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STUDY ON THE SPATIAL DISTRIBUTION OF HERITAGE TREES AND INFLUENCING FACTORS IN SHENZHEN CITY

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Abstract

Heritage trees (HTs) are natural and historical legacies that bear witness to the evolution of cities and transformations in human society. However, the development of urbanization and intensified human activities have significantly degraded the survival environment of these trees. Understanding the spatial distribution and ecological conditions of heritage trees is crucial for promoting the sustainable development of regional history, culture, and heritage resources. This study uses Shenzhen, a city undergoing rapid urbanization, as a study to examine the determinants underlying variations in the composition and spatial configuration of heritage trees (HTs) in the post urbanization context. The results indicate that, species of *Ficus microcarpa*, *Cinnamomum camphora*, and *Dimocarpus longan* dominate the heritage trees population in Shenzhen, collectively accounting for 64.57% of the total, and the majority are less than 300 years old, comprising 94.57% of the total. The highest density of heritage trees is observed in central Dapeng new district, with substantial spatial heterogeneity and a significant positive spatial autocorrelation. The spatial configuration of heritage trees is influenced by multiple factors, ranked by degree of impact as follows, population density > elevation > slope > road density > NDVI > land use > slope direction > water sources. Results revealed that human factors exert a dominant influence on the growth of heritage trees, surpassing natural factors. These findings provide a scientific basis for protecting the healthy growth of heritage trees, supporting sustainable resource management, and informing conservation strategies for ancient and valuable trees in Shenzhen.

Key words: Shenzhen; Heritage trees; Spatial distribution; Influencing factors

Introduction

Heritage trees offer a wide range of ecosystem services and play vital roles in urban development. Heritage trees are integral components of urban forests, contributing to ecological, historical, social, psychological, and landscape functions in urban environments (Dwyer *et al*., 1992; Nowak, 2001; Jim & Chen, 2006; Nowak & Dwyer, 2007; Konijnendijk, 2008; Wu *et al*., 2020; Cannon *et al*., 2022; Gilhen-Baker *et al*., 2022). Considerable attention has been devoted to the preservation and management of heritage trees, focusing on species characteristics, environmental conditions, habitat protection, regulatory frameworks, and policy measures (Loeb. 1992; Kuo *et al*., 1998; Jim, 2002; Tello *et al*., 2005; Sieghardt *et al*, 2005; Lewington, 2012; Jim *et al.*, 2013). Heritage trees are often regarded as living fossils that bear witness to and record the evolution of urban history (Forrest & Konijnendijk, 2005; Huang *et al*., 2020). They represent essential and enduring memories of a place, even when their original habitats have disappeared. However, in the course of industrialization and urbanization, many cities rich in HTs have experienced substantial transformations, which have profoundly altered the original habitats and spatial distribution of these trees (Jim *et al*., 2013; Chen *et al.*, 2017; Hong *et al*., 2020). The conservation of heritage trees has become an urgent priority.

Extensive research on heritage trees covered a wide range of thematic areas. First, definitions and evaluation criteria for heritage trees differ across regions and countries. For instance, heritage trees classification in the United States and Europe emphasizes morphological characteristics such as canopy size and height, whereas in China, emphasis is placed on tree age and historical-cultural significance (Blicharska & MikusiŃSki, 2014; Lindenmayer *et al*., 2016; Lai *et al*., 2019; Liu *et al*., 2022). However, despite variations among regions, a notable consistency has emerged in investigation and monitoring techniques, driven by the extensive deployment of advanced tools like unmanned aerial vehicles (UAVs) (Singh *et al*., 2015; Chen *et al.*, 2017; Qiu *et al*., 2018). Foresters have particularly focused on rejuvenation techniques and pest control, conducting species-specific studies to support tree vitality (Andersson &. Östlund, 2004; Zhang *et al*., 2013; Takács *et al*., 2020). In addition, previous studies have highlighted the close relationship between HTs and the daily lives, cultural practices, and spiritual beliefs of local communities, thereby uncovering both direct and indirect historical-cultural values (Blicharska & Mikusiński, 2014; Cannon *et al*., 2020). To assess heritage trees and quantify their economic value, the researchers employed the contingent valuation method to examine the public's willingness to pay for their preservation (Lin *et al*., 2020; Takács *et al*., 2020; Liu *et al*., 2022). With growing public awareness of heritage trees conservation, region-specific regulations and practical conservation efforts have gradually emerged (Lindenmayer & Laurance, 2016)

In recent years, ongoing research efforts on heritage trees have led to the gradual development and refinement of dedicated heritage trees information systems. As a result, an increasing number of studies have focused on the configuration of HTs. The spatial distribution and driving

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mechanisms of heritage trees have become a frontier research topic at the intersection of ecology, geography, and sociology. Their distribution is often characterized by a "cultural–ecological" dual coupling pattern (Jim, 2005; Lai *et al*., 2019). HTs is strongly associated with Fengshui forests and river corridors, reflecting the synergistic co-evolution of nature and human society (Coggins *et al*., 2012).

Investigations into the spatial configuration of HTs are typically divided into three broad categories.

(1) Spatial analysis methods have evolved from basic descriptive statistics to spatial quantitative analyses. However, most studies still concentrate on quantitative assessments across regions and categories (Liu *et al*., 2022; Asanok *et al*., 2021). Comprehensive analyses of the types, trends, and determinants of heritage tree configuration remain limited, thereby constraining their applicability in resource integration and urban planning.

(2) Influencing factors can be broadly categorized into natural and anthropogenic factors. Natural factors include geographic coordinates, topographic features (Huang *et al*., 2020; Wan *et al*., 2020), and climatic conditions (temperature and precipitation) (Coggins *et al*., 2012; Li & Zhang, 2021). Human factors primarily reflect the human activities and the extent of land development. Notably, HTs are frequently closely linked to historical figures, significant events, and architectural landmarks, thus representing a key element of local cultural identity. In particular, ancient capitals with rich historical and cultural legacies act as important determinants shaping the configuration of HTs (Ray *et al*., 2014). The interaction between natural and human factors results in an uneven spatial distribution of variables influencing the occurrence of heritage trees, exhibiting significant spatial autocorrelation and heterogeneity. Historically rooted factors have received comparatively limited attention in existing research.

(3) Most existing studies examining the relationship between influencing factors and heritage tree distributions primarily rely on qualitative inferences or basic regression analyses (Zhang *et al*., 2017; Xie *et al*., 2022). Given the spatial autocorrelation and heterogeneity inherent in heritage trees and their ecological communities, influencing factors often display significant spatial nonstationary (Wang *et al*., 2021). Geographically weighted regression (GWR) models allow the examination of spatial variations in a study subject and its associated influencing factors, while also enabling predictions of future outcomes. The regression coefficients of independent variables vary across spatial locations, rendering GWR particularly suitable for investigating the configuration of HTs and their determinants (Osborne & Suárez-Seoane, 2002; Chen *et al*., 2021). The GWR has been widely applied in socio-economics, natural resource management, and public administration (Foody, 2004; Austin, 2007; Nolan *et al*., 2020), its use in examining the HTs remains relatively rare, particularly in rapidly developing major cities in China.

Heritage trees are irreplaceable natural and cultural resources, shaped by the intricate interplay of time and geography. They serve as living archives of geographic and environmental change, offering valuable insights into historical geography (Huang *et al*., 2020; Xie *et al*., 2022). Investigating the spatial distribution patterns of heritage trees in rapidly urbanizing cities, through the lens of the geographic concept of the "human–land relationship", enables a more comprehensive understanding of their dynamics and informs effective conservation strategies. This study integrates the natural, cultural, and geographical characteristics of heritage trees through a synergistic "nature–humanity–technology" framework. Using the heritage trees in Shenzhen as the research object, this study quantitatively examined their species composition and spatial distribution, and further applied the GWR model to assess the relative influence of natural and anthropogenic factors on their spatial patterns. The findings aim to support the scientific conservation of Shenzhen's ecological heritage and promote the effective exploration of the socio-economic, historical, and cultural values embodied by heritage trees. Through multi-source data integration, the study further reveals the resilience thresholds of heritage trees survival in megacity clusters, offering theoretical support for biodiversity conservation and management of HTs.

Object and Method

Study location: Rapid urbanization has induced profound transformations in both the environment and society. At the present time, high-density residential areas constitute a distinctive feature of young cities. Shenzhen, the first Special Economic Zone (SEZ) established following China's reform and opening-up in the late 1970s, consists of nine administrative districts covering a total area of approximately 190,000 hectares. Located in Guangdong Province in southern China, Shenzhen is a vibrant and youthful metropolis (Fig. 1). Shenzhen spans from 22°26′59″ to 22°51′49″ N latitude and from 113°45′44″ to 114°37′21″ E longitude, situated in a subtropical maritime climate zone characterized by ample sunshine and abundant rainfall. The city experiences an average annual temperature of approximately 22 °C and an annual precipitation of about 1,883 mm. Shenzhen maintains a high urban tree canopy, with forest coverage reaching approximately 45%, and harbors a significant number of HTs. The city's zonal vegetation comprises subtropical evergreen broad-leaved forests and tropical evergreen monsoon rainforests. Shenzhen boasts a rich historical and cultural legacy, integrating diverse traditions including sea defense, Hakka, and Guangfu cultures, as well as revolutionary and reform-era innovations. The city has witnessed multiple large-scale migrations of Han Chinese from the Central Plains. In terms of folk traditions, Guangfu and Hakka cultures predominate, each exhibiting distinct styles and characteristics. As an emerging megacity, Shenzhen has profoundly reshaped the trajectory of China's social development. In just over three decades, it has transformed from a small town into a metropolis with a population exceeding ten million. However, the accelerated pace of urban expansion has progressively diminished the habitats of trees, undermining both the conservation of Shenzhen's historical heritage and the integrity of its natural landscape. This study investigates the influence of natural and anthropogenic factors on the configuration of HTs in Shenzhen, aiming to develop strategies for preserving the city's cultural heritage and enhancing its urban landscape.

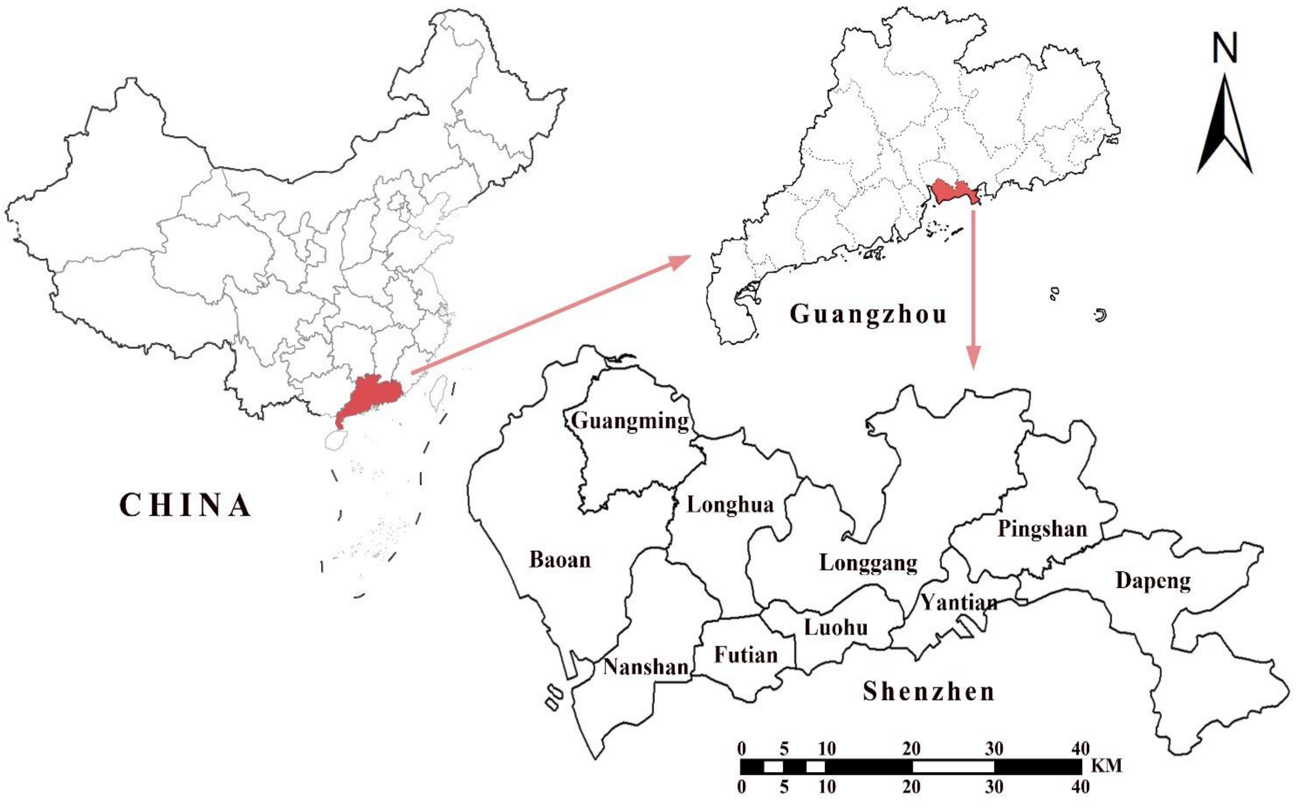

Fig. 1. Location of Shenzhen.

Data sources: The data on Shenzhen's ancient trees were obtained from the List of Shenzhen's Ancient and Famous Trees issued by the Shenzhen Municipal Bureau of Planning and Natural Resources (2023), in combination with the Guangdong Province Ancient and Famous Trees Information Management System, which compiles and filters information on the city's ancient tree resources by excluding incomplete records, resulting in a final dataset of 1,510 ancient trees. The elevation and slope data were collected in 2023 from the Geospatial Data Cloud (https://www.gscloud.cn/). Data on rivers, land use, vegetation index, and population density were obtained in 2023 from the Resource and Environmental Science and Data Center, Chinese Academy of Sciences (https://www.resdc.cn/). Road network data for Shenzhen were obtained from the official OpenStreetMap (OSM) public dataset (https://www.openstreetmap.org/)collected in 2023, and all datasets were spatially aligned under a unified coordinate system to integrate various natural and anthropogenic factors.

Method: This study utilized ArcMap 10.5.1 to construct a geographic database of HTs in Shenzhen. Kernel density and spatial autocorrelation analyses were then employed to explore the configuration characteristics of these resources across different geographic areas in Shenzhen. Additionally, the spatial heterogeneity of factors influencing heritage tree resources was examined using the GWR model.

Density analysis: Kernel density analysis is a method for measuring the unit density of points or lines within a defined neighborhood, based on the spatial distribution characteristics of sample points or line elements. This technique transforms discrete point data into a continuous density surface, providing an intuitive representation of spatial clustering. By mathematically modeling the "diffusion" of point data and simulating the probability density of each point across the surrounding space, this process generates a continuous heat surface that reflects the spatial dispersion of heritage trees. The formula is,

$$f(x) = \frac{1}{nh^2} \sum_{i=1}^{n} K\left(\frac{d(x,x_i)}{h}\right) \quad (1)$$

$f(x)$, Density values within old-growth resources
n, Total number of old trees
h, Bandwidth, the radius of a circle
K, Spatial weighting function
$d(x,x_i)$, Distance between two HTs

Spatial autocorrelation: Spatial autocorrelation refers to the phenomenon where adjacent or neighboring geographic elements may exhibit similarities or differences in their attribute values. However, heritage trees may display varying spatial heterogeneity across different regions. It is quantified using Moran's Index (Moran's I), which assesses the degree of spatial correlation by analyzing the spatial disparities among heritage trees. This method is used to identify both the overall and local spatial configuration patterns of HTs. In this study, Moran's I was applied to find the spatial configuration of HTs in Shenzhen, and was calculated using the following formula,

$$I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} * \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i-\bar{x})(x_j-\bar{x})}{\sum_{i=1}^{n}(x_i-\bar{x})^2} \quad (2)$$

n, Total number of samples
w_{ij}, Spatial weighting matrix
x_i , x_j, Element space attribute values
$\bar{x}$, Attribute Mean

The value of Moran's index ranges [-1, 1]. When Moran's I statistic significantly greater than zero indicates positive spatial autocorrelation, suggesting that heritage trees follow a clustered distribution pattern. The larger the value of Moran's I, the more significant the correlation. When Moran's I value statistically indistinguishable from zero reflects the absence of significant spatial autocorrelation, implying that the configuration of HTs is random. When Moran's I statistic significantly less than zero indicates negative spatial autocorrelation, suggesting that heritage trees follow a dispersed distribution pattern. The P-value reflects the probability of an event occurring; the smaller the P-value, the less likely it is that the observed spatial pattern is randomly generated. The Z-value represents the number of standard deviations, indicating the degree of dispersion in the data.

GWR: The GWR is a local regression technique employed to analyze spatial data. It is based on the principle that regression coefficients vary by geographic location, thus capturing spatial heterogeneity. Unlike traditional regression analysis, GWR estimates a distinct local regression equation for each location, using the dependent and explanatory variables within a defined spatial domain. The shape and size of the neighborhood depend on the kernel function and bandwidth selection parameters. Geographic weights are assigned to observations in each local regression: those farther from the target location receive lower weights and have less influence, whereas those closer are assigned higher weights and exert a greater impact. By introducing spatial weights and local parameter estimation, the GWR model overcomes the limitations of traditional global regression approaches in spatial analysis. It is particularly suitable for scenarios where relationships between variables exhibit spatial non-stationarity. Therefore, GWR facilitates more accurate analyses of how influencing factors vary across geographic space. The GWR model can be expressed as follows,

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{p} \beta_k(u_i, v_i)\, x_{ik} + \epsilon_i \quad (3)$$

y_i, Dependent variable at position i
x_{ik}, kth independent variable of the ith influencing factor
u_i, v_i, Latitude and longitude coordinates of the ith position
$\beta_k(u_i, v_i)$, Regression coefficient of the kth independent variable at position i
p, Number of independent variables
ϵ_i, Residual

Results

Species composition of heritage trees: In Shenzhen 1,510 heritage trees were identified, representing 39 families and 64 genera (Fig. 2). A word cloud analysis was conducted based on the family and genus data of these heritage trees to visualise their taxonomic composition. Based on the analysis of *Familia* and *Genus* data, 655 trees of *Moraceae*, 261 of *Sapindaceae*, and 225 of *Lauraceae* represented the most prevalent *Familia* among the heritage trees. In terms of genera, *Ficus* (651), *Cinnamomum* (197), and *Dimocarpus* (172) were the most dominant. *Ficus* species (603, 39.93%) were the most abundant and widely distributed across various regions. It was followed by *Cinnamomum* (197, 13.05%) and *Dimocarpus* (172, 11.39%). These heritage trees exhibit unique biological traits and economic significance. They are primarily native to southern regions and have adapted to the warm, humid climate with their large size, long lifespan, and both ornamental and economic value. Statistical results indicate that among the heritage trees in Shenzhen, *Ficus* species dominate due to their longevity and adaptability to the southern subtropical environment. Meanwhile, the presence of other rare species enhances the overall biodiversity of these heritage trees.

According to the Technical Specification for the Census and Identification of HTs, the protection grades of HTs in Shenzhen are classified into three categories: Grade I for trees less than 300 years old (1,428), Grade II for those between 300 and 500 years old (53), and Grade III for trees older than 500 years (29). The number of trees under different protection grades varied significantly, with fewer individuals recorded at higher age levels. This indicates a clear decreasing trend in the number of HTs as tree age increases, with trees aged 0–300 years being dominant.

Density analysis of heritage trees: Among Shenzhen's 10 administrative districts, Dapeng New District hosts the highest number of HTs (475), followed by Longgang District (240), Pingshan District (151), and Luohu District (130). In contrast, Futian (65), Guangming (37), and Yantian (37) Districts have relatively fewer preserved heritage trees, mainly due to early-stage urban planning, rapid construction, and insufficient awareness of heritage trees heritage conservation. Most of the remaining HTs in these areas are located in mountainous zones or urban fringe regions. Overall, heritage trees located outside urban areas tend to be older than those within urban centers.

The spatial distribution of heritage trees in Shenzhen was analyzed using the kernel density estimation (KDE) method (Fig. 3). The results indicate substantial variation in the number of HTs across different districts. In Dapeng New District, Longgang District, and Luohu District, heritage trees exhibit a clustered spatial pattern, with a maximum local density reaching 5.4 trees/km^2. Overall, the heritage trees in Shenzhen exhibits a "two-core and one-belt" configuration. The "two cores" refer to the concentration zones centered in Dapeng New District and Luohu District. The "one belt" corresponds to a low-density zone aligned with the southern foothills of the Shenzhen Mountain range. Although Luohu District does not have the highest number of heritage trees, its limited area results in the highest tree density (1.9 trees/km^2); in contrast, heritage trees in Guangming District and Bao'an District are sparsely distributed, with the lowest recorded density being 0.23 trees/km^2.

Autocorrelation analysis of heritage trees: The global Moran's I value for HTs in Shenzhen was 0.15806 (>0), significantly higher than the expected value, indicating a positive overall spatial correlation. The corresponding Z-score was 4.28, exceeding the 99% confidence threshold (Fig. 4). The results substantiated the presence of significant positive spatial autocorrelation in the configuration of HTs in Shenzhen. Since the Z-score exceeds 2.58, the spatial pattern can be characterized as a clustered distribution.

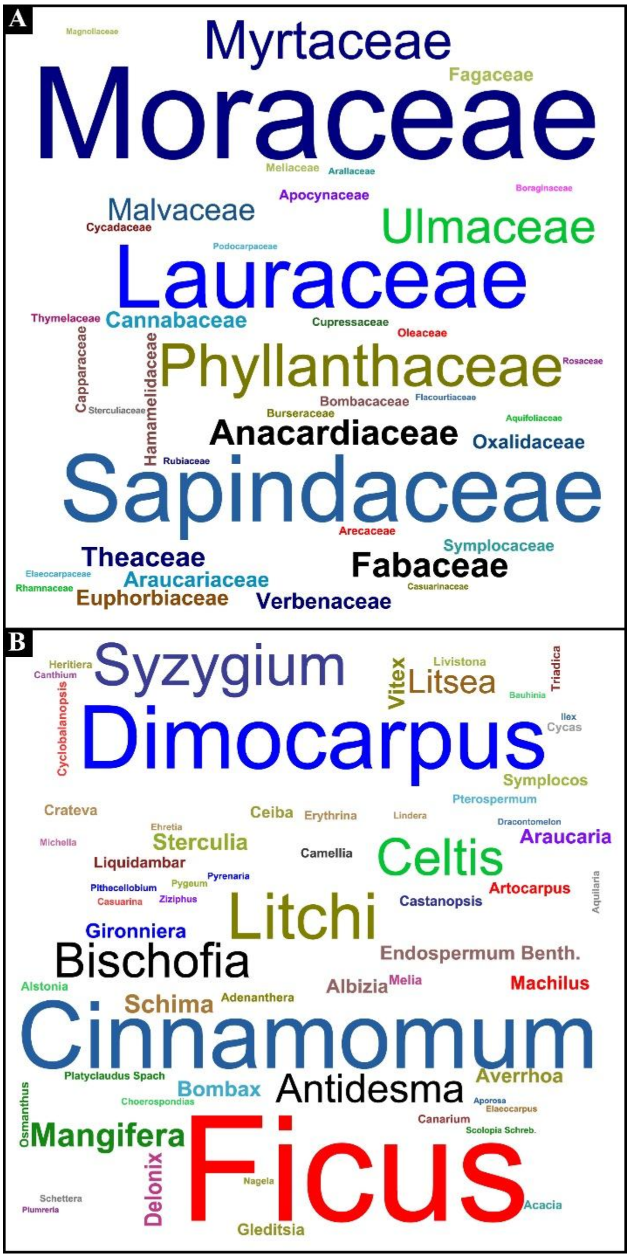

Fig. 2. Classification of HTs in Shenzhen: (A) Composition of ancient trees of the *Familia*; (B) Composition of ancient trees of the *Genus*.

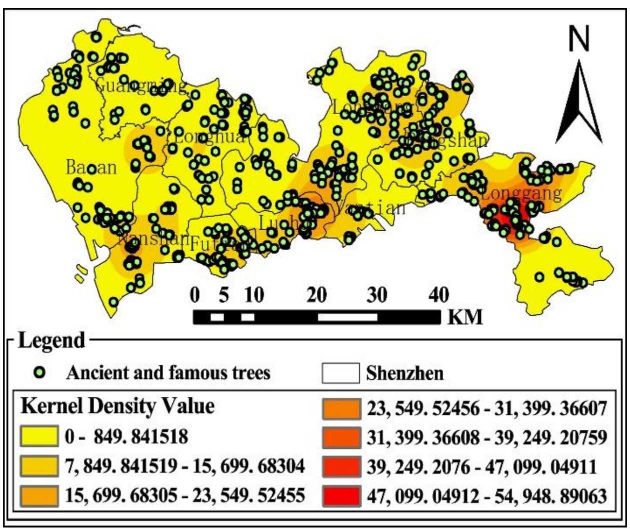

Fig. 3. Kernel density analysis of HTs in Shenzhen city.

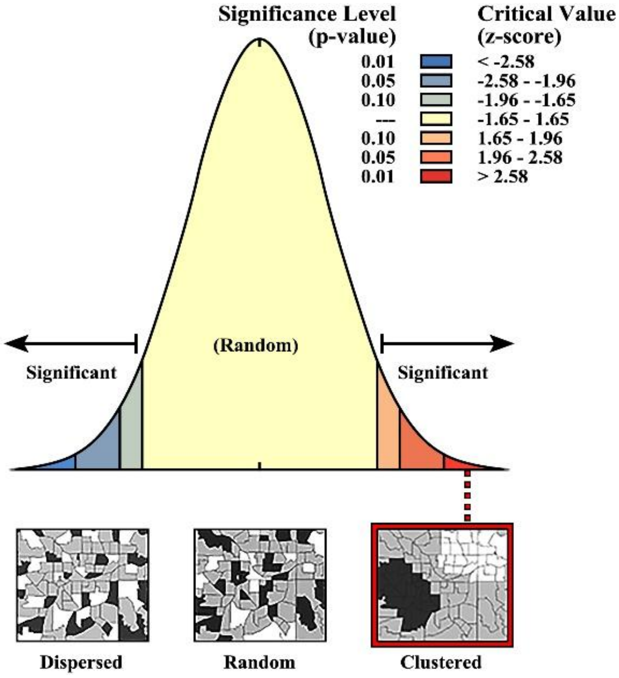

Fig. 4. Global Moran's I.

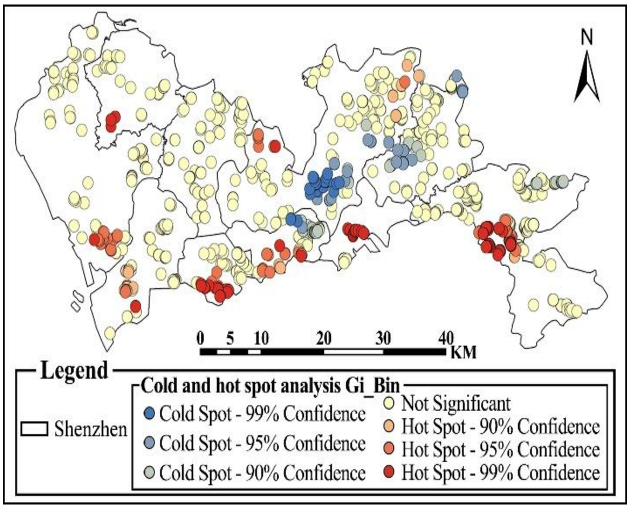

Fig. 5. Cold hotspot analysis of HTs in Shenzhen.

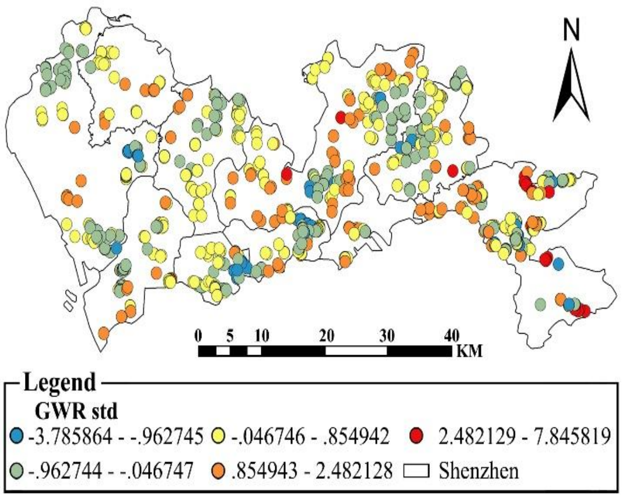

Fig. 6. Standardized residuals of the GWR model.

Local spatial distribution was further examined using hot spot and cold spot analysis. Z-score intervals of [−3, 3], [−2, 2], and [−1, 1] correspond to 99%, 95%, and 90% confidence levels, respectively. Fig. 5 illustrates the configuration of hot and cold spots formed during the development of heritage trees in Shenzhen. Hotspots were primarily concentrated in the central Dapeng New District, southern Futian District, and central Yantian District, with secondary hotspots appearing in Luohu District and southern Bao'an District; in contrast, cold spot clusters were mainly located in central Longgang and northern Luohu. The spatial distribution of hot and cold spots is uneven: hotspots are limited in size and highly dispersed, whereas cold spots are also limited in area but more spatially concentrated.

Factors influencing of heritage trees: The spatial configuration differences of HTs in Shenzhen result from long-term interactions between natural and human factors. Based on prior studies on HTs, 8 quantitative indicators (Fig. 7) were selected from both natural (elevation, slope, slope direction, water sources, NDVI) and anthropogenic (land use, population density, road density) dimensions. The GWR model was constructed to explore the different spatial influences of these factors on the configuration of HTs.

The GWR model was developed to examine spatial trends in the regression coefficients and to assess the key driving factors influencing of HTs in Shenzhen by evaluating the spatial variability in the relationships between the dependent variable and each influencing factor. Regression coefficients were classified using the natural breaks method (Fig. 6). The final model results showed a significance level of 0.072, AICc of −3581.87, R^2 of 0.93, and adjusted R^2 of 0.92. These results indicated a strong model fit, with over 92% of the variance explained. Before conducting the Geographically Weighted Regression (GWR) analysis, we first performed an Ordinary Least Squares (OLS) regression and found that the Variance Inflation Factor (VIF) values were all below 7.5, indicating the absence of significant multicollinearity among the explanatory variables. The Residual Squares value of the regression model was 7.344, indicating that a lower Residual Squares corresponded to a better model fit between the observed and predicted values. This suggested that the GWR model provides a closer approximation to the actual spatial patterns, thereby enhancing the reliability of the results. The sign of each coefficient was used to determine whether the influencing factor had a positive or negative correlation with the HTs. The magnitude of the values of the regression coefficients reflected the strength of influence. The results revealed that slope and NDVI were positively correlated with the configuration of HTs, while elevation, slope direction, water sources, land use, road density, and population density showed negative correlations. Among these, population density, elevation, slope, and road density exhibited the strongest associations (Table 1). Based on the absolute values of the regression coefficients, the relative influence of each factor on heritage trees in Shenzhen was ranked as follows: population density > elevation > slope > road density > NDVI > land use > slope direction > water sources.

Elevation influences the distribution of heritage trees due to variations in soil properties, moisture content, and air temperature across different altitudes. In Shenzhen, heritage trees are distributed across an elevation range of 1–460 meters above sea level. Areas below 40 meters account for 78.28% of the total, while those at 51–100 meters comprise 16.75% (Fig. 8). According to the GWR model, the regression coefficients ranged substantially between -2.61 and 1.69 (mean = -0.43), indicating substantial spatial heterogeneity in elevation's influence on heritage trees distribution. The negative mean coefficient suggests that elevation is generally negatively correlated with heritage trees presence, with tree abundance declining significantly at higher elevations. As shown in Fig. 8, higher regression coefficients are mainly concentrated in Dapeng New, Pingshan, Longgang, Futian, and Longhua. These heritage trees are predominantly found at lower elevations, typically located in central urban areas or at the urban fringe. In contrast, the central parts of Dapeng New District, Bao'an District, and Guangming District exhibit negative regression coefficients, indicating a negative correlation between elevation and heritage trees presence. These areas, characterized by mountainous terrain and sparse population, provide favorable environments for the natural growth and preservation of HTs.

Heritage trees in Shenzhen are primarily distributed across plains and gently sloping areas. Among these, 1218 trees are found on slopes of 0–5°, followed by 16.49% of trees located on slopes of 5–15°. As shown in Table 1, the mean GWR regression coefficient for slope is 0.23, indicating a positive correlation with the spatial configuration of HTs. Higher coefficient values are mainly observed in Dapeng New District, particularly in suburban and mountainous regions. Moderate slope gradients facilitate natural drainage, which may support the survival and longevity of HTs. In the later stages of Shenzhen's urban development, planning efforts increasingly referenced international ecological city models and principles of sustainable development. As a result, greater attention has been given to the conservation of HTs during urban construction activities.

Slope direction influences light exposure, temperature, and humidity, thereby affecting plant growth and distribution. The GWR coefficients for slope direction ranged [-0.11, 0.13], (mean=-0.003; SD=0.019). These results indicate that slope direction has a minimal impact on heritage trees, with limited variation across locations. Statistical analysis confirmed that heritage trees were distributed across all slope directions. In terms of spatial heterogeneity, negative regression coefficients were primarily observed in the western and northern regions of Shenzhen, while positive coefficients were concentrated at the junction of Dapeng New District and Pingshan District (Fig. 9).

Table 1. Regression coefficients of GWR model.

Factors	Mean of coefficients	SD	Max	Min
Elevation	-0.43294	0.131498	1.693577	-2.61244
Slop	0.234306	0.079559	1.390889	-0.19008
Slope direction	-0.00383	0.019033	0.126597	-0.11377
Water sources	-0.00066	0.01891	0.180025	-0.41187
NDVI	0.049452	0.026375	0.372584	-0.15871
Land use	-0.00543	0.018164	0.236603	-0.17692
Population density	-0.63925	0.111075	1.772629	-3.24155
Road density	-0.17074	0.078555	2.995205	-3.16446

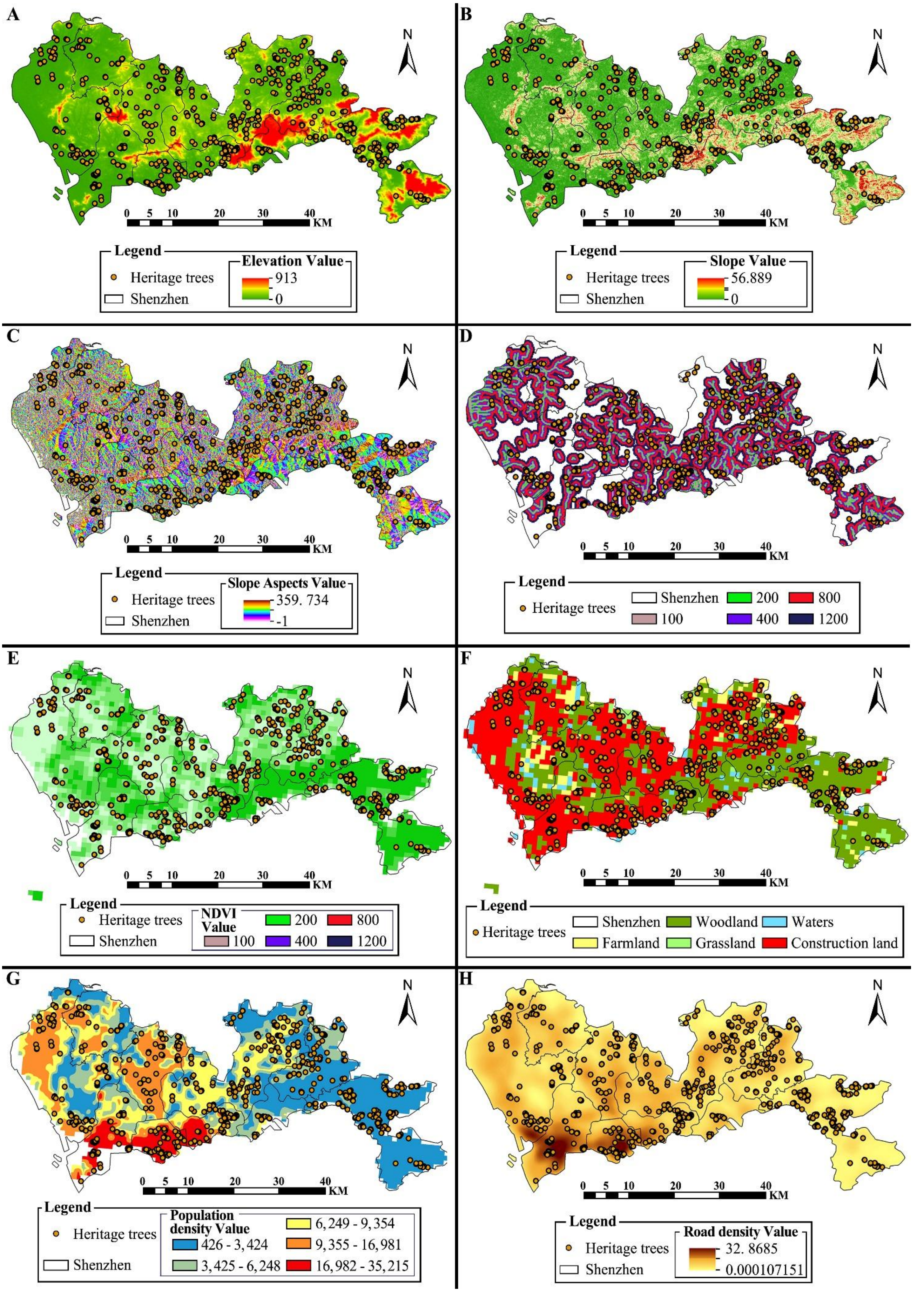

Fig. 7. Factors influencing of HTs in Shenzhen: (A) elevation; (B) slope; (C) slope direction; (D) water sources; (E) NDVI; (F) land use; (G) population density; (H) road density.

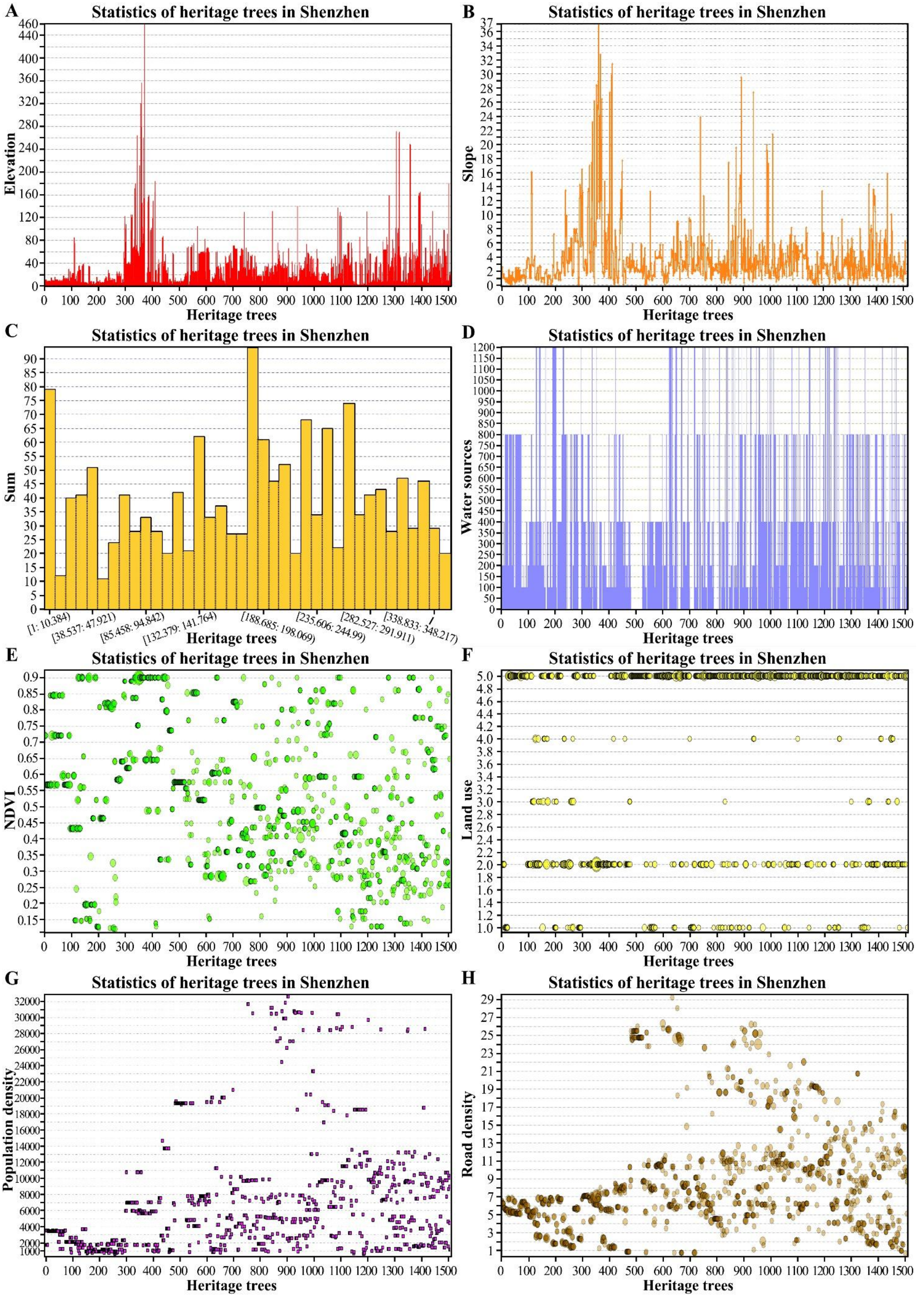

Fig. 8. Distribution of heritage tree in Shenzhen under different influencing factors: (A) elevation; (B) slope; (C) slope direction; (D) water sources; (E) NDVI; (F) land use; (G) population density; (H) road density.

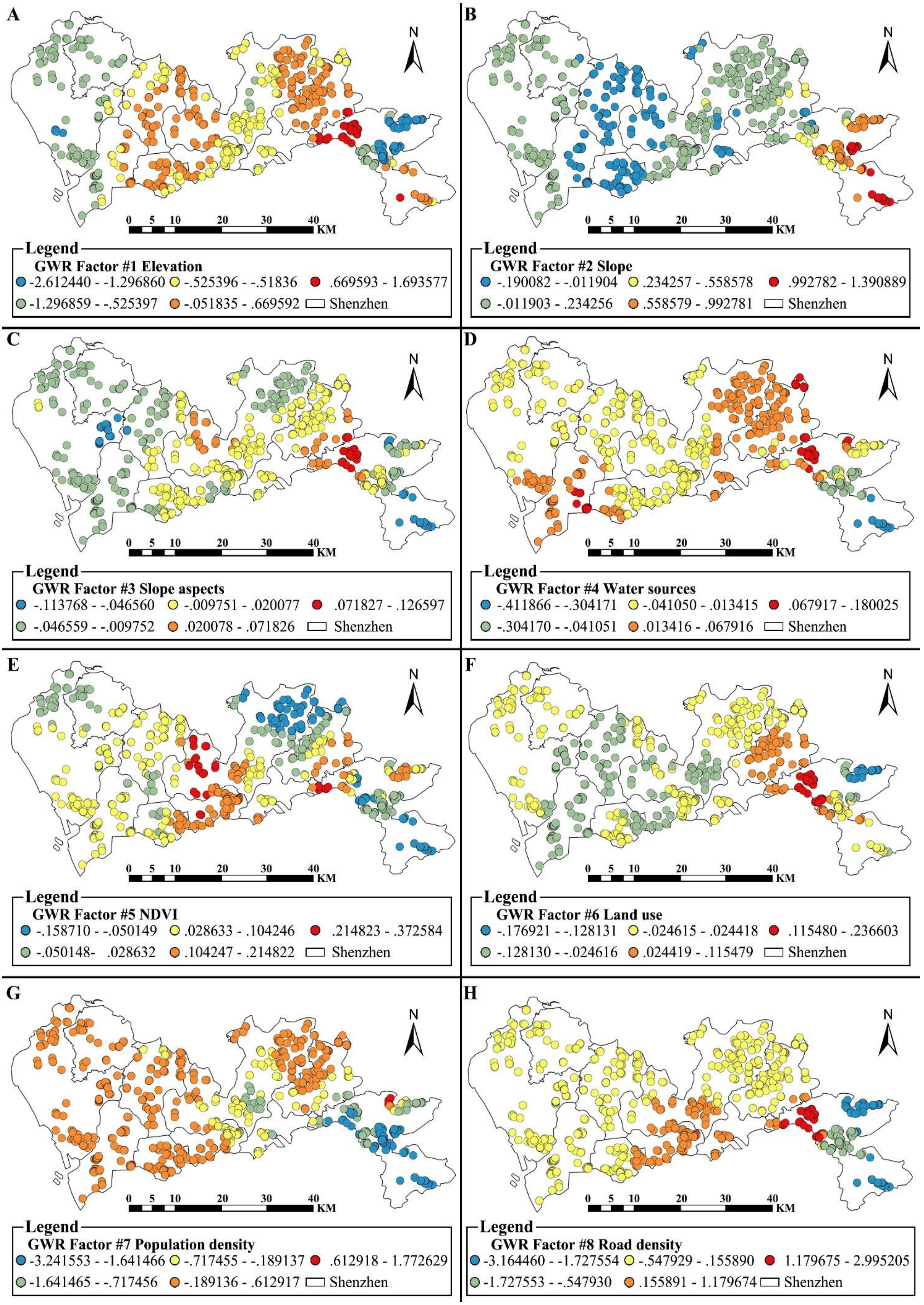

Fig. 9. Spatial heterogeneity of influences on (A) elevation; (B) slope; (C) slope direction; (D) water sources; (E) NDVI; (F) land use; (G) population density; (H) road density.

Water sources influence the configuration of HTs. As shown in Fig. 8, 69.47% of heritage trees are concentrated within 400 meters of a water source, with a clear decline in numbers as distance increases. The mean regression coefficient was -0.0006, indicating a weak and spatially heterogeneous influence of water sources on heritage trees. Among all influencing factors, the absolute value of the water sources coefficient was the smallest, which might be attributed to the geographical and climatic conditions of Shenzhen. Soil moisture was generally sufficient throughout the region, allowing even trees located farther from water sources to thrive under the perennial warm and humid conditions.

NDVI reflects the health and vigor of surface vegetation, thereby indirectly indicating the ecological conditions surrounding heritage trees. The GWR regression coefficient for NDVI ranged [-0.16, 0.37], (mean=0.049; SD=0.026), indicating a spatially heterogeneous impact of vegetation on heritage trees. Higher coefficient values are concentrated in central Shenzhen, while lower values are more spatially dispersed. The majority of HTs are located in areas with NDVI values between 0.3 and 0.6. This suggested that a moderate NDVI value was conducive to the growth of heritage trees. It ensures adequate vegetation without excessive competition for space, while also avoiding the negative effects of sparse vegetation. Vegetation contributes positively to the ecological stability of the surrounding environment, and a well-balanced plant community can support the healthy development of heritage trees.

Human environment factor: Based on remote sensing land use data, six primary land use categories and 25 subcategories were identified. This study focused on the primary classification level (six primary land use categories) to analyze the land use types associated with heritage trees in Shenzhen. By overlaying the data of HTs with land use data, the specific land use category associated with each heritage trees were determined. The results indicated that the majority of HTs (1,020, 63.58%) were located in residential land, followed by forest land, which accounts for 24.04% of the total. The average coefficient estimated from the GWR model for land use was −0.0054, indicating its limited contribution to explaining heritage trees. Spatial heterogeneity was most pronounced in eastern Shenzhen, while in central and western regions, the regression coefficients were generally negative and the distribution more dispersed. It was observed that most heritage trees in Shenzhen were located in residential and forested areas characterized by relatively good ecological conditions. Therefore, natural or semi-natural land uses appear to influence the spatial distribution of heritage trees to some extent. A favorable ecological environment contributes to the stable growth and long-term preservation of heritage trees.

The GWR regression coefficients for population density ranged [-3.24, 1.77], (mean=-0.64), indicating a strong negative correlation between population density and heritage trees, accompanied by high coefficient variability. It was observed that districts in Shenzhen with a higher concentration of heritage trees were mostly underdeveloped or less urbanized areas, and had relatively lower population density, which exerted less pressure on the preservation and growth of HTs. In contrast, areas with sparse configuration of HTs are primarily the urbanized zones of Shenzhen, where the growth conditions of heritage trees are significantly constrained. Lower regression coefficients are concentrated in Dapeng New District, while higher coefficients are mainly scattered across the western and northern regions of Shenzhen. Population density exhibited the strongest negative influence on heritage trees, representing the most influential explanatory variable among all considered factors. The spatial heterogeneity associated with this factor was also the most pronounced (Fig. 9).

Road density reflected the urban transportation infrastructure in Shenzhen and provided insights into human activity patterns, thereby revealing the spatial heterogeneity in the configuration of HTs. The results indicated that most HTs in Shenzhen were concentrated in areas with low road density, while relatively fewer were found in high-density areas. Their number decreased with the increase of road density. The GWR regression coefficients for road density ranged [-3.16, 2.99], with a mean of -0.17 and a SD of 0.08, indicating that road density significantly influenced the spatial configuration of HTs. The spatial configuration of the coefficients shows that lower coefficient values are primarily concentrated in Dapeng New District, where the relatively sparse road network exerted less influence on HTs distribution. Overall, road density had a substantial influence on the spatial configuration of HTs in Shenzhen. While densely built-up areas generally hosted fewer heritage trees, a number had been retained within highly urbanized settings as a result of enhanced environmental management and dedicated preservation initiatives.

Discussion

The spatial distribution of heritage trees within urban environments reflects complex interactions between natural ecosystems and human activities. From the perspective of urban geospatial analysis and heritage conservation, this study examines the spatial distribution patterns of heritage tree resources and their driving factors in Shenzhen using spatial autocorrelation and the GWR models. The results reveal, to a certain extent, the spatial compression of ecological heritage associated with rapid urbanization. Rapid urbanization often leads to the spatial compression and marginalization of natural and cultural heritage resources. Heritage trees are significantly and negatively correlated with indicators of human activity, including population and road density. This pattern is particularly evident in the core urban areas of Shenzhen, where heritage trees exhibit a distinct pattern of spatial retreat and clustering, supporting the theoretical framework of ecological heritage displacement under urban expansion pressure.

The study also identified the mediating and moderating effects of natural environmental factors, on the spatial patterns of HTs, highlighting the critical role of Ecological Niche Retention (ENR) in heritage conservation. Areas characterized by higher elevation, slopes, and dense vegetation cover tend to experience lower levels of human disturbance, thereby providing stable ecological conditions conducive to the long-term survival and regeneration of HTs. Consequently, the current spatial configuration pattern of these trees results from the dual influences of urbanization pressure and ecological suitability. This spatial reconfiguration reflects both urban land-use differentiation and the selective retention of ecological resources.

Heritage trees resource characteristics and human history: Heritage trees not only function as vital ecological assets but also embody the historical memory and cultural identity of the city (Blicharska *et al*., 2014; Cloke *et al*., 2020) . At present, most heritage trees are distributed across topographic transition zones such as gentle slopes and low hills, which are ecologically favorable and highly compatible with traditional settlement patterns (situated near mountains, facing water, and sheltered from prevailing winds and sunlight) (Coggins *et al*., 2012; Bixia *et al*., 2014). *Ficus microcarpa*, *Cinnamomum camphora*, and *Dimocarpus longan* constitute the dominant heritage tree species in Shenzhen. Their spatial distribution is closely linked to local agricultural traditions and the region's distinctive geographical and climatic conditions. The Ficus species is tolerant to heat and humidity, long-lived, and provides substantial shade. Historically, it was often planted around temples, villages, and ancestral halls as feng shui or commemorative trees, symbolizing the close relationship between heritage tree distribution and the evolution of human settlements. Over the course of historical development, Shenzhen's heritage trees have been preserved as "historical nodes" that embody both cultural continuity and ecological symbiosis, representing the long-term interaction between natural and anthropogenic forces. This co-evolutionary mechanism between nature and human society has been largely overlooked in previous research. This study systematically investigates the spatial heterogeneity of heritage tree distribution from a geospatial perspective, thereby offering a valuable reference for future research and reflection on the spatial characteristics of heritage trees.

Heritage trees and urbanization: Natural geography serves as a foundational determinant of the species composition and configuration patterns of HTs in Shenzhen. Heritage trees exhibited significant positive spatial autocorrelation, with the "dual-core and single-belt" configuration, underscores the disparities in heritage tree retention resulting from uneven urban–rural development. The high density of heritage trees in Dapeng new district and Luohu district can be attributed to a combination of factors, including a well-preserved natural environment, historically delayed urban development, and robust ecological protection policies. In contrast, the core urban districts of Futian and Nanshan, which have experienced intensive land development, exhibit relatively sparse distributions of heritage trees, primarily confined to urban parks or peri-urban foothill zones. This spatial pattern partially reflects the trajectory and pace of Shenzhen's urban expansion. The spatial framework developed in this study reveals the underlying mechanisms and multidimensional drivers of heritage trees distribution within the context of a rapidly expanding coastal megacity. Compared to previous spatial analyses (Jim *et al*., 2013; Benner *et al*., 2021; Hou *et al*., 2022), this research suggests that urbanization and heritage trees preservation are not inherently antagonistic; rather, their spatial differentiation reflects a synergistic co-evolution between natural and human systems that is distinctive to southern China.

The typical subtropical monsoon climate has fostered the formation of unique plant communities in Shenzhen. The interwoven pattern of mountains and waterways, together with the dense green vegetation cover, provides a stable and favorable growth environment for heritage trees. Over the past four decades, Shenzhen has transformed from a rural county into a global hub for science and technology. During this process, the relationship between urban expansion and the preservation of valuable trees has shifted from initial conflict to a more harmonious coexistence. In older urban areas, high population density has led to a pronounced "hollow core" phenomenon in configuration of HTs. In recent years, growing public awareness of HTs conservation has prompted the construction of parks and green spaces around these trees, both providing suitable ecological conditions and reinforcing urban cultural heritage (Jim *et al*., 2013; Huang *et al*., 2020)

Spatial patterns and influences on heritage trees: The spatial configuration of HTs in Shenzhen was examined using eight factors, including natural variables (elevation, slope, slope direction, water sources, and NDVI) and anthropogenic variables (land use, population density, and road density). Spatial autocorrelation analysis was employed to investigate the configuration of HTs, and the GWR was applied to compare influencing factors. The results indicate that the configuration of HTs in Shenzhen exhibits a clustered pattern, primarily concentrated in the central and eastern regions of the city. The observed positive spatial autocorrelation suggests that the growth and preservation of HTs are not random but are influenced by spatial aggregation mechanisms. These trees are predominantly found in areas with stable ecological conditions and minimal human disturbance, such as mountainous forests and low-density residential zones, which possess higher ecological carrying capacity and support long-term succession and natural regeneration.

In terms of physical geography, heritage trees are primarily concentrated in low-altitude and gently sloping areas, reflecting their adaptability to soil moisture, thermal stability, and drainage conditions. This pattern is consistent with observations in other southern Chinese cities (e.g., Guangzhou and Xiamen) and suggests that areas with gentle topography and favorable ecological conditions are more likely to support the formation of heritage tree clusters (Jim, 2002). Adequate light availability and efficient drainage provide optimal conditions for the growth and longevity of heritage trees (Lindenmayer *et al*., 2016; Hou *et al*., 2022). In Shenzhen, heritage trees are predominantly distributed at elevations below 40 m above sea level, and their abundance declines progressively with increasing altitude. From the perspective of slope characteristics, flat, gently sloping, and south-facing (sunny) areas exhibit the highest density of heritage trees. Among the various natural factors, elevation and slope depicted the strongest explanatory power for the spatial distribution of heritage trees. The positive correlation with NDVI suggests that robust vegetation cover supports the stable growth of heritage trees. However, the influence of water sources bodies was minimal, likely due to Shenzhen's humid climate and abundant rainfall, which allowed heritage trees to meet their water requirements even at greater distances from water sources. This implies that water availability is not a primary limiting factor for their survival in this region.

Most human-induced factors exhibit a negative association with the spatial density of HTs, as they tend to restrict suitable growth environments, particularly impacting those located in urban cores. Among the human factors, population density exerts the strongest negative influence on the spatial distribution of heritage trees, followed by road density, indicating the increasing survival pressure faced by heritage tree resources under rapid urbanization. The GWR model enables localized analysis of the influence coefficients for each individual tree, facilitating targeted protection strategies. Densely populated areas often imply higher land-use intensity and more frequent traffic activities, which together exert stress on the normal growth of heritage trees. This finding is consistent with Jim's study on the driving mechanisms of heritage tree distribution in Hong Kong (Jim *et al.*, 2013). Additionally, increased road density often leads to reduced green space and soil degradation, which undermine root system stability and hinder water uptake (Jim, 2004; Jim, 2005; Tian *et al.,* 2024). Although many heritage trees are located within residential land, this does not imply that human habitats inherently provide protective conditions. On the contrary, without effective institutional and technological interventions, urban redevelopment can severely disrupt the ecological integrity of heritage trees environments (Jim, 2005; Jim, 2004). Therefore, spatial constraints for the protection of heritage trees should be reinforced within land use planning frameworks.

Conservation and valorization of heritage trees: As unique ecological resource, HTs exhibit distinct spatial associations with both natural and human factors (Huang *et al*., 2020; Xie *et al*., 2022). They serve not only as a foundation for ecological civilization but also as carriers of local history and culture, which underscores their significance in protection efforts and cultural value exploration (Blicharska *et al*., 2014; Samuels , 2005). To mitigate natural disasters in areas with steep slopes, ground cover vegetation should be planted to prevent landslides and maintain soil moisture levels. Additionally, although heritage trees in urban areas face more ecological disturbances, their growth environment can be improved through strengthened protection and the establishment of dynamic regulatory mechanisms (Le Roux *et al*., 2014; Chen,2015; Xia *et al*., 2023).

Human activities significantly influence the spatial distribution of heritage trees, resulting in a fragmented and dispersed pattern in urban areas, while those in mountainous and forested zones are more clustered and long-lived. The distribution exhibits marked spatial heterogeneity, with the magnitude of response to factors such as population density, slope, and elevation varying across regions. These differences provide a scientific basis for region-specific conservation strategies. In Dapeng New District, ecological space protection and development boundary control should be prioritized, whereas in densely urbanized areas such as Futian District, engineering measures including in-situ conservation, relocation cultivation, and landscape-embedded preservation can promote the coexistence of heritage trees and urban functions. Under the premise of protection, moderate urban development remains feasible. As cultural carriers of nostalgia, heritage trees embody collective memory and humanistic emotion, while serving as valuable resources for rural tourism. Integrating regional history and culture, developing themed tour routes, and coordinating heritage tree preservation with surrounding landscapes can enhance their ecological, cultural, and economic value.

Conclusion

This study investigated the configuration pattern of 1,510 HTs in Shenzhen using kernel density estimation, spatial autocorrelation analysis, and hotspot–coldspot analysis. Additionally, The GWR model was employed to assess the influence of factors (natural and anthropogenic) on their distribution. The objective was to clarify the influence of individual factors on heritage trees, thereby informing targeted conservation strategies and maximizing their ecological value. The main conclusions are summarized as follows.

Firstly, *Ficus microcarpa*, *Cinnamomum camphora*, and *Dimocarpus longan* trees together account for 64.57% of all heritage trees in Shenzhen, a distribution pattern closely associated with the region's subtropical monsoon climate. Specifically, 697 trees belong to the *Moraceae*, representing 46.15%, while 829 trees fall under the *Ficus*, accounting for 54.90%. As tree age increases, the number of HTs declines. Secondly, the configuration of HTs varies significantly across regions, with central Shenzhen and the eastern Dapeng New District serving as the primary clustering areas. In contrast, other areas exhibit more dispersed distributions. The global Moran's I was 0.158 with a Z-value of 4.28, indicating a statistically significant positive spatial autocorrelation and a clustered configuration pattern. Hotspot–coldspot analysis reveals that hotspots are spatially scattered, while cold spots are more concentrated. Thirdly, the GWR was constructed to examine the influencing factors the distribution of heritage trees. The model achieved a high explanatory power with an R^2 of 0.92, revealing the complex and heterogeneous effects of various factors. Elevation, slope direction, water sources, land use, population density, and road density were negatively correlated with the configuration of HTs, whereas slope and NDVI showed positive correlations. Among these, the effects of water sources, slope direction, and land use were relatively weak. The relative importance of influencing factors was ranked as follows: population density > elevation > slope > road density > NDVI > land use > slope direction > water sources.

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