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Original article

Exploring the environmental justice of street tree provision: Adding biodiversity to automatic assessment of street-level greenery

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A R T I C L E I N F O

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A B S T R A C T

Tree species play a crucial role in enhancing environmental sustainability, public health, and social equity beyond the quantity of urban trees. Previous studies have identified the luxury effect (socioeconomic status) and legacy effect (i.e., historical development) as two primary drivers of spatial inequality of street trees diversity. Nevertheless, there is a lack of research examining the driving factors of street tree diversity inequality in the cities in China, which follow a centralized top-down urban development strategy, distinct from that in many Western cities. This study examines which effect, i.e., the luxury effect (measured by housing price) or legacy effect (measured by building ages) can explain environmental inequality of urban street tree diversity in a typical northern city, Jinan China. Drawing on advanced computer vision technology and prevalent Street View Images, this study automatically examines not only the quantity but also the species and other individual features of street trees. The study area includes both the old town with dense, low-rise buildings and newly built urban districts characterized by high-rise developments. We utilized Pearson correlation analysis and Principal Component Analysis (PCA) to elucidate the link of tree abundance, diversity, and other metrics with housing price and building ages. Our findings indicate that housing price shows no significant association with tree metrics. Instead, building age and the interactive effect of building age and housing price are positive linked with both quantity and biodiversity of street trees. These results highlight the importance of legacy effect in shaping urban street trees, while the luxury effect on street tree diversity is heterogeneous across areas developed in different times. These results confirm our hypothesis regarding the unique influence of China's centralized greening policies on urban forest composition. Our findings contribute to the political ecology discourse on environmental inequality and urban greenery distribution both locally and globally.

1. Introduction

Urban trees are significant component in urban environments, offering various benefits to both the environment and the society (Johnson, 2006). They deliver environmental advantages through air purification (Grundström and Pleijel, 2014), urban biodiversity (Liu and Slik, 2022) and carbon sequestration (Zhao et al., 2018). Furthermore, urban trees promote social well-being (Jiang et al., 2014; Wolf et al., 2020), encourage outdoor activities (Lu, 2019), and play a pivotal role in stimulating community engagement by fostering a sense of ownership and social cohesion (de Guzman et al., 2018). Street trees, although constituting a small proportion of urban tree stock, serve as crucial and accessible green spaces, especially for low to medium-income residents lacking other green spaces (Heynen et al., 2006).

Beyond mere quantity, tree diversity plays a critical role in mediating the benefits of trees on human beings (Liu et al., 2025a). For example, the composition of tree species within an area significantly influences the ecosystem services they provide (Gaglio et al., 2022). Diverse tree species ensure a robust and resilient urban forest capable of withstanding diseases, pests, and climate change impacts (Rosenthal et al., 2021). Moreover, tree species diversity directly translates into biodiversity support, offering habitats for various wildlife species essential for ecological balance within urban areas (Liu & Slik, 2022). The benefits of urban biodiversity also extend profoundly into the realm of human health and well-being. Exposure to a greater variety of plant life has been linked to improved mental health, reducing stress and promoting

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attention restoration more effectively than monotonous green spaces (Zhou et al., 2024). Recent research also suggests that greater exposure to diverse plant- and soil-associated microbes may strengthen the human immune system and reduce the prevalence of allergies and autoimmune diseases, a concept known as the "biodiversity hypothesis" (Hanski et al., 2012).

While greenery is significant to urban dwellers, it is well established in the literature that inequality in urban tree quantity and diversity is prevalent, particularly in areas with lower socio-economic status (SES), where tree cover levels are disproportionately lower, resulting in unequal access to tree-related services (Liu et al., 2025b). Higher provision of urban trees has been correlated with higher income levels (Locke & Grove, 2016), and fewer minority residents (Watkins et al., 2017). The disparity in access to urban forests among low-income and minority residents suggests inequitable access to the related physical, mental, and social health benefits, constituting environmental injustice (Jiang et al., 2022). The environmental injustice exists not only in the quantity of street trees but also in the species diversity of street trees, such as species richness and species mix (Allegretto et al., 2022). Numerous empirical studies have identified positive correlations between the diversity of urban greenery and SES (Anderson et al., 2023; Cubino & Retana, 2023; Nizamani et al., 2023). Recently, researchers have found that the race distribution are also linked to the biodiversity of urban greenery and the species richness of urban forests (Burghardt et al., 2023). Generally, higher urban tree diversity is associated with areas of higher SES and is lower in regions with a higher proportion of disadvantaged groups (Allegretto et al., 2022; Lin et al., 2021; but see Berland & Hopton, 2014; Staudhammer et al., 2015). The consequences of this "biodiversity gap" are profound, exacerbating existing health and social disparities (Naeem et al., 2016). Neighborhoods with low tree diversity and cover are more susceptible to the urban heat island effect, leading to dangerously high temperatures during heatwaves and increasing the risk of heat-related illness and mortality, which disproportionately affects vulnerable populations (Wang et al., 2021). These areas also receive fewer of the air-purifying, noise-reducing, and mental health benefits that biodiverse green spaces provide (Aerts et al., 2018).

Researchers have summarized two driving factors influence the unequal distribution of the quantity and biodiversity of urban greenery, known as the luxury effect and legacy effect (Aznarez et al., 2023). The luxury effect hypothesize that neighborhoods with higher SES have greater plant diversity and canopy cover (Clarke et al., 2013). Urban dwellers of higher socioeconomic status have a greater ability to allocate resources to vegetation, thereby affecting the dynamics of overall urban green space (Magle et al., 2021). Moreover, residents with higher SES status often have greater influence and agency over public and private decisions, such as land use planning and neighborhood investments, due to their advocacy capacity and access to decision-makers, including both public and private investors (Baró et al., 2019). The legacy effect indicates that the spatial distribution of vegetation cover and biodiversity in urban landscapes is shaped by the age of buildings, reflecting variations in historical management practices (Hope et al., 2003). Hence, older urban areas display higher plant diversity, reflecting long-term management practices (Aznarez et al., 2023). The interactive influence of the luxury and legacy effects on species diversity is also evident; for example, the relationship between vegetation quantity and income intensifies over time (Luck et al., 2009) as cultural historical legacies and management practices collectively shape neighborhood biodiversity (Clarke et al., 2013).

Different countries have different process to plant and manage street trees which can directly impact on the spatial distribution of street trees (Kinzig et al., 2005). However, most studies focus on North America and Europe (Allegretto et al., 2022). Compared with Western countries, urban planning and tree management in China are more centralized, with government agencies making decisions at national or municipal levels (Jim and Chen, 2003). This centralized approach can result in uniformity in tree species selection and cityscapes, reflecting historical policies and past government priorities instead of socioeconomic status (Jim and Chen, 2003). In recent decades, China has undergone a rapid urban expansion, creating new districts or satellite towns to accommodate population growth and modernization. The current mode of urban development has notably altered urban greenery in terms of quantity, tree size, and species composition (Cheng et al., 2022). Consequently, the derived concepts of the "luxury effect" and "legacy effect" may not be universally applicable across regions with distinct cultural and socio-institutional frameworks. Nevertheless, no study has specifically examined the biodiversity of street trees in China.

The scarcity and uneven distribution of research in this area may stem from limitations in assessment methodologies. Assessing the species of street trees and their spatial distribution involves acquiring individual tree profiles. Traditional field study can assess individual trees comprehensively, but is time-, labor-, money- consuming, which is only suitable for small-scale assessment (Fassnacht et al., 2016). Recent evolving computer technologies and boosting big data sources enable people to automatically and collectively quantify street trees from both top-down aspect (e.g. Normalized difference vegetation index) (Gascon et al., 2016) and eye-level aspect (e.g. Green View Index) (Li et al., 2015). However, these studies have ignored the species and other individual features of street trees. Recently, studies utilized Light Detection and Ranging (LiDAR) data for tree species identification which is costly to establishing a comprehensive citywide tree database (Li & Yao, 2020). Only a handful of cities have succeeded in constructing fine-grained street tree inventories with individual tree features including species, coordinates, tree size, and etc. (McCoy et al., 2022; Roman et al., 2017). Besides, most of these existing tree inventories exist in developed countries in Europe and North America (McCoy et al., 2022). Some researchers utilized street view images (SVI) and computer vision technology to evaluate street trees by species and other individual tree characteristics, subsequently creating a tree inventory (Liu et al., 2023). This method can not only provide fine-grained tree profiling, but is also automatics, cost-effective and adaptable for large-scale studies in cities and regions cannot affording the cost of manual tree inventories (Liu et al., 2023).

In this study, we employed a recent novel approach to detect and assess street tree via SVIs in order to obtain citywide and timely data about tree species and other features (Liu et al., 2023). Then, we utilized the Shannon index and species count to indicate street species mix and species richness of each spatial unit. Additionally, average tree height and crown diameter were used to represent tree size, while tree count, and Green View Index (GVI) were employed to quantify street trees. To examine whether the legacy effect, luxury effect, or their interaction remains significant in shaping the spatial distribution of street trees in urban China, we used housing price as a proxy for the luxury effect and building age as an indicator of the legacy effect.

We hypothesize that:

1. Both tree quantity and biodiversity are influenced by the luxury effect (measured by housing price) or the legacy effect (measured by building ages).

2. The legacy effect has a stronger influence on biodiversity than housing price due to the influence of China's centralized greening policies.

2. Methodology

2.1. Study area

We selected the inner city of Jinan as the study area (Fig. 1). Jinan is a megalopolis in north China and the capital of Shandong Province. Known as the "City of Springs," Jinan's urban landscape is shaped by its natural springs and topographical constraints, creating a mosaic of tree distribution tied to historical water management and phased urban expansion. The city's socioeconomic stratification—ranging from industrial legacy zones with limited green space to modern commercial

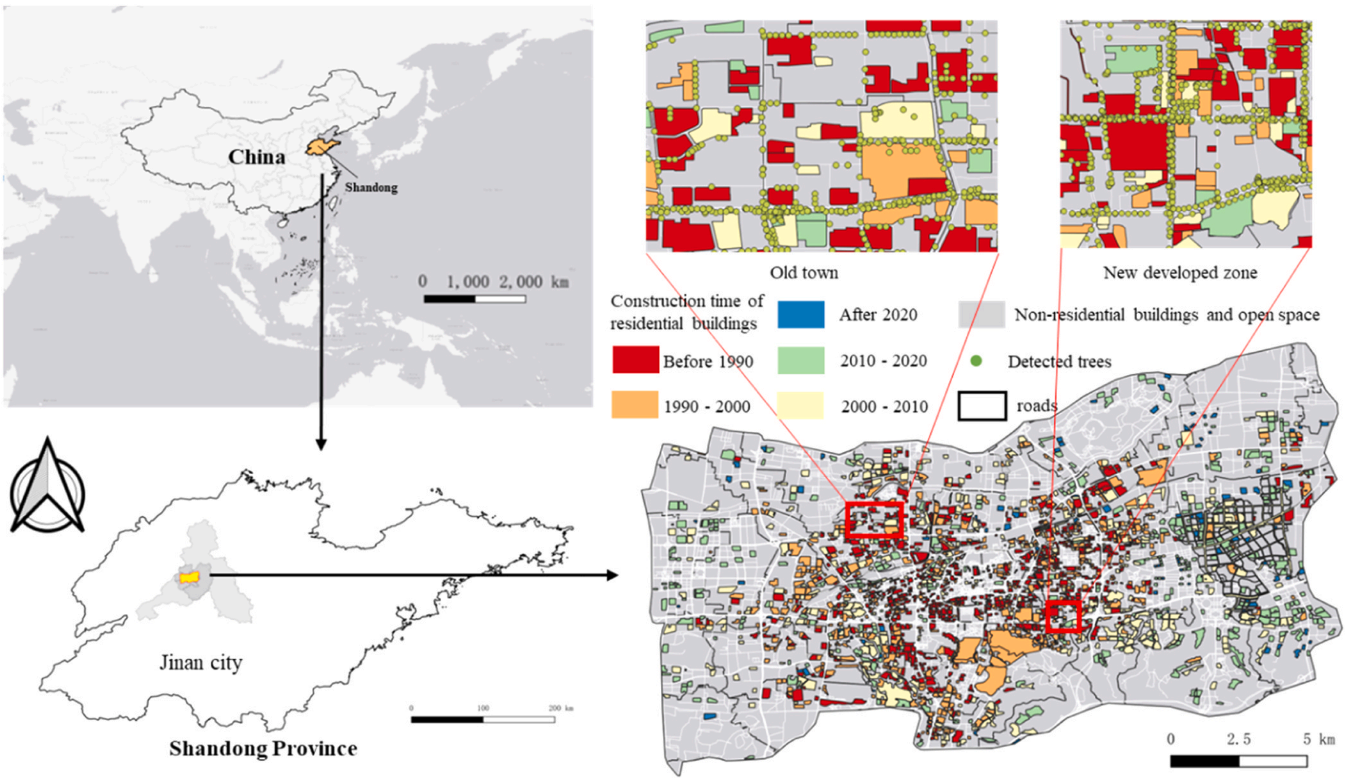

Fig. 1. The inner city of Jinan was selected as the study area. Jinan City located in the eastern part of North China. Two representative areas of the city are shown on the right side. Residential buildings built in different time periods are filled with different colors. Green dots represent detected street trees in this study.

hubs with curated greenery—provides a microcosm for analyzing how tree coverage and biodiversity correlates with income and historical marginalization. Jinan's semi-arid climate, environmental stressors like water scarcity and air pollution, and its role as a policy laboratory for national greening initiatives further highlight the urgency of equitable tree distribution. Additionally, the cultural significance of heritage trees underscores how symbolic value can exacerbate spatial inequities. Jinan has a temperate continental monsoon climate, and its street trees primarily consist of broad-leaved deciduous species. According to statistics, more than 90 % of the street tree inventory in Jinan comprises nine indigenous common taxa: oriental plane tree (Platanus spp.), poplar (Populus spp.), willow (Salix spp.), locust tree (Robinia spp.), cypress (Platycladus spp.), privet tree (Ligustrum spp.), boxwood (Buxus spp.), wax tree (Toxicodendron spp.), and pine (Pinus spp.) (Jinan Forestry Bureau, 2007).

2.2. Tree species classification

2.2.1. Data sources and data collection

In this study, Baidu Street View was selected as the source of images. Unlike other street view imagery (SVI) platforms in mainland China, such as Tencent Map and Gaode Map, Baidu uniquely offers SVIs across multiple times in a year. Therefore, Baidu SVIs captured from March to August were chosen for tree species classification, as street trees are generally verdant and identifiable during this period.

SVIs were automatically obtained via the Baidu Map API at intervals based on a threshold distance (T) along the centerlines of all streets in the study area. To avoid excessive or incomplete coverage along the street, T was calculated according to the distance between the camera and curb based the approach proposed by Liu et al. (2023). For each sampling point, two SVIs were collected using heading parameters of 90° and 270°, corresponding to the right and left sides of the vehicle-mounted camera.

Ultimately, 185,831 SVIs were obtained. The timestamps for all SVIs fall within the period from April 2019 to August 2019. To ensure an adequate SVIs for training models, more than 1000 images per species was maintained. The training dataset consisted of 2700 randomly selected images for further analysis. The images were annotated and randomly partitioned into training, validation, and testing sets in a 7:2:1 ratio (Liu et al., 2023). The study focused on the nine predominant local species in Jinan City, while any additional identified species were classified as "other trees." To ensure accurate species identification, two trained research assistants annotated the street trees in the training dataset.

2.2.2. Model

To attain optimal effectiveness and precision in tree identification, we selected YOLO v5 (Redmon and Farhadi, 2017) as our model for species classification. This single-stage object detection model has gained significant popularity because of robust capability to detect objects of varying scales and overlapping objects, both of which are typical features of urban street trees.

More technological details of labeling, training, and evaluating are introduced in Appendix.

2.3. Street tree profiling

Besides tree species, other individual-level tree features including height and crown diameter, were extracted from SVIs based on the detection results of YOLOv5 following the approach of Liu et al. (2023).

Google API provides depth map corresponding to each SVI, which was obtained by LiDAR sensors and can be used as ground truth. We evaluated the performance of our tree profiling approach on 741 Google Street View images and obtained a satisfactory accuracy of 0.783, which is close to, if not exceeds other state-of-the-art models around the world (Liu et al., 2023).

2.4. Indicators for luxury and legacy effects

Since fine-grained household income is hard to obtain, we employed housing price to measure SES of each spatial unit and the luxury effects. Housing price reflects wealth, income, neighborhood quality, investment, educational opportunities, and economic stability which makes it an effective proxy for area-level SES and luxury effect, especially in China (Reardon, 2018).

For legacy effect, we employed the building age to indicate the time the neighborhood developed. To further explore the impact of legacy effect, we divided our study area using the Second Loop Road and Jing 10th Road (Liu et al., 2023). Inside the Second Loop Road is the old town, featuring dense and narrow streets and low-to-medium-rise buildings, while the new development areas in the west and the east are dominated by high-rise buildings. The eastern new district emphasizes high-end services and technological innovation, while the western new district focuses on medical healthcare and ecological livability. Another major boundary in this area is Jing 10th Road. The north side of the road features a densely populated plain, whereas the south side encompasses a mountainous region characterized by high-quality, low-density residences.

The building age and housing price data were obtained from transaction records on the secondary housing market platform Anjuke, one of the largest and most authoritative online real estate agencies in China (https://jinan.anjuke.com/), with all transactions occurring between April 2022 and October 2022. All demographic data were obtained from China's Seventh National Population Census, conducted in December 2020.

We also included demographic variables, including the proportion of older residents (≥65 years old), and the proportion of child residents (≤15 years old) in each unit.

2.5. Tree metrics

The quantity of trees in each spatial unit is measured by the number of detected street trees and the GVI (Table 2). To evaluate the individual-level features of street trees, we focused on their size and diversity. For size assessment, we utilized the average tree height and average crown diameter of all detected street trees within each spatial unit. Diversity was assessed by employing both the number of species and the Shannon index as indicators in each spatial unit. Additionally, we calculated the proportions of nine dominant species, as well as the proportions of evergreen trees, low-pollen trees, trees with spherical crown, and spreading crown. The species of low-pollen refers to the study of Yang et al. (2015).

2.6. Covariate

In addition to tree metrics and main independent variables mentioned above, the regression analysis incorporates a set of control covariates (Table 1) including population density, building floor area, and land use mix (Jiang et al., 2024). Prior research underscores the necessity of accounting for such factors in environmental justice studies (Watkins et al., 2017).

2.7. Statistical analysis

The entire study area was subdivided into a grid system with 1 km × 1 km grids, serving as the spatial units for the calculation of all variables and all subsequent statistical analyses. 1 × 1 km^2 rectangle grid is commonly used as an analysis spatial unit in urban inequality studies (Seburanga et al., 2014; Wang et al., 2022; Zhou et al., 2017).

We performed a Pearson correlation analysis to identify significant correlations between land-related and demographic variables with street tree metrics. To further investigate the luxury and legacy effects, we categorized the study area into four distinct groups with median housing prices and median building ages serving as the thresholds for classification. Then, we conducted descriptive statistics for all tree metrics and demographic variables within each group to compare discrepancies. To illustrate the interactive effect between building age and housing prices, we categorized building age into a tertile: new, medium,

Table 1
Description and descriptive statistics of land-rated variables, demographic variables, and control variables in regression model.

Variable	Description	Mean (SE)
Housing price	The average housing price (RMB per m^2)	16941.60 (7763.45)
Building age	The building age (after construction)	23.76 (13.05)
Old town	Whether the spatial unit is in old town	
West	Whether the spatial unit is in the west of the Second Loop Road	
North	Whether the spatial unit is in the north of Jing 10th Road	
Rate of elderly	The percentage of elderly within the resident population	0.163 (0.055)
Rate of children	The percentage of children within the resident population	0.156 (0.036)
Population density	Number of residents per square kilometer	691.84 (436.73)
Building floor area	Building floor area (m2) per square kilometer	554124.41 (323571.84)
Land use mix	$\sum_i (p_i \ln p_i)/\ln N$ pi represents the proportion of the ith land use, and N denotes the total types of land uses. Five land uses types (residential, business, industrial, open space, and commercial) are considered (N = 5)	0.72 (0.32)

Table 2
The results of the descriptive statistics of tree metrics using 1 km× 1 km grids as the spatial unit.

Tree properties	Description	Mean (SE)
GVI	The average GVI	0.150 (0.063)
Number of trees	The number of street trees detected	286.78 (298.55)
Shannon's index	The Shannon's index of tree species diversity: $-\sum_{i=1}^{s} p_i \ln p_i$ P_i is the proportion of species i	0.960 (0.332)
Number of species	The count of detected tree species	9.193 (2.635)
Height	The average height of street trees	8.621 (1.959)
Crown diameter	The average crown diameter of street trees	7.005 (3.137)
Locust tree (proportion)	The proportion of trees of the specific species among the detected street trees	0.203 (0.190)
Poplar (proportion)		0.094 (0.095)
Plane tree (proportion)		0.240 (0.141)
Privet tree (proportion)		0.008 (0.033)
Boxwood (proportion)		0.264 (0.185)
Wax tree (proportion)		0.011 (0.023)
Willow (proportion)		0.042 (0.095)
Pine tree (proportion)		0.018 (0.035)
Cypress (proportion)		0.047 (0.064)
Evergreen (proportion)	The percentage of evergreen trees	0.065 (0.073)
Low pollen (proportion)	The percentage of low-pollen trees	0.052 (0.101)
Spherical crown (proportion)	The percentage of trees with spherical crown	0.252 (0.138)
Spreading crown (proportion)	The percentage of trees with spreading crown	0.211 (0.196)

and old. We then plotted the linear relationships, using tree features and quantity as the dependent variable (y) and housing price as the independent variable (x) for each age group. We further conducted linear mixed-effects models to explicitly examine the interactive effect of luxury effect and legacy effect on quantity and biodiversity of street trees.

The model formula for the linear mixed-effects models is as following:

$$yij = (\beta0 + u0j) + (\beta1 + u1j)\cdot Ageij + (\beta2 + u2j)\cdot Priceij + \beta3\cdot(Ageij\cdot Priceij) + \mathrm{CijT}\gamma + \epsilon ij$$

Where:

yij is the dependent variables including (Shanno index, number of species, number of trees, average tree height, average crown diameter) for building i in grid j).

Ageij and Priceij are the predictor values.

β0: The overall intercept.

β1: The fixed coefficient for building age.

β2: The fixed coefficient for housing price.

β3: The fixed coefficient for the interaction.

u0j: The random intercept for grid j. It's the deviation of grid j's intercept from the overall intercept β0.

u1j: The random coefficient for building age in grid j. It's the deviation of grid j's slope from the overall slope β1.

u2j: The random coefficient for housing price in grid j. It's the deviation of grid j's slope from the overall slope β2.

The model assumes the random effects (u0j,u1j,u2j) are drawn from a multivariate normal distribution with a mean of zero and a specific variance-covariance matrix.

Cij: This is a vector containing the values of p control variables for a specific observation (building i in grid j).

γ: This is the corresponding vector of p coefficients for each of those control variables.

ϵij is the random error for building i in grid j, representing unexplained variance.

This study involves assessing correlations among multiple tree features, demographic variables, socioeconomic factors, and built environment attributes. These factors are interdependent and exhibit reciprocal causality. Therefore, we also employed Principal Component Analysis (PCA) to reduce dimensionality and elucidate patterns of collective variation for tree metrics, land-related variables, and demographic variables (Wold et al., 1987), which is especially useful for dimension reduction when dealing with many variables.

3. Results

3.1. Pearson correlation analysis

The result shows that housing prices show no significant association with any tree metrics, whereas the age of buildings and the interactive term of building age and housing price exhibit significant and positive correlations with both quantitative and qualitative metrics of street trees (Table 3). The proportions of elderly and children are significantly correlated with tree quantity and diversity indicators but not with tree size indicators. The old town area is positively associated with GVI, species number, and Shannon index, but negatively associated with the number of trees and tree height. The northern part of the city is positively associated with diversity indices and negatively associated with tree quantity. Conversely, the western part of the city is negatively associated with both tree quantity and tree size.

3.2. Interactive effect of building age and housing price

Most grids containing older buildings are situated in or around the old town, as indicated by the pink and orange color (Fig. 2). Grids with higher housing prices are primarily concentrated in the southeast region of the study area, depicted in red and blue. Regions characterized by older and expensive housing exhibit the highest proportion of elderly residents, whereas grids with expensive housing prices and newer buildings have the highest proportion of child residents.

Areas with older and expensive housing have the highest mean value in nearly all tree metrics including GVI, number of trees, number of species, Shannon index, and tree height (Table 4). Among them, its indices of diversity and tree size are obviously higher than those of the other three groups. Areas with affordable housing price and older buildings has the second highest mean value in number of trees, number of species, Shannon index, and tree height while area with higher housing price and newer buildings has the second highest mean value in GVI. Areas with older and expensive housing also have the highest mean value in the proportion of poplar but the lowest mean value in the proportion of evergreen trees, locust trees, plane trees, willow, and cypress. Areas with newer and expensive housing have the highest mean value in the proportion of evergreen trees, boxwoods, pine trees, and cypress.

The linear mixed-effects model examines the relationships between building age, housing prices, and their interaction with street tree quantity and biodiversity metrics. Both tree quantity and average tree height are significantly associated with building age, housing prices, and their interaction (Table 5). The Shannon index is significantly associated with building age and the interaction effect but not with housing prices (Table 5). The number of species is significantly associated only with the interaction effect. GVIs are significantly associated with housing prices and the interaction effect. Average crown diameter is significantly associated solely with the fixed effect of housing prices.

We also visualize the effect of housing price on tree features by grouping spatial units according to building age. For the Shannon index, there is a clear positive interactive effect; in both new and medium groups, the Shannon index shows no correlation with housing price, while in the old group, there is a notable positive relationship between the two variables (Fig. 3). This may indicate that building age positively correlates with species diversity, particularly in affluent neighborhoods, while building age is less important in relatively poor areas. Regarding the number of species and the GVI, the new group shows no significant

Table 3
The outcomes of Pearson correlation analysis.

	Number of trees	GVI	Height	Crown diameter	Number of Species	Shannon index
Housing price	0.043	0.109	0.095	-0.007	0.048	0.065
Building age	0.209**	0.211**	0.181**	0.131**	0.288***	0.288***
Housing price* Building age	0.272***	0.273***	0.155**	0.073	0.286***	0.232**
Rate of elderly	0.318 ***	0.289***	0.110	0.057	0.329***	0.329***
Rate of child	-0.279 ***	-0.209**	-0.108	0.032	-0.311***	-0.341 ***
Old town	-0.130*	0.226**	-0.141*	0.058	0.218**	0.218**
Northern	-0.190**	-0.155**	-0.032	0.030	0.252***	0.252***
Western	-.0188**	-0.195**	-0.493***	-0.144*	0.027	0.027

Note: *p < 0.05, **p < 0.01, ***p < 0.001.

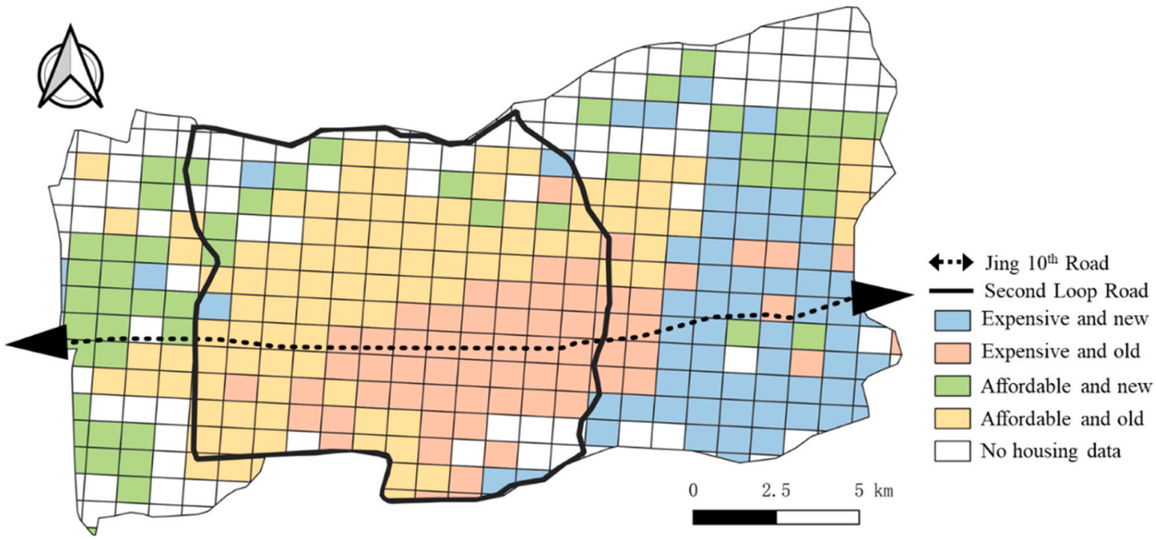

Fig. 2. Classification of study areas into four groups, according to the average housing price per square meter and the average building age in each grid. The old town area is enclosed by the second Loop Road, while Jing 10th Road serves as the dividing line between the southern and northern sections of urban Jinan.

Table 4
Results of the descriptive statistics of four groups of grids.

	new and expensive	New and affordable	Old and expensive	Old and affordable
GVI	0.147 (0.056)	0.132 (0.047)	0.182 (0.063)	0.143 (0.072)
Number of trees	214.46 (199.97)	262.14 (335.84)	456.37 (310.92)	267.60 (309.70)
Number of species	8.529 (2.978)	8.518 (2.629)	10.321 (2.313)	9.588 (2.140)
Shannon index	0.890 (0.396)	0.876 (0.344)	1.098 (0.281)	0.997 (0.249)
Elderly proportion	0.085 (0.013)	0.090 (0.016)	0.151 (0.047)	0.126 (0.029)
Child proportion	0.179 (0.023)	0.141 (0.032)	0.140 (0.012)	0.139 (0.023)
Crown diameter	6.773 (3.223)	6.735 (3.774)	6.686 (1.801)	7.659 (3.313)
Height	8.833 (2.056)	7.558 (2.437)	8.985 (1.057)	8.887 (1.722)
Evergreen (proportion)	0.086 (0.099)	0.068 (0.072)	0.043 (0.028)	0.055 (0.055)
Low pollen (proportion)	0.050 (0.132)	0.077 (0.100)	0.031 (0.050)	0.045 (0.087)
Spherical crown (proportion)	0.231 (0.155)	0.225 (0.160)	0.278 (0.104)	0.274 (0.119)
Spreading crown (proportion)	0.191 (0.200)	0.263 (0.264)	0.179 (0.148)	0.218 (0.162)
Locust tree (proportion)	0.181 (0.195)	0.251 (0.251)	0.171 (0.146)	0.213 (0.160)
Poplar (proportion)	0.062 (0.075)	0.046 (0.064)	0.168 (0.097)	0.110 (0.096)
Plane tree (proportion)	0.218 (0.157)	0.212 (0.160)	0.266 (0.114)	0.266 (0.120)
Privet tree (proportion)	0.009 (0.047)	0.012 (0.034)	0.006 (0.017)	0.006 (0.024)
Boxwood (proportion)	0.311 (0.239)	0.271 (0.194)	0.237 (0.121)	0.230 (0.139)
Wax tree (proportion)	0.013 (0.019)	0.013 (0.026)	0.013 (0.037)	0.008 (0.013)
Willow (proportion)	0.041 (0.121)	0.065 (0.099)	0.025 (0.047)	0.039 (0.008)
Pine tree (proportion)	0.022 (0.055)	0.014 (0.032)	0.019 (0.017)	0.016 (0.021)
Cypress (proportion)	0.063 (0.083)	0.054 (0.063)	0.024 (0.020)	0.040 (0.055)

correlation, but the medium and old groups exhibit a positive correlation (Fig. 3). For the number of trees, housing price has a negative relationship with this dependent variable in the new group, a positive relationship in the medium group, and an even stronger positive relationship in the old group. For average height and crown diameter, the slope of the lines decreases from the new to the medium to the old groups.

3.3. Principal component analysis

The first five principal components (PCs) derived from the Principal Component Analysis (PCA), which collectively account for 56.3 % of the cumulative variance in the data. Additionally, Table A4 (in appendix) outlines the proportion of the total variance attributable to each of these PCs individually. Table A4 details the loadings for all five selected PCs.

Collectively, PC1 and PC2 account for 33.1 % of the variance and are chiefly influenced by building age, old town, and the proportions of elderly and children. Hence, the variability of the studied area is largely derived from construction periods and associated demographic variations. Among them, building age, old town, and the proportion of elderly formed a cluster in the loading plot (Fig. 4), while number of species, number of trees, Shannon index, the proportion of plane trees and trees with spherical crown formed another significant cluster.

4. Discussion

Utilizing SVIs and computer vision methodologies, this research quantifies the citywide spatial distribution of street tree and their individual-level features, including species, tree height, and crown diameter. Previous research identified socioeconomic influences on urban forest quantity and diversity, highlighting the luxury effect as primary drivers (Aznarez et al., 2023). Our findings support that the legacy effect measured by building age, exerts a substantial influence on spatial distribution of street tree biodiversity in Jinan while the luxury effect on street tree diversity is heterogeneous across areas developed in different time. Meanwhile, building age and housing price are both positive associated the quantity metric of street trees such as number of trees, GVI, and average height.

Table 5
Results of linear mixed-effects model on the relationship between building age and housing prices with street tree quantity and biodiversity.

Dependent variable	Independent variable	Estimate	p-value
Shannon index	Building age	0.3232	0.021*
	Housing price	-0.0275	0.494
	Building age* Housing price	0.2741	0.046*
Number of species	Building age	0.2451	0.053
	Housing price	-0.1904	0.184
	Building age* Housing price	0.6693	0.014*
Number of trees	Building age	-113.63	0.013**
	Housing price	-114.25	< 0.000***
	Building age* Housing price	222.83	< 0.000***
Green View Index	Building age	0.0005	0.387
	Housing price	0.0018	0.021*
	Building age* Housing price	0.0012	0.038*
Average tree height	Building age	1.0768	< 0.001***
	Housing price	0.7536	< 0.001***
	Building age* Housing price	-0.8717	0.011**
Average crown diameter	Building age	1.0539	0.032 *
	Housing price	0.5071	0.193
	Building age* Housing price	-0.8006	0.159

Note: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

In detail, our analysis revealed a significant positive correlation between building age and various tree metrics, including the number of tree species, the Shannon index, average tree height, and crown diameter. However, building age is negatively related to the proportion of evergreen trees and low-pollen trees. Like other Chinese cities, Jinan has experienced rapid development and urbanization. Large residential areas have been swiftly constructed to accommodate the accelerating pace of urban growth. This rapid development has led to several challenges in new districts, such as a lack of tree species diversity. Similarly, compared to the old town, the street trees in newer areas exhibit smaller crown diameters and heights, potentially offering insufficient shade and other tree-related benefits to residents. Besides, the rapid urbanization over the past two decades has led to an increase in road networks in newly developed areas (Ren et al., 2018). According to the Chinese urban road development standards, roadside tree planting is mandated (Standard for Urban Comprehensive Transportation System Planning, GB/T51328–2018). Hence, smaller-sized roadside trees are more common in newly developed areas.

The inverse correlation between the proportion of evergreen and low-pollen street trees and building age indicates that the government's preference for planting these types of trees in newly developed areas indicates an increasing emphasis on 'healthy cities' (Cariñanos et al., 2019). Low-pollen trees are advantageous as street trees over other types of trees primarily due to their potential to reduce allergenic pollen exposure in urban environments. This reduction in airborne pollen can significantly decrease allergy symptoms among city residents, enhancing public health and comfort. Evergreen trees, as street trees, offer year-round benefits including continuous shade, privacy, and aesthetic appeal due to their non-deciduous nature, reducing maintenance needs linked to leaf disposal. They provide year-round ecological services such as air quality improvement and noise reduction, making them highly suitable for urban settings.

We further found that areas characterized by old and expensive housing display the greatest tree species richness and diversity, and tallest trees among all groups. This is followed by the areas with old and affordable housing, then by the areas with new and expensive housing, and lastly, the areas with new and affordable housing. Although the housing price itself is not directly correlated with species diversity indices, this combining effect indicated that the luxury effect on street tree diversity is heterogeneous across areas developed in different time, a pattern consistent with the findings of Chu et al. (2023). For example. older and wealthier neighborhoods may benefit from synergistic effect of historical landscaping, sustained financial and community support for urban forestry, and long-term natural processes, which together lead to higher tree diversity (Aznarez et al., 2023).

The individual-level features and diversity of street trees exhibit a strong spatial heterogeneity across areas with different building ages. Furthermore, they also vary for different demographic populations. The proportion of elderly is positively correlated with both quantity and diversity of street trees while the proportion of child has an inverse relationship. Such findings can inform tailored tree managing and planting strategies. The newly developed areas tend to have a higher population of children and a lower proportion of elderly residents compared to the citywide demographics. However, the tree diversity is low in these areas. The diversity of street tree species is critical for children's development, offering a myriad of benefits that span from enhanced cognitive development and physical health to psychological well-being. Varied tree species promotes stress reduction, mood enhancement, and supports educational opportunities through direct interaction with nature (Tzoulas et al., 2007). Furthermore, a rich urban canopy encourages outdoor play which is vital for both physical and social development, fostering community connections and environmental stewardship from a young age (Tzoulas et al., 2007). Therefore, it is necessary to increase tree diversity in these areas. Secondly, the old town with higher populations of elderly residents have a greater proportion of high-pollen street trees. These trees can significantly impact the health of the elderly due to their high pollen production and associated allergenicity (Katz et al., 2024). Studies has highlighted that street trees can significantly influence localized environmental health, particularly concerning pollen exposure for vulnerable groups including the elderly (Lai & Kontokosta, 2019). Hence, it is reasonable to reduce high-pollen street trees in the old town.

4.1. Planning and policy implication

By recognizing the legacy effect and its benefits, local government should finetune policies and management related to street trees for different areas to enhance the urban living quality across demographically diverse populations in Jinan. On the one hand, it is critical to foster tree diversity and quantity in newly developed areas, and to replace high-pollen tree species in the old neighborhoods. Planting diverse tree species in newly developed areas, featuring a high proportion of children, can enhance cognitive development, physical health, and psychological well-being in children, fostering a connection with nature from an early age. Concurrently, replacing high-pollen trees with low-pollen and evergreen varieties in old neighborhoods where elderly populations are more concentrated can mitigate health risks associated with allergies and improve overall comfort and air quality. On the other hand, the legacy effect suggests that higher coverage and diversity of street trees may emerge as a consequence of the natural evolution of the street landscape system. Consequently, preserving existing landscapes is essential, particularly in the context of new infrastructure development and urban regeneration. Additionally, public afforestation initiatives should adhere to a balanced approach, fostering year-round benefits through evergreen trees while increasing tree diversity to enhance urban canopy efficacy and shade provision. This balanced approach addresses immediate urban needs for environmental health improvements while supporting long-term urban forest sustainability.

To cope with the dual influences of legacy and luxury effects on street tree biodiversity, policymakers should adopt a stratified approach that aligns interventions with neighborhood age and socioeconomic context. In older neighborhoods, where the luxury effect is more evident, targeted socioeconomic incentives, such as tax rebates for tree planting, subsidized maintenance programs, or community-led greening grants, can empower residents to enhance biodiversity while addressing

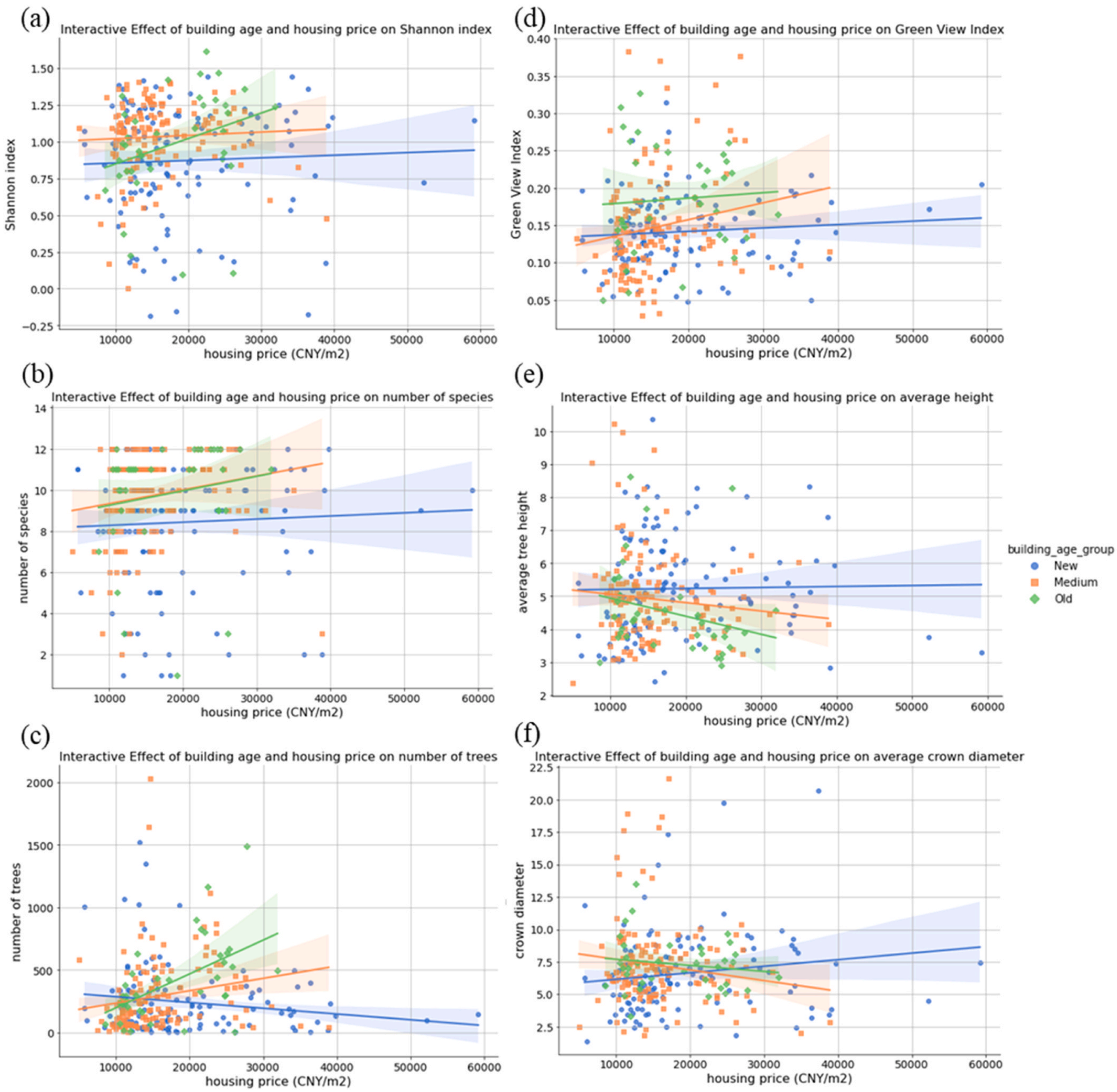

Fig. 3. Plots of interactive effect of building age and housing price on (a) Shannon index, (b) number of species, (c) number of trees, (d) GVI, (e) average tree height, and (f) average crown diameter. The shaded area encompassing each line represents the 95 % confidence interval.

historical inequities. Simultaneously, for newer developments, adaptive management frameworks should mandate biodiversity-sensitive design standards, requiring developers to integrate diverse native tree species into street layouts and enforce minimum canopy coverage thresholds during project approval. To ensure long-term efficacy, these measures must be paired with robust longitudinal monitoring systems that track tree diversity trends alongside demographic shifts and building age dynamics. This data-driven approach should be complemented by participatory governance models, such as neighborhood green committees or citizen science platforms, to engage residents in co-designing and stewarding green spaces.

Although Jinan is a city with unique socio-political and historical factors, the results of our studies can also benefit other cities globally. First, our study provides a framework by using SVIs and computer vision technology to automatically assess street trees and the environmental justice of street tree provision. Second, our findings underscore the importance of conserving existing landscapes and integrating historical legacies into urban planning which is globally applicable. We advocate for policies that prioritize the protection of mature trees and natural landscapes, which are often more biodiverse and ecologically valuable than newly planted ones. Third, we highlight the importance of long-term planning, the role of historical land-use patterns, and the need to integrate ecological considerations into urban development are lessons that can inform urban planning practices worldwide.

5. Conclusion

This study applied a computer vision-based approach using SVIs to quantify the spatial inequality of street trees in Jinan, China. The analysis revealed that the legacy effect, rather than the luxury effect,

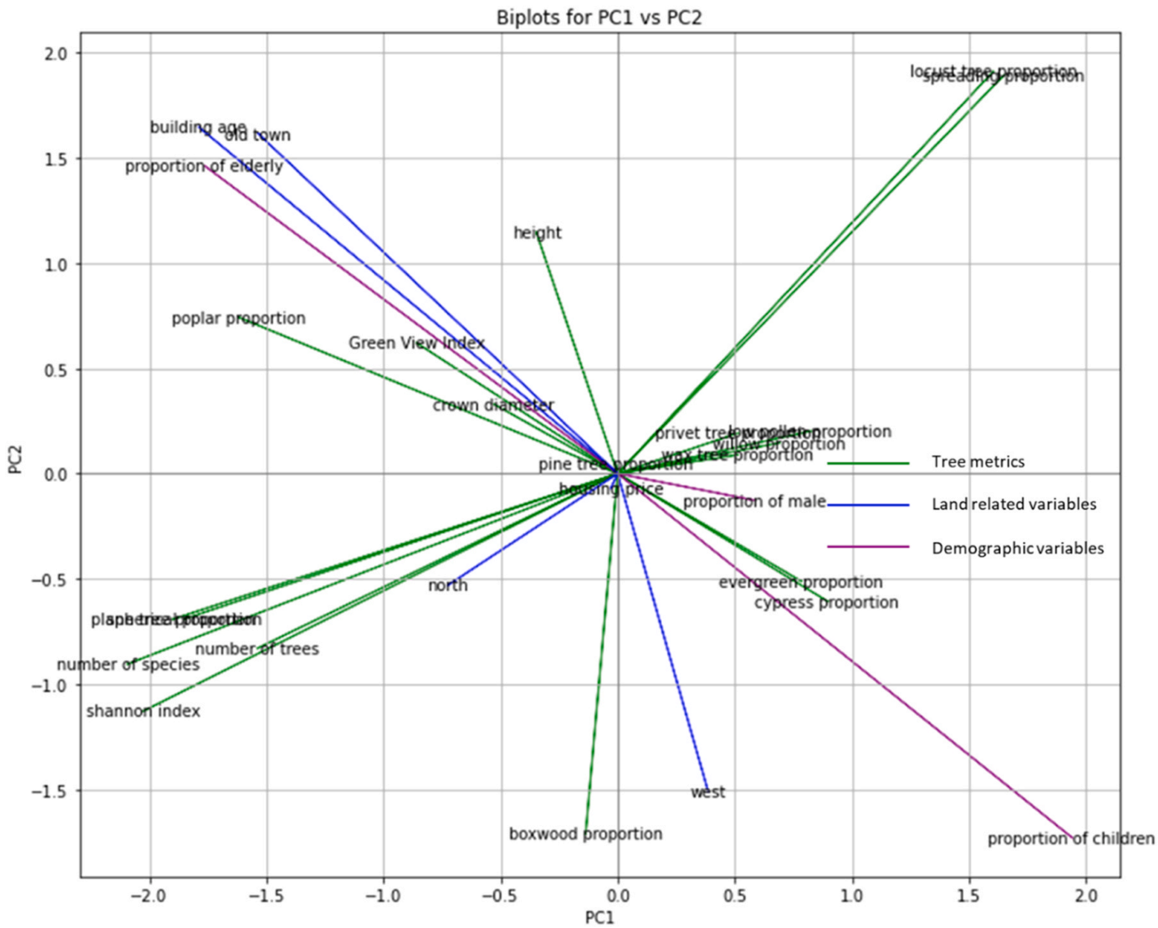

Fig. 4. Biplot of PC1 and PC2. Green lines represent tree metrics while blue and purple lines represent land related variables and demographic variables respectively.

plays a dominant role in shaping patterns of tree diversity and structure, with newly developed districts exhibiting lower species diversity compared to the older town. These findings highlight that historical urban development and top-down planning practice continue to shape present-day environmental inequalities.

Several limitations should be acknowledged. The reliance on SVIs restricts observation to street-facing trees, excluding vegetation in parks and private areas, while the model's taxonomic coverage is limited to nine common indigenous tree species. Furthermore, qualitative attributes such as tree health and maintenance were not assessed. Future research could integrate additional data sources, such as aerial imagery, park inventories, and field-based assessments, to provide a more holistic understanding of urban tree inequality.

Overall, this study underscores the need for comprehensive and equitable urban forestry policies that simultaneously enhance species diversity in new developments and increase low-pollen and evergreen trees in older neighborhoods. Such measures are essential for advancing environmental justice and ensuring that the ecological and social benefits of urban greenery are fairly distributed across all communities.

CRediT authorship contribution statement

Yuxiao Jiang: Investigation, Data curation. **LU Yi:** Writing – review & editing, Supervision, Project administration. **Dongwei Liu:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2025.129184.

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