatial-temporal differentiation of the accessibility of park green spaces as its starting point and uses the Gaussian two-step floating catchment area method, which comprehensively considers both supply and demand, to analyze the accessibility of multi-scale park green spaces in Shenzhen under multipletravel modes in 2013 and 2020. High-value areas and low-value areas are divided by whether the ratio of the accessibility of park green spaces to per capita park green space area is greater than 1. Furthermore, the accessibility values are classified into four levels—low, relatively low, relatively high, and high—using the geometric interval classification method.



	Futian District	Luohu District	Nanshan District	Yantian District	Bao'an District	Longgang District	Guangming District	Pingshan District	Longhua District	Dapeng New District
Total number of parks in 2013	69.5	99.5	79	33.5	124.5	108.5	32	35.5	49	24
Total number of parks in 2020	115	89.5	110.5	45.5	162	198	231.5	50.5	121.5	45
Increment	45.5	-10	31.5	12	37.5	89.5	199.5	15	72.5	21

Figure 4 Comparison of the number of parks in 2013 and 2020



	Futian District	Luohu District	Nanshan District	Yantian District	Bao'an District	Longgang District	Guangming District	Pingshan District	Longhua District	Dapeng New Dis
Total area of parks in 2013	8.17	11.66	6.58	1.72	8.45	11.54	2.14	3.63	1.40	0.48
Total area of parks in 2020	8.58	11.92	8.60	2.12	12.72	16.77	13.63	4.30	4.70	1.08
Increment	0.41	0.26	2.02	0.40	4.27	5.23	11.49	0.67	3.30	0.61

Figure 5 Comparison of park areas in 2013 and 2020

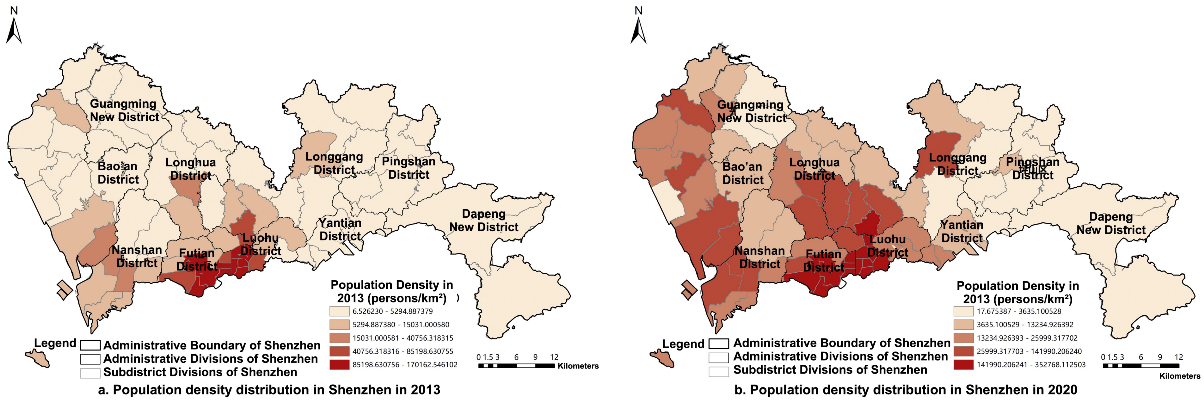


Figure 6 Population density distribution in Shenzhen in 2013 and 2020

Overall, from 2013 to 2020, the accessibility of park green spaces in Shenzhen showed an upward trend. The proportion of communities with high accessibility gradually increased. The average accessibility of community parks saw the most significant increase. The accessibility of comprehensive parks remained relatively stable. Specialized parks saw the most significant increase in standard deviation and a greater degree of spatial differentiation. Over the past decade, Shenzhen has prioritized park construction as a crucial aspect of enhancing the city's overall competitiveness and sustainable development capabilities. Park construction has entered a period of rapid development, with overall accessibility improvements relying on the implementation of multiple green space strategies such as "City of a Thousand Parks" and "Park City."

From the perspective of the spatial-temporal differentiation of accessibility, the accessibility of community parks has improved the most, which is most significant in Guangming District. The main reason is that in recent years, Guangming District has served as a typical model for Shenzhen's efforts to build an ecologically civilized city. Itrecorded the most significant increase in parks and is located in the outer areas, where population demand is relatively low. The oversupply has led to a significant improvement in the accessibility of community parks. The accessibility level of comprehensive parks is basically stable. The high accessibility value areas exhibit a trend of migration from inner areas to outer areas. This is because the development level of the inner areas is high, resulting in a continuous increase in population density. However, the inner areas have long entered the stage of stock development, and the available land resources for green space construction are limited. On the other hand, outer areas are in the stage of development and construction, with low population demand and a strong supply capacity for green spaces, which gradually improves accessibility. Accessibility of specialized parks, however, has slightly decreased, and spatial differentiation has become more pronounced. The main reason is that 72.5% of the newly added specialized parks are concentrated in Guangming District. The rapid increase in supply capacity has led to a significant improvement in accessibility, resulting in a significant uneven spatial distribution of accessibility throughout the city (Figures 7-12).

3.4 Exploring the influencing mechanism of the accessibility of park green spaces

3.4.1 Identification of influencing factors based on geographic detectors

The accessibility of park green spaces isinfluenced by a variety of factors. This paper selects 10 influencing factors, categorized into five categories, as independent variables, and the comprehensive accessibility index as the dependent variable (Table 3). The effect of each influencing factor on the changes in the accessibility of park green spaces in 2013 and 2020 is analyzed using a geographic detector.

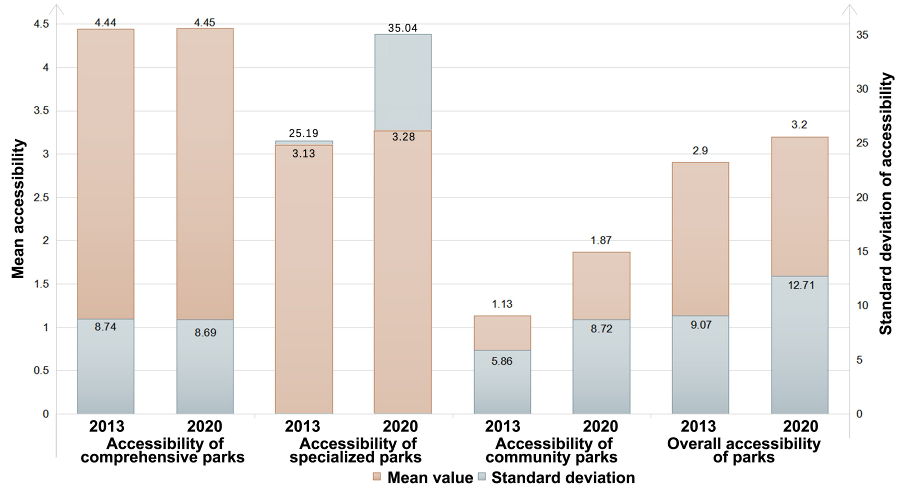


Figure 7 Accessibility coefficients of different types of parks in 2013 and 2020

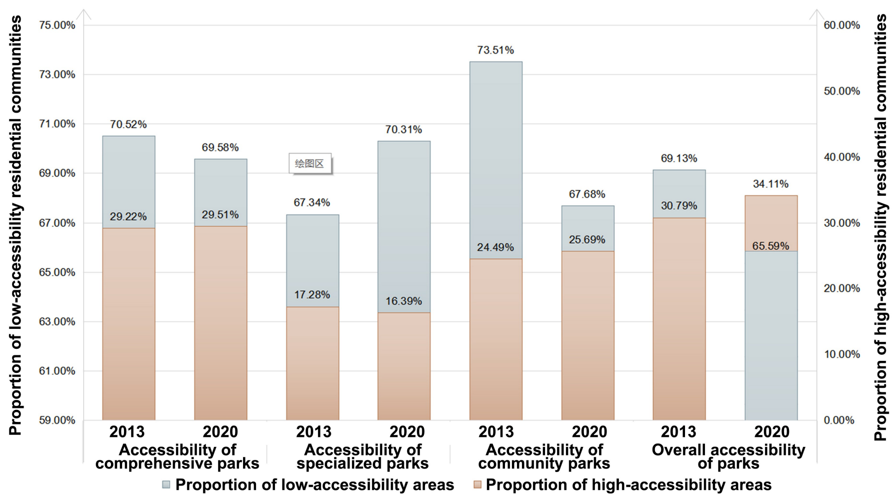


Figure 8 Spatial-temporal comparison of changes in the accessibility of multi-scale park green spaces in Shenzhen

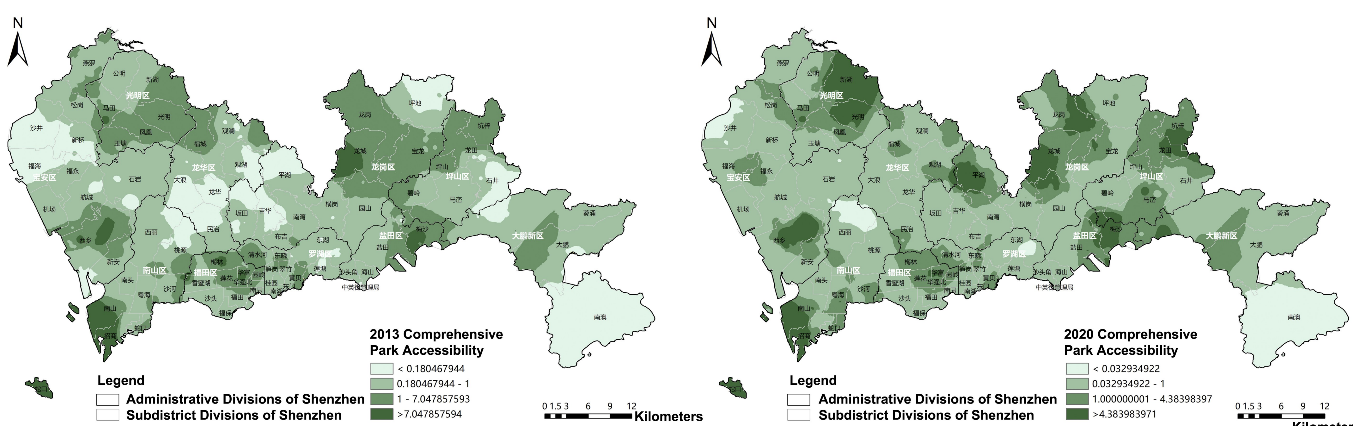


Figure 9 Accessibility of comprehensive parks in 2013 and 2020

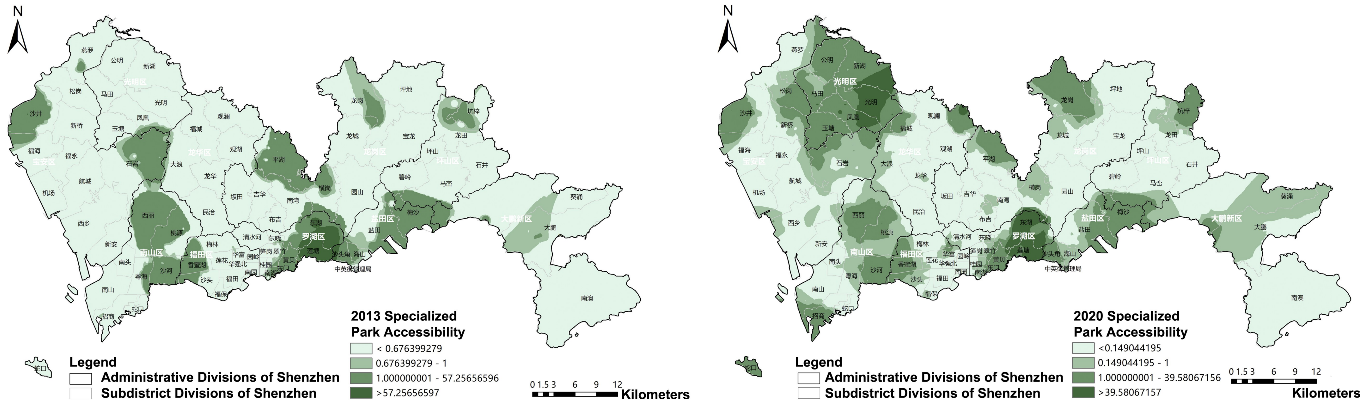


Figure 10 Accessibility of specialized parks in 2013 and 2020

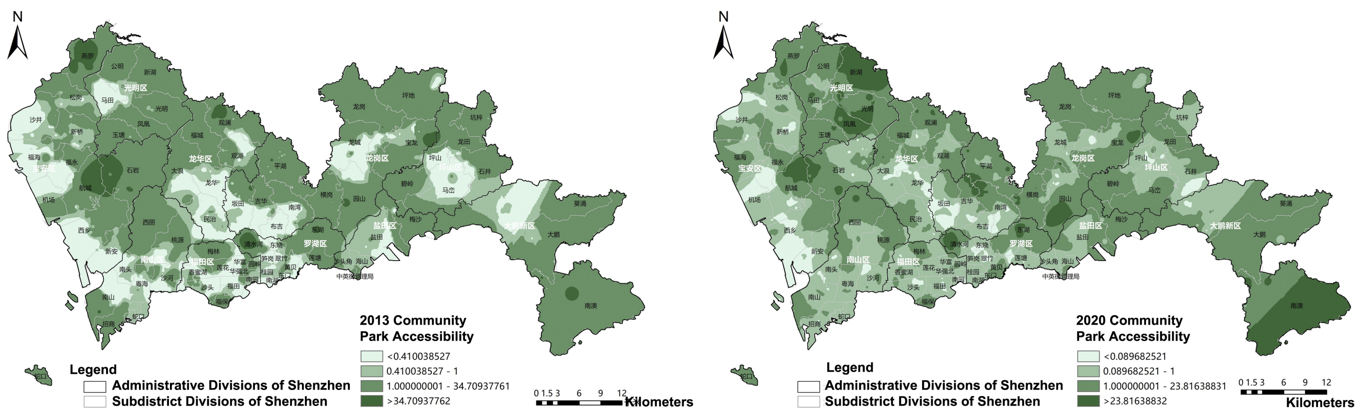


Figure 11 Accessibility of community parks in 2013 and 2020

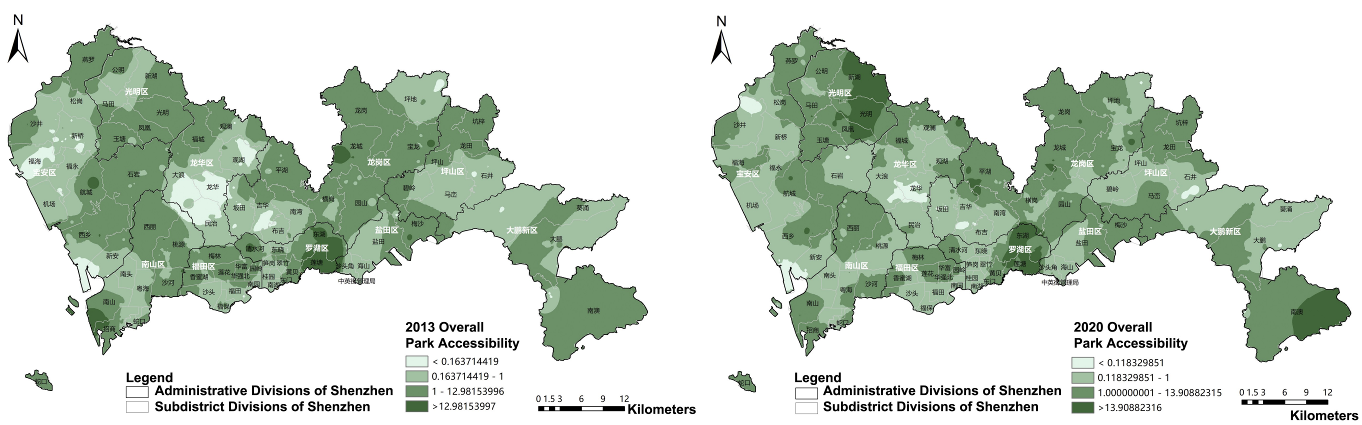


Figure 12 Overall accessibility of parks in 2013 and 2020

The results of the accessibility influencing factor q-value detection (Table 4) show that in 2013, all influencing factors had p-values of 0 and passed the 0.01 significance test. However, in 2020, only the three influencing factors X1, X2, and X4 passed the 0.01 significance test. This indicates that between 2013 and 2020, the spatial distribution of park accessibility was more strongly and structurally associated with green-space and road-related factors. The reason for this is that with the integrated development of the urban economy and the progress of science and technology, the economy and commerce of each district have become the focus of development. The gap in commercial service facilities, technical difficulties, and the cost of development and construction have gradually decreased, resulting in a continuous decline in the correlation between location factors, economic factors, and natural factors, and park accessibility. Further investigation into the significant influencing factors, as indicated by the q values, revealed that, at the dynamic level, the q values of X1, X2, and X4 all showed a decreasing trend. The ranking of their q-values of determination power was X4 (0.10275) > X1 (0.0536) > X2 (0.0472), indicating that X4 is the dominant factor in park accessibility, with an explanatory power of over 10%, far exceeding that of other factors. X2 and X1, on the other hand, are important factors in park accessibility. The primary reason is that roads are a crucial infrastructure for urban development. Areas with higher road density have relatively higher levels of urban development and construction, more complete park green space facilities, and more convenient travel routes that significantly improve residents' access to park green spaces. Therefore, road density has the strongest determination power. In addition, the accessibility of park green spaces is inseparable from their construction. The larger the area of a park or green space, the more entrances and exits it will have, as well as the wider its service area, thus improving its accessibility.

Table 3 Accessibility Influencing Factor Index System

Category	Influencing factors	Influencing factor	Code	Classification
Influencing factor (X)	Green space factors	Proportion of park area	X1	6
		Park entrance and exit density	X2	6
	Traffic factors	Straight-line distance from the residence to the nearest park	X3	6
		Road density	X4	6
	Location factors	Traffic Location	X5	6
		Central potential	X6	6
	Economic factors	GDP	X7	6
		Commercial POI density	X8	6
	Natural factors	Elevation	X9	6
		Slope	X10	6
Dependent variable (Y)	Accessibility	Comprehensive Accessibility Index	Y	6

Table 4 Results of the accessibility influencing factor q-value detection

Influencing factors	2013		2020		2013-2017	
	Determination power q	Significance level p	Determination power q	Significance level p	Determination power q	Average value
X1	0.0755	0.0000	0.0317	0.0038	- 0.0438	0.0536
X2	0.0578	0.0000	0.0366	0.0031	- 0.0212	0.0472
X3	0.0974	0.0000	0.0098	0.4737	—	—
X4	0.1585	0.0000	0.0470	0.0000	- 0.1115	0.10275
X5	0.1702	0.0000	0.0012	0.9972	—	—
X6	0.1874	0.0000	0.0128	0.8128	—	—
X7	0.1472	0.0000	0.0394	0.1849	—	—
X8	0.0598	0.0000	0.0484	0.2456	—	—
X9	0.0876	0.0000	0.0224	0.0918	—	—
X10	0.0618	0.0000	0.0040	0.9490	—	—

Table 5 Regression model indicator system

Indicator Name	Indicator code
Overall accessibility index	Y
Proportion of park area	X1
Park entrance and exit density	X2
Road density	X4

3.4.2 Spatial heterogeneity analysis of influencing factors based on GWR

Geographic detector models primarily focus on analyzing factors that influence spatial differentiation at the global scale, while neglecting the spatial differentiation of these factors' effects at the local scale. Therefore, after testing with the geographic detector model, this paper selected three effective factors—proportion of park area(X1), park entrance and exit density (X2), and road density (X4)—as explanatory variables, and constructed a regression model index system with the accessibility index in 2020 as the explained variable (Table 5).

OLS regression was performed on the accessibility index and each of the dominant factors. The results showed that the residual fit did not follow a normal distribution. To improve the fit, the GWR model was subsequently introduced. First, we used Geoda 1.14 to analyze the spatial autocorrelation of the overall accessibility index of parks in Shenzhen in 2020. The results showed that Moran's I was 0.823753, which passed the Z-test for significance ($p < 0.05$), indicating significant spatial autocorrelation in the accessibility index in 2020. Then, the influencing factor data were standardized, and geographically weighted regression analysis was performed using GWR4 to further explore the spatial differentiation of the influencing factor effects. The results (Table 6) show that the fitted R^2 increased from 0.172066 to 0.403038, and the AICc value decreased from −61.379260 to −73.339113, with a difference of 11.959853. These results indicate that the GWR model provided a significantly better fit and more accurate spatial representation than the OLS model.

Table 6 Comparison of OLS and GWR model fitting results

Model	AICc	R^2	Adjust R^2
OLS	- 61.379260	0.172066	0.137569
GWR	- 73.339113	0.403038	0.307432

The regression coefficients fitted by the GWR model (Figure 13) show that road density(X4) has the most significant influence and variability on the accessibility index (regression coefficients range from −0.963989 to −0.097715), exhibiting a spatial characteristic of being higher in the east and lower in the west. This is due to the obvious east-west polarization of development in Shenzhen, with the eastern Longgang and Pingshan districts lagging behind in development and having less developed road systems than the west. As a key factor in accessibility, road density has a significantly greater impact on accessibility improvement in the east than in the west. Park entrance and exit density (X2, with regression coefficients ranging from −0.252221 to 1.386147) exhibits a decreasing regression coefficient from west to east. The positiveeffects are concentrated in the western Guangming, Bao'an, Longhua, and Nanshan districts of Shenzhen, where there are many parks and a high density of entrances. The negative impact is mainly concentrated in the eastern Pingshan and Dapeng districts, where the supply of green space resources is relatively poor. Proportion of park area (X1) showed the smallest spatial variation (regression coefficients ranged from -0.074609 to 0.251136), with a predominantly positive effect. Only six subdistricts in Guangming District and Bao'an District showed a negative impact. The distribution of regression coefficients revealed significant spatial zonation. Due to the larger area of the eastern administrative district, but with less green space compared to the western district, the influencing effect in the eastern region is markedly stronger than that in the western region.

4 Conclusions and outlook

As an important public resource in the city, park green spaces serve as vital spaces for residents' daily leisure activities, possessing ecological and cultural functions. Their accessibility has a profound impact on the quality of life for residents. In 2012, Shenzhen released the *Shenzhen Urban Greening Development Plan Outline* (2012-2020), which set a working cycle from 2012 to 2020 and proposed new goals for the future development of urban greening in Shenzhen. The first batch of park directory data was officially released in 2013. Therefore, this paper takes 2013 and 2020 as the research time frames, uses the Gaussian two-step floating catchment area method to explore the spatial-temporal differentiation characteristics of the accessibility of park green spaces in Shenzhen, and uses a geographic detector and a geographically weighted regression model to examine the influence level of different factors on the accessibility of park green spaces and its spatial heterogeneity characteristics. The main conclusions are as follows: 1) Within the scope of construction land, the number and area of park green spaces in Shenzhen have continued to grow, and spatially they show the characteristics of "more in the west and less in the east", "from the inner areas to the outer areas", and expansion from south to north. 2) Between 2013 and 2020, the accessibility of park green spaces in Shenzhen showed an overall upward trend. The accessibility of outer areas gradually surpassed that of inner areas. Among the different park types, community parks exhibited the most significant increase in mean accessibility, while specialized parks demonstrated the most substantial spatial variation in accessibility, and the accessibility level of comprehensive parks remained relatively stable. 3) Road density, park entrance and exit density, and proportion of park area are the main influencing factors. In contrast, the correlations between location, economic, and natural factors and accessibility have weakened over time, owing to the integrated development of the urban economy and technological progress. 4) Different factors exhibit significant spatial heterogeneity in their effects on the accessibility index. Road density(X4) and proportion of park area(X1) have a greater impact in the eastern part of the study area, while park entrance and exit density(X2) has a greater impact in the western part of the study area.

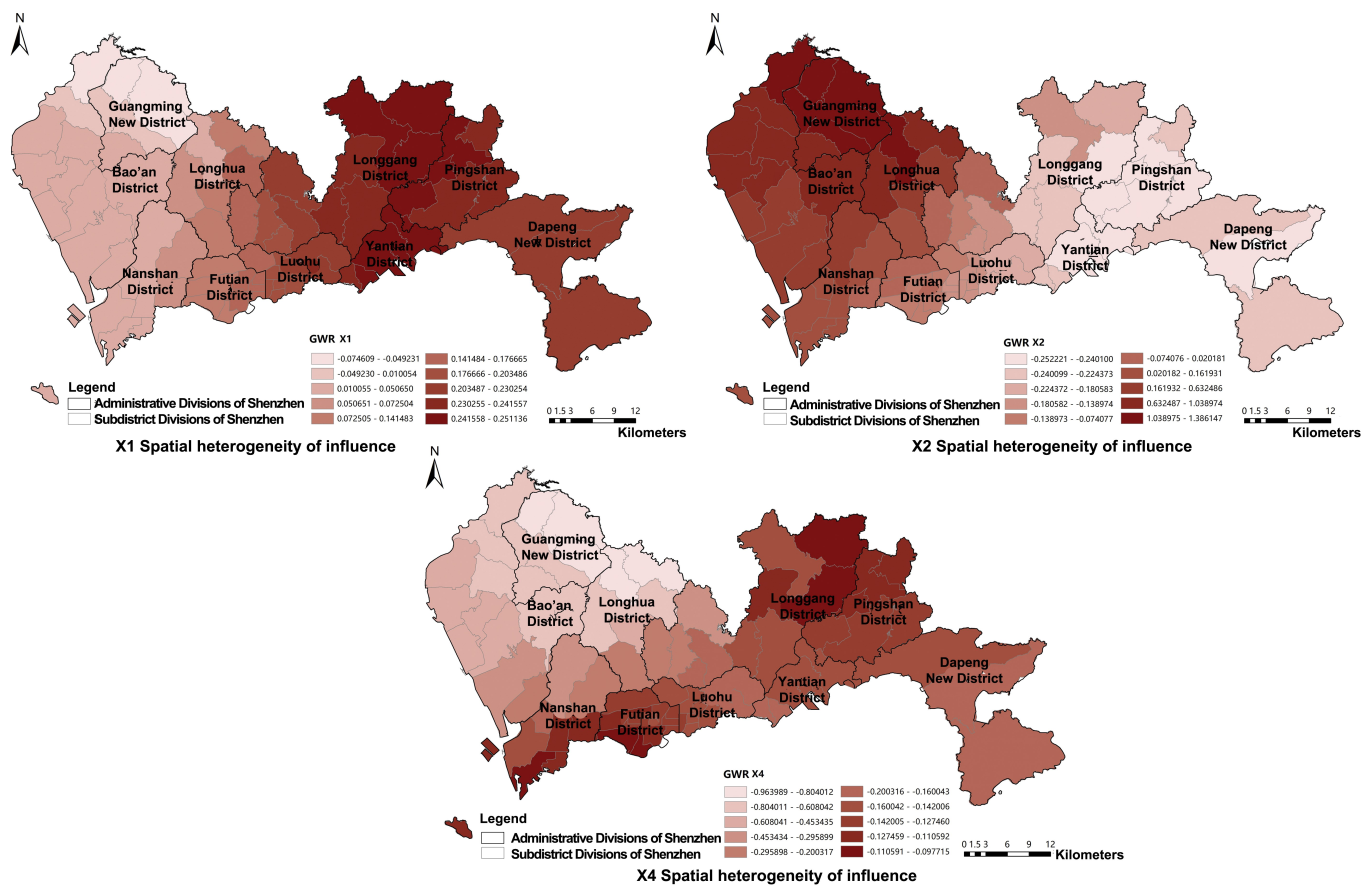


Figure 13 Spatial heterogeneous distribution of the effects of effective factors

Against the backdrop of rapid urbanization, the inequality of social, economic, and ecological benefits caused by differences in accessibility of park green spaces has attracted the attention of many scholars[35-37]. However, there remains a lack of in-depth research on the dynamic characteristics and the influencing mechanism of the accessibility of park green spaces. This study quantitatively expresses and spatially analyzes the spatial-temporal differentiation characteristics and driving factors of the accessibility of various park green spaces in Shenzhen, summarizes their distribution characteristics and development patterns, and provides a reasonable explanation for the mechanism of their spatial-temporal differentiation from multiple perspectives. This can provide differentiated and targeted suggestions for the planning and construction of Shenzhen's green space system. Furthermore, the research framework and conclusions of this paper have specific reference and guiding significance for the overall assessment, optimal allocation, and spatial equity of other similar urban park green spaces. The methodology can also provide useful reference for the accessibility analysis of other geographical phenomena.

However, this study also has certain limitations due to factors such as data collection. Because accurate population data are difficult to obtain, this paper utilizes WorldPop population density raster data, which may result in discrepancies between the population of residential areas and the actual population. Although district-level corrections were made using data from theSeventh National Population Census, differences in the demand level at the residential-community scale remain. Secondly, both the 2013 and 2020 park directories contain a small number of records with missing information on the area of parks or classification, as well as ambiguous location data. Such data deviations may affect the estimation of green-space supply and, consequently, the results of accessibility analysis. In addition, this study does not fully account for subjective factors among different population groups or the intrinsic attractiveness of parks, both of which may influence accessibility. Future research could further evaluate park attractiveness through questionnaire surveys and satisfaction scoring, and improve the accuracy of the analysis by refining park datasets and enriching the indicator system of influencing factors.

Source of Figures and Tables

All figures and tables in this article were drawn by the author

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