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Urbanization and greenspace effect on plant biodiversity variations in Beijing, China

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ABSTRACT

It is of great significance to understand how urbanization and greenspace areas gradient affect urban plant biodiversity for urban renewal and planning toward urban biodiversity conservation. However, the factors affecting plant diversity under rapid urbanization remain unknown in many cities. To this end,702 vegetation sampling plots from 219 2 km × 2 km grids were selected to explore the urban plant biodiversity variation within two perpendicular 10 km width transects running across the urban center in north-south and east-west directions within the 6th ring road in Beijing, China. Impervious surface area (ISA) and Greenspace area (GSA) of each grid were interpreted from high resolution remote sensing images. ISA mainly includes road surface, asphalt, and buildings, and GSA includes tree, shrub and herb canopy. A total of 396 plant species were recorded, including 95 tree species, 87 shrub species, and 214 herb species. The 396 species belonged to 298 genus and 93 families. We found that woody plant diversity, tree size attributes (DBH, height, canopy breadth), and total plant taxa increased significantly with increased urbanization while herb plant diversity decreased significantly. However, the GSA has no significant impact on plant diversity and taxa. We further found the higher woody plant diversity and lower herb plant diversity in ISA's with a percentage > 50%, and in the ISA percentage < 50% with larger ISA and GSA area (ISA+GSA percentages (i.e., >80%). ISA and GSA can thus be predictive factors for estimating urban plant diversity, which was related to urban planning and different greening decision-makers. The results of this study have important implications for further understanding how current urbanization factors affect plant diversity, which could implement better scientific urban planning to conserve and restore urban biodiversity in many cities around the world.

1. Introduction

Conserving and restoring urban biodiversity plays a key role not only in urban planning and greenspaces management to achieve the sustainable goals of greener, healthier, and more resilient cities, but also in global actions to achieve the biodiversity conservation goal on a large scale urbanized landscapes (Shwartz et al., 2014). Urban greenspaces with a high tree, shrub, and herb species diversity can provide multiple ecosystem services sustainably (Escobedo et al., 2015). Such services include urban heat island mitigation (Wang et al., 2021), airborne pathogens reduction and pollutants removal (Bonilla-Bedoya et al., 2021; Li et al., 2021; Zhang et al., 2019), carbon sequestration (Jo and McPherson, 1995; Nowak and Crane, 2002), urban stormwater regulation (Nagase and Dunnett, 2012). A 'common sense' guideline of no more than 10% of any particular species, 20% of any genus, and 30% of any family is proposed and applied in urban forest planning and management (Kendal et al., 2014). In addition, higher plant biodiversity, in the form of both species diversity and genetic diversity within a species, in urban forests can more effectively prevent catastrophic losses caused by pests and diseases, such as Eucalyptus and elm disease in the Netherlands, chestnut disease in America (Laćan and McBride, 2008; Raupp et al., 2006; Sanders, 1984). Plant family and genus measure the diversity of evolutionary relationships between species, reveal plant kinship, and provide valuable information for species conservation and

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mechanisms of species assembly (Knapp et al., 2008; Vane-Wright et al., 1991).

However, a big challenge in biological conservation is understanding how urbanization-related factors affect biodiversity, including plant species' compositions and their associations (Alvey, 2006; Faeth et al., 2011; Primack et al., 2009). Numerous studies indicated that some factors in the process of urbanization increased plant diversity (Jha et al., 2019; Schmidt et al., 2014; Xiao et al., 2016; Ye et al., 2012), such as the multiple suitable natural factors (e.g., soil, climate, vegetation, landform) and socio-economic factors (Kim and Zhou, 2012). To be specific, the plant luxury effect, where wealthier residents have greater access to high urban biodiversity than poorer residents as high-price housing attract buyers or renters by optimizing the residential environment (Iverson and Cook, 2000; Jiao et al., 2021; Martin et al., 2004; Zhu et al., 2021), and human preferences for different plant species also contributed to plant diversity (Szantoi et al., 2012; Troy et al., 2007). In addition, some legacy plant species related to urban history and cultural traditions were conserved in urban areas to increase the plant diversity (Jha et al., 2019). However, some studies found that urban industry and policy or governance-related factors in the process of urbanization could decrease plant diversity (DeCandido, 2004; Vakhlamova et al., 2014). For example, urban industrial structure impacts the environment and compressed urban greenspaces area, which has negative correlation with plant diversity (Vakhlamova et al., 2014). Policy or governance-related factors also exert dramatic impacts on the plant diversity in urban settings (Pregitzer et al., 2019). For example, the anthropogenic processes, such as exotic plant species introduction, may create new niche opportunities and generate environmental heterogeneity, allowing resource partitioning and increasing the extinction risk of native species (Banerjee and Dewanji, 2017; Lehan et al., 2013). Therefore, a separate analysis of the native and exotic plants may provide a more mechanistic understanding of urban plant diversity (Bernard-Verdier and Hulme, 2015), and urban-specific studies in varying cultural, political, and geographic contexts are required to improve our understanding of how urbanization may drive patterns of urban plant diversity and provide realistic planning of sustainable urban greenspaces (Aronson et al., 2014; Hope et al., 2003).

There are considerable opportunities for urban biodiversity conservation, such as reconciling urban greenspaces and biodiversity conservation (Aronson et al., 2014; Cilliers et al., 2013). Given the various ecosystem services that plant diversity provides (Aronson et al., 2017), greenspace area (GSA) have been integrated into urban planning and design (Millard, 2008). Studies have shown that GSA has an overall positive effect on urban plant diversity due to higher biodiversity carrying capacity (Hansen et al., 2015; Ishii et al., 2010; Zipperer, 2002). However, some studies suggested that increased GSA does not improve urban plant diversity as biodiversity can increase with high heterogeneity due to increases niche dimensionality, which lead to suitable area available for individual species decreased per area unit (Boecklen, 1986; Heidrich et al., 2020; Wang et al., 2014). Such different conclusion is usually associated with different artificial GSA greening management (Wang et al., 2014). Management of GSA for plant diversity faces a series of challenges in different countries, including the involvement of multiple stakeholders (at the city scale) and the difficulties in understanding how socio-economic and cultural factors influence landowner goals, values, and decision making (at the neighborhood and individual parcel scales) (Aronson et al., 2017). In China, since the Ministry of Housing and Urban-Rural Development proposed the construction of the National Garden city and National Ecological Garden City (MHUDC 2002a, b), many cities in China have increased their GSA (Zhao et al., 2013). However, the roles of GSA in supporting biodiversity and the linkages between biodiversity and ecosystem function have so far received insufficient attention in China (Ziter, 2016).

Urban-rural gradient analysis is a typical method for urbanization studies. Urban ring road related gradients (Chen et al., 2014; Zhang et al., 2016), percentage of ISA (road surface, asphalt, buildings) (Jha et al., 2019; Yan et al., 2019), and distance from the city center (Fang et al., 2011) have been used in defining urbanization gradient. An analysis of multiple-scale urbanization gradients could provide insight into the impact of urbanization on plant diversity (Chen et al., 2014). In addition, urban forest structure could reflect the layout of urban tree planning and help project how they will change in the future, such as recent tree planting and removal activities in urban greenspaces (Cheng et al., 2021). Diameter at breast height (DBH), height, and canopy breadth of urban trees are the most basic measurements of stand structure for a forest community by reflecting the age structure of the urban forest and the dynamic process of urban vegetation turnover (Cheng et al., 2021).

The plain area in Beijing is the central city function-core area. The typical concentric expansion represents Beijing's historic development pattern, forming a ring-shaped expansion pattern from the inner center to the outskirts. The 2nd, 3rd, 4th, 5th, and 6th rings were completed and opened to traffic was 1991, 1999, 2001, 2003, and 2009 respectively. The ring roads in Beijing as a reference for distance to the city center, representing the level of urbanization and development in time. Rapidly urban sprawl also made impervious surface area increased significantly, and the Beijing government has implemented many afforestation projects to build a world-class harmonious and livable capital (Li et al., 2023, 2020). Consequently, in recent years, most of the new patches of greenspaces regenerated from lands previously covered by impervious surfaces in Beijing (Qian et al., 2015). Therefore, the goals of this paper include the following: (a) How does the urbanization and greenspace area affect the plant diversity in Beijing, China? (b) explore the relation between ISA, GSA, and plant diversity in Beijing, China. The results of this study will benefit the conservation of plant diversity and urban planning in many cities around the world.

2. Materials and methods

2.1. Study area

Our study was conducted in metropolis Beijing (115.7°–117.4°E, 39.4°–41.6°N), the capital city of China for 800 years, located in the north of the North China Plain. The climate is temperate humid continental monsoon, and the zonal vegetation type is primarily a warm temperate deciduous broad-leaved forest. The annual average temperature and precipitation are 12.3 ℃ and 572 mm, respectively. The geophysical conditions within the built-up areas are relatively similar and thus should not result in differences in the plant species assemblage (Li et al., 2020). Metropolitan Beijing has a built-up area of 1458 km^2 and a population of 22 million in 2019. The total population increased by 137%, from 8.7 million in 1978–20.7 million in 2012. In addition, the increase in developed land totaled 850 km^2 from 2000 to 2010 (Beijing Municipal Statistical Bureau, 2013). Our study area is primarily located within the 6th ring road of Beijing with an area of 916 km^2 and across the city center (39°54'20"N, 116°25'29"E) (Fig. 1).

2.2. Sampling design and field data collection

Two perpendicular 10 km width transects running across the urban center in north-south and east-west directions were selected to represent the development history, urbanization degree, population, and function zone within the 6th ring road (Fig. 1b). First, we obtained Beijing No. 2 Satellite images with a spatial resolution of 0.8 m from August to September 2019 with six land cover classes: 1) urban tree canopy, including urban trees and shrubs, 2) grassland, 3) bare land, 4) impervious surfaces (road surface, asphalt, buildings), 5) water body, and 6) farmland. (Fig. 1c). The accuracy of the classification results was assessed using reference data generated by visual interpretation. Stratified random sampling was first used to generate random points in Arcgis 10.8, with 5% selected for each category (Li et al., 2023). The total number of random points sampled in 2019 were 36,250 (Li et al.,

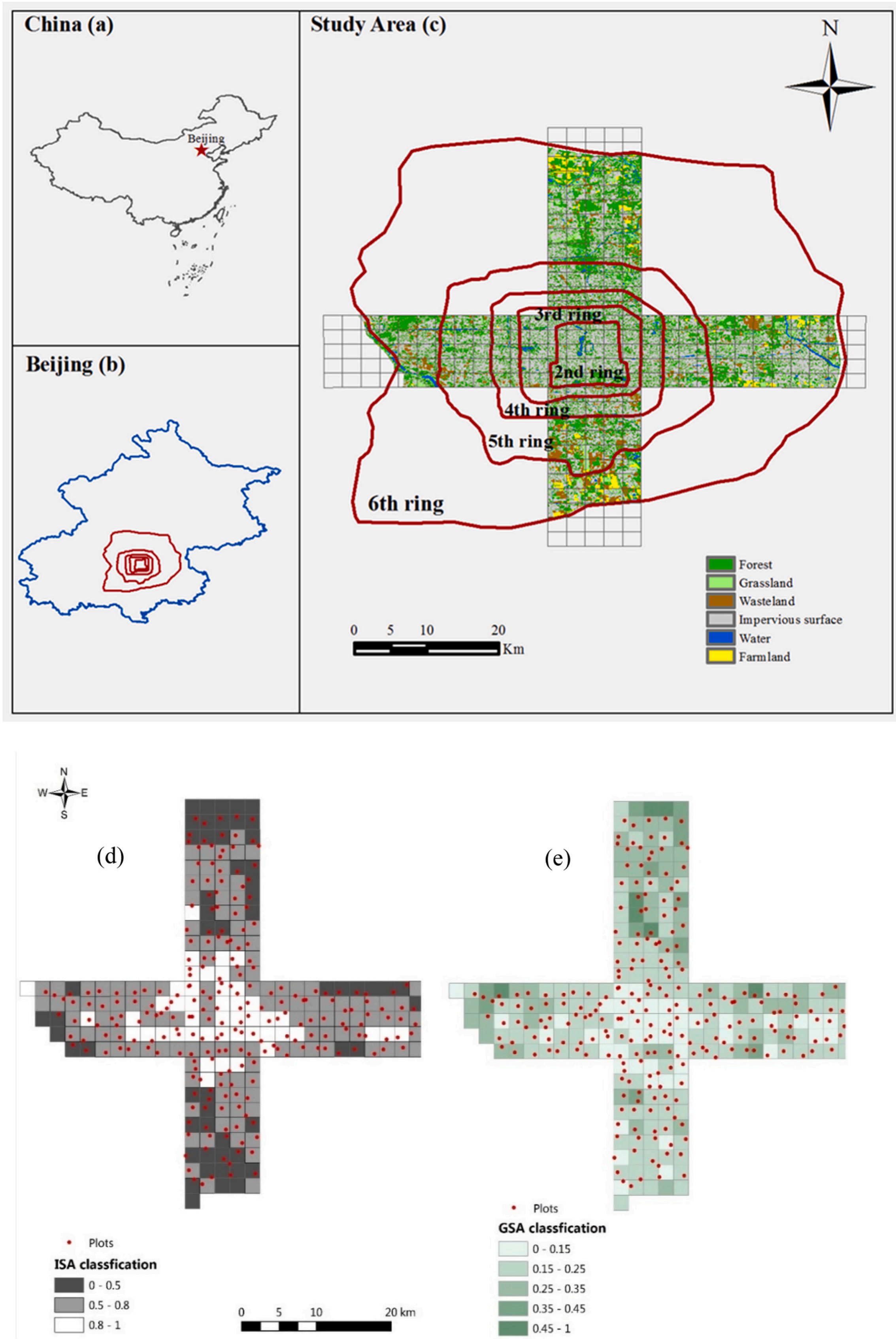

Fig. 1. Beijing, the capital city of China (a), Ring Road in Beijing (b), 2 km × 2 km grids of two perpendicular 10 km wide transects and the study area of Beijing shown by six land-cover categories inside the 6th Ring Road (c), the center of the three vegetation field survey plots (red dots) within each grid shown on top of Impervious surface area (ISA) fraction map (d), and the same vegetation field survey plots overlayed on the Greenspace Area (GSA) fraction map within the 6th Ring Road of Beijing (e).

2023). We then use visual inspection to determine the accuracy of the patch classification to which the point corresponds. The overall accuracy were 94.01%, and the Kappa statistics equaled 0.9013 (Li et al., 2023). Then we divided transects into 2 km × 2 km grids. Each grid's impervious surface area (ISA) and green space area (tree, shrub, grassland) was interpreted using ArcGIS based on Beijing No. 2 Satellite images. eCongnition Developer 9.0 (Definiens Imaging corporate, Germany) software was employed as the interpretation platform. The area of ISA and GSA accounts for 86.0% of the total study area. The ISA is 588 $km^{2,}$ covering 64.2%, and the GSA is 200 km^2 covering 21.8% of the total study area.

A stratified random sampling scheme was used to determine 3–5 plots for plant survey within each grid. We did not adopt a completely random sampling approach mainly because some plots could not be accessed if they fell on water-covered areas (e.g., Lake of the Yuyuantan park) or impervious surfaces (such as Tian'anmen Square). Therefore, we increased the number of plots within each grid to minimize the bias as much as possible. The plot area was 400 $m^{2,}$ preferably set to 20 × 20 m^2 square-shaped when applicable. As a result, 702 plots within 219 grids were selected and measured from May to August 2021. Each grid selected one representative plot (the most number of total plant species) as a red dot in the figure (Fig. 1d, e). A portable GPS (4 G LTE Real-Time Portable GPS Tracker) unit was used to locate the center point of the plot. All trees with a DBH greater than 3 cm were recorded and measured following the standard forest inventory protocol including species, DBH, height, and canopy breadth. Five 5 × 5 m^2 subplots and five 1 × 1 m^2 quadrats were selected randomly within each plot for shrub species and herb species survey, respectively.

All plants were recorded and identified, including family, genus, and species, as well as their origin (e.g., native and exotic) according to the vegetation classification system of China, which is used in the *Flora of China* (Compilation Committee of the Flora of China1959–2004; http://flora.huh.harvard.edu/china/), *Flora of Beijing* (He, 1992). In addition, other reliable sources from formerly published papers describing Beijing plants also identified our recorded plant species (Meng et al., 2004; Wang et al., 2012; Zhao et al., 2010). Appendix Table S1 gives a complete list of all plant species encountered in this study with their characteristics.

2.3. Determining the urbanization intensities and green space area intensities

We used two methods to determine the urbanization intensity. First, we used the ring road and distance from the city center to represent the urbanization process and urban development. Second, we used the percentage of ISA representing the current status of the urbanized landscape. The closer the ring number is to the city center, the greater the intensity of urbanization. The study area then was divided into the 2nd ring-road zone (the area within the 2nd ring road) (16 grids); 3rd ring-road zone (the area between the 2nd and the 3rd ring road) (21 grids); 4th ring-road zone (the area between the 3rd and the 4th ring road) (28 grids), 5th ring-road zone (the area between the 4th and the 5th ring road) (51 grids), and 6th ring-road zone (the area between the 5th and the 6th ring road) (103 grids) (Fig. 1).

We defined the ISA percentage as the metric for urbanization intensity within each grid: low urbanization (ISA percentage <50%), medium urbanization (50%≤ISA percentage≤80%), and heavy urbanization (ISA percentage>80%) (Hutyra et al., 2011). As a result, we obtained 45 low, 127 medium, and 47 heavy urbanization grids, respectively (Fig. 1d). According to the actual situation of urban green space construction in China and the practicality of future urban green space planning, the GSA percentage of each grid was divided into five groups: < 15% (47 grids), 15%– 25% (111 grids), 25%– 35% (46 grids), 35%– 45% (10 grids), ≥ 45% (5 grids) (Fig. 1e) according to the *Evaluation standard for urban landscaping and greening (GB/T 50563–2010)*.

2.4. Plant diversity indices and tree size attributes

We used the number of plant families, genus, and species from the field inventory to measure plant diversity. In addition, the Shannon-Wiener Index, incorporating species abundance, richness, and rarity, was used to quantify the plant diversity for different live forms (Shannon et al., 1950).

Consequently, tree, shrub, and herb diversity were calculated for each grid plant diversity is calculated as follows: 1) Tree diversity: the mean value of tree Shannon-Wiener Index in all 20 m × 20 m plots for each grid; 2) shrub diversity: the mean value of shrub Shannon-Wiener Index in all 5 m × 5 m subplots for each grid; 3) herb diversity: the mean value of shrub Shannon-Wiener Index in all 1 m × 1 m quadrats for each grid; 4) total native and exotic species: the native and exotic plant species mean value of all plots, subplots, and quadrats for each grid.

Plant taxa (families, genus, and species) is the total number of trees, shrubs, and herbs. 1) Tree taxon: the mean value of tree families, genus, and species in all 20 m × 20 m plots for each grid; 2) shrub taxon: the mean value of shrub families, genus, and species in all 5 m × 5 m subplots for each grid; 2) herb taxon: the mean value of herb families, genus and species in all 1 m × 1 m quadrats for each grid.

We used the relative abundance as the measurement of the most common family, genus, and species of trees: Y= (Ni/N) × 100%.

Ni/N is the number of plants for species i/total number of plants in each plot.

We measured three tree size attributes, including diameter at breast height (DBH, cm), tree height (m), and canopy breadth (m). The DBH was measured at 1.3 m above ground level and recorded only when over 3 cm. Canopy breadth value was measured as the mean of projection size in north-south and east-west directions.

2.5. Data analysis

General linear model was constructed to explore the effect of distance from city center, continuous ISA percentage, and GSA percentage on palnt Shannon-Wiener index, taxa (families, genus, and species), and origin (i.e., exotic and native). ANOVA was used to test the differences of plant biodiversity in terms of the plant taxa (families, genus, and species), Shannon-Wiener index, and plant species origin (exotic and native) between ring road zones, classified ISA percentage, and classified GSA percentage. Differences of urban tree size attributes of DBH, height, and canopy breadth between ring road zones, classified ISA percentage, and classified GSA percentage were also analyzed by ANOVA. Data were tested for normality and log transformed to meet general linear model and ANOVA assumptions (Chi et al., 2016; Yan et al., 2019; Yu et al., 2015). The analysis was performed using SPSS Statistics software (ver. 26.0, IBM Corporation, New York, USA).

3. Results

3.1. Flora composition

In 702 sampling plots, 396 species were recorded, among which 219 were native species and 177 exotic ones (Table 1). The total number of 12,589 trees, 11,123 shrubs, and 109,012 herbs belonging to the registered 95, 87 and 214 species were measured. A total of 396 species of vascular plants, belonging to 93 families and 298 genera was recorded. The number of exotic shrub species were higher than their native counterparts, while the number of native species trees and herbs were higher than their exotic counterparts.

3.2. Plant diversity/taxa versus urbanization intensity

3.2.1. Plant diversity along the distance to city center and rings

Although the Shannon-Wiener of tree species decreased from 1.46 ± 0.14 (*SE*) within the 2nd ring road to 1.36 ± 0.05 within the 6th ring

Table 1
Plant flora and lifeform composition from this survey in the Beijing, China.

Plant flora and lifeform	Number	Percentage
Family	93	100%
Genus	298	100%
Species(native)	219	55.30%
Species(exotic)	177	44.70%
Tree species	95	23.99%
Tree(native)	52	13.13%
Tree(exotic)	43	10.86%
Shrub species	87	21.97%
Shrub(native)	31	7.83%
Shrub(exotic)	56	14.14%
Herb species	214	54.04%
Herb(native)	136	34.34%
Herb(exotic)	78	19.70%

road, there was no significant difference along the ring road gradient (Fig. 2A). The Shannon-Wiener of shrub species decreased, and the difference was significant among the 2nd ring road (0.44 ± 0.06), the 4th ring road (0.29 ± 0.05), the 5th ring road (0.21 ± 0.03), and the 6th ring road (0.25 ± 0.03) (Fig. 2B). The Shannon-Wiener of tree (R^2 =0.24, $p = 0.04$) and shrub species (R^2 =0.64, $p < 0.001$) decreased significantly with distance from the city center (Fig. 2(a), (b)). The Shannon-Wiener of herb species increased significantly and reached the peak (1.15 ± 0.03) in the 6th ring road (Fig. 2C). The Shannon-Wiener of herb species (R^2 =0.6, $p = 0.001$) increased significantly with distance from the city center (Fig. 2(c)).

The total number of plant taxa (families, genus, and species) decrease significantly as the ring roads go further away from the urban center (Fig. 2D, E, F). The number of families (R^2 =0.41, $p = 0.01$) decreased significantly with distance from the city center (Fig. 2(d)). However, the number of genera (R^2 =0.21, $p = 0.09$) and species (R^2 =0.24, $p = 0.07$) showed no significant relationship with distance from the city center (Fig. 2(e), (f)).

3.2.2. Plant diversity against ISA gradients

The Shannon-Wiener of tree species increased significantly by 42.7%, 43.0% from low to medium and heavy urbanization intensity, respectively, while the Shannon-Wiener of tree species was no significant difference between medium and heavy urbanization intensity (Fig. 3A). The Shannon-Wiener of shrub species increased significantly by 135.0% and 271.8% from low to medium and heavy urbanization intensity, respectively (Fig. 3B). However, The Shannon-Wiener of herb species decreased significantly by 11.43% and 27.62% from low to medium and heavy urbanization intensity, respectively (Fig. 3C). As the ISA percentage increases, Shannon-Wiener of tree (R^2 =0.22, $p < 0.001$) and shrub species ($R^2 = 0.16$, $p = 0.007$) increased statistically significantly (Fig. 3(a),(b)), while Shannon-Wiener of herb species (R^2 =0.18, $p < 0.001$) was decreased significantly(Fig. 3(c)).

Significant differences existed in the number of plant families, genus, and species between low and medium or heavy urbanization intensity. At the same time, there is no significant difference between medium and heavy urbanization intensity. Similarly, As the ISA percentage increases, the number of plant families (R^2 =0.21, $p < 0.001$), genus (R^2 =0.17, $p < 0.001$), species (R^2 =0.17, $p < 0.001$) increased statistically significantly (Fig. 3(d), (e), (f)).

3.3. Plant diversity and GSA gradients

There was a sudden jump in Shannon-Wiener of shrub species when GSA percentage exceeded 45% (Fig. 4B). The Shannon-Wiener of tree species (R^2 =0.13, $p = 0.008$) and the number of families (R^2 =0.15, $p = 0.02$) significantly decreased with increasing GSA percentage. There was no significant trend in Shannon-Wiener of herb species and the number of genus and species with increasing GSA percentage (Fig. 4C, E, F, (c), (e), & (f)). Because the data in GSA percentage was larger and more dispersed, the R^2-value in GSA percentage was lower than the distance from city center gradient (Fig. 2 & 4).

The analysis of Fig. 5 is all in a 0–50% ISA percentage grid (Fig. 1d). The Shannon-Wiener of trees, shrubs, families, and species increased, and herbs decreased significantly from 0% to 50%, 50–80% to 80–100% of ISA and GSA (Fig. 5A, B, C, D, F). The Shannon-Wiener of trees, shrubs, families, genus, and species increased significantly with increasing ISA and GSA percentage while the Shannon-Wiener of herbs decreased significantly (Fig. 5(a), (b), (c), (d), (e), & (f)).

3.4. Urban tree size attributes and plant relative abundance variations

The mean DBH, height, and canopy breadth of trees increased significantly from low and medium to heavy urbanization intensity, respectively. However, there are no statistically significant differences between low and medium urbanization intensity in the DBH, height and canopy breadth of trees. The mean DBH and canopy breadth decreased significantly from 0% to 15% to > 45% GSA. There has no statistically significant difference in different GSA intensities (Table 2).

The relative abundance of plant families and genus was less than 30% and 20% in Beijing, respectively. The number of plant species exceeded the 10% in low and medium urbanization intensity, and in 0–15%, 25–35%, 35–45% and > 45% GSA (Fig. 6A). In addition, the relative abundance increased with increasing GSA percentage (Fig. 6B).

3.5. Native and exotic species along the urbanization and GSA gradients

The number of native species (R^2 =0.14, $p = 0.18$) and exotic species (R^2 =0.56, $p = 0.002$) decreased with distance from the city center, and native species decreased statistically significantly (Fig. 7).

The number of native trees, shrubs and herbs species, exotic trees, and shrub species increased with increasing ISA percentage, and consistent with the changing of total plant species (Table 3). The mean number of total, exotic and native species increased significantly by 25.38%, 67.85%, and 14.21% from low to heavy urbanization intensity, respectively. The ratio of exotic/native also increased with increasing ISA percentage, while the number of native herb species decreased. On the contrary, the total number of exotic and native species decreases with increasing GSA percentage, while the results were statistically insignificant (Table 3).

4. Discussion

4.1. Effect of urbanization gradient on plant diversity

The woody plant diversity and taxa increasesd with increasing ISA percentage and decreasing ring road zones. On the contrary, the herb plant diversity decreased with increasing ISA percentage and decreasing ring road zones (Figs. 2,3). The plant species of greenspaces within the 6th ring road of the city were almost cultivated species since intact natural areas are converted to impervious surfaces during rapid urbanization (Luck and Wu, 2002). The plant species and diversity, therefore, could be affected by urban planning and greening management, such as human preference (Jha et al., 2019; Li et al., 2020). Higher population density in the area with higher ISA percentage, city center and lower ring road zones bring more attention from greening decision-makers to construct urban forests and manage plant communities to increase the species diversity considerably (Hope et al., 2003; Morgenroth et al., 2016; Ye et al., 2012). In Beijing, greening decision-makers mainly included the following aspects: 1) Municipal Administration of Landscape and Greening is responsible for managing the urban forests in public areas, such as roadsides and parks, as well as the afforestation projects (Jim and Liu, 2001). The history of municipal planning has improved urban plant diversity. More heritage conservation parks, historical gardens, and modern urban parks is located in the area with higher ISA percentage and closer to the city center, where preserved

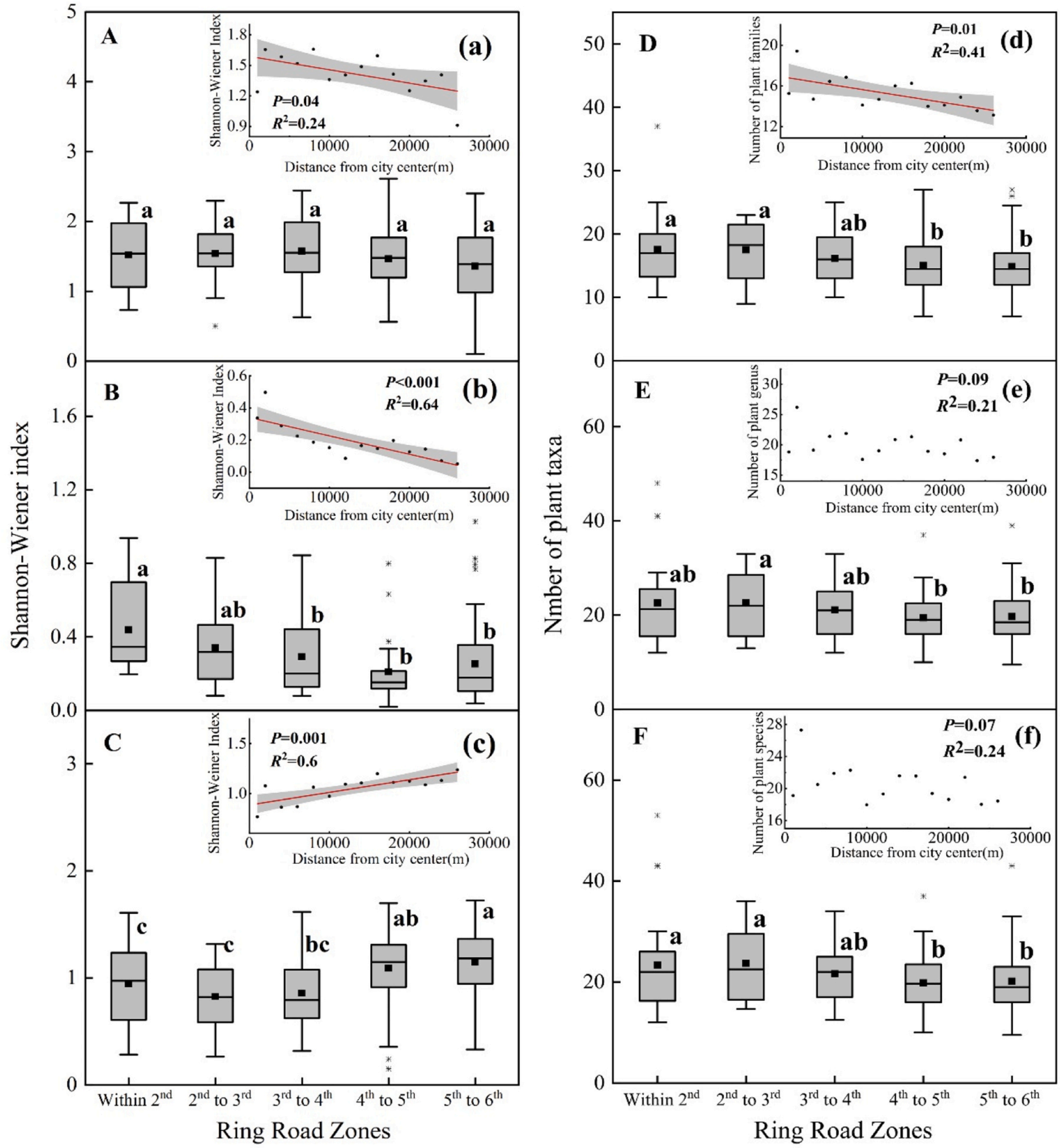

Fig. 2. Shannon-Wiener diversity against rings for tree (A), shrub (B), and herb (C) and the number of plant taxa (D-families; E-genus; F-species). Boxplots show the mean (black square), median (black line in the box), inter-quartile range (25–75% in the box), and outliers (the whisker). Mean values sharing different letters are significantly different ($p < 0.05$), and mean values sharing the same letters are not significantly different ($p > 0.05$). Inserted panels are relationships between plant diversity ((a)-trees; (b)-shrubs, and (c)-herbs), number of plant taxa ((d)-families; (e)-genus; (f)-species) and distance from the city center. The R^2 and p values are shown in each panel. Significant relationships ($p < 0.05$) are denoted with solid red lines, and gray areas indicate the 95% confidence interval of the fit.

many old tree species to increase tree diversity. (e.g., Jingshan Park, Prince Gong Mansion) (Liu et al., 2019). In addition, various exotic plant species were introduced for landscaping and other horticultural purposes and promoted plant diversity in the city center and higher ISA. However, more suburban parks and ecological conservation greenspaces with single tree species and few shrubs away from the city center and in lower ISA region (mainly concentrated between the 5th and 6th ring road). The main function of suburban parks and ecological conservation greenspaces were to protect ecological security rather than aesthetics. Consequently, native plant species were emphasized planting in the suburban parks and ecological conservation greenspaces, such as "One Million-Mu (666 km^2) Plain Afforestation Project" in 2012 (Ma et al., 2019; Yao et al., 2019). 2) Residential greenspaces managers. Real estate developers designed more beautiful community greening environment of high-priced residential areas to attract buyers, which is often referred to as the "luxury effect", where usually included convenient transportation and municipal infrastructure and facilities such as hospitals and education closer the city center and higher ISA (Wang et al., 2016). 3) Unit attached greenspaces decision-makers. Public institutions, such as the government unit, hospitals, and universities, often gather in higher ISA, where selected ornamental cultivars to pursuit the aesthetic effect and promote plant diversity (Chen et al., 2014; Wang et al., 2016; Yan et al., 2019). For example, the plant diversity of the university greenspaces could reach high level, playing a role in the urban plant species pool (Jim and Liu, 2001; Meng et al., 2004).

In addition, plant species can be considered as arising from human-cultivated and spontaneously occurring (establishing without assistance) species in urban greenspaces (Cheng et al., 2022). Spontaneous

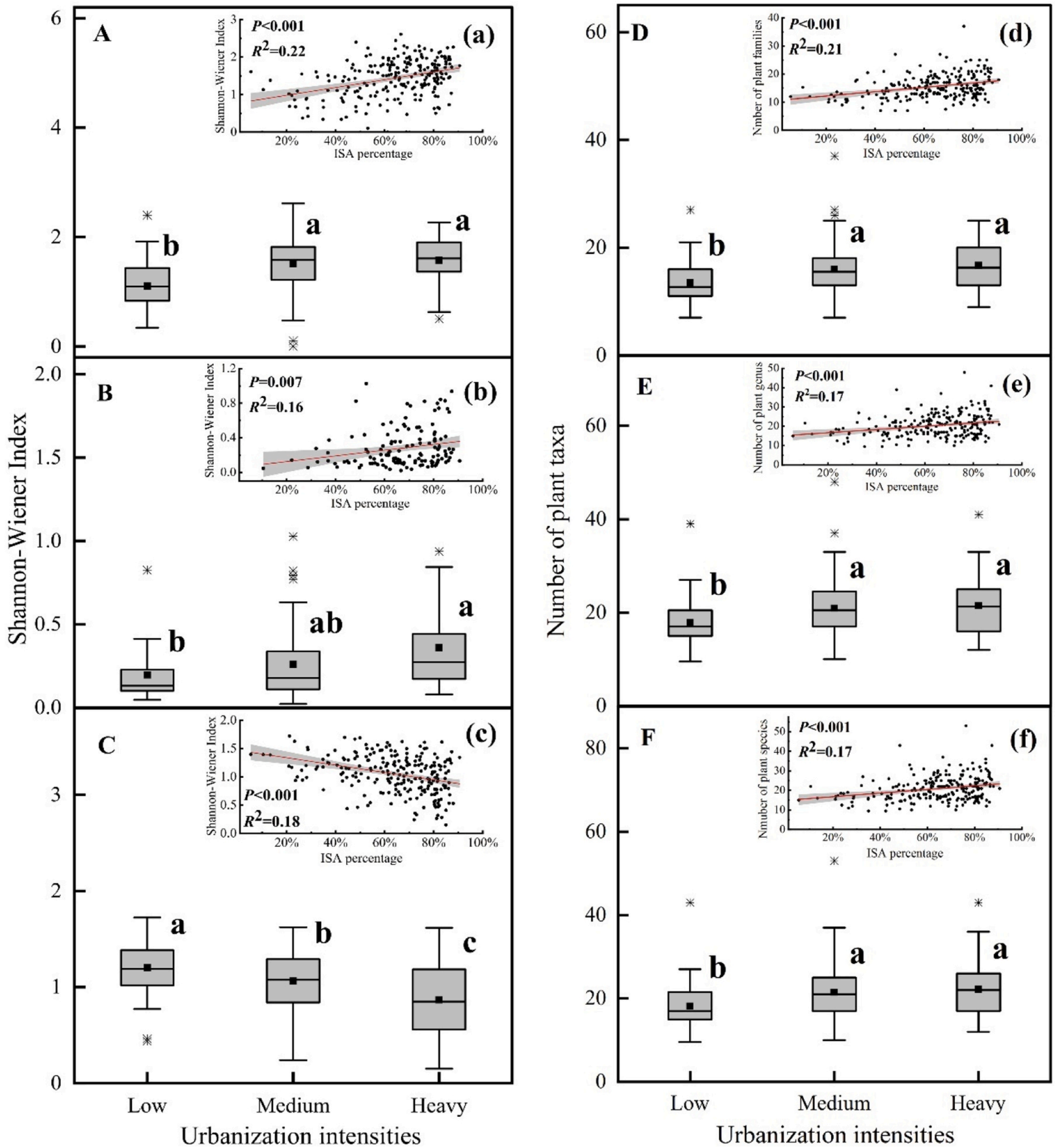

Fig. 3. Different urbanization intensity against plant diversity (A-trees; B-shrubs, and C-herbs) and the number of plant taxa (D-families; E-genus; F-species). Boxplots show the mean (black square), median (black line in the box), inter-quartile range (25–75% in the box), and outliers (the whisker). Mean values sharing different letters are significantly different ($p < 0.05$), and mean values sharing the same letters are not significantly different ($p > 0.05$). Inserted panels are relationships between plant diversity ((a)-trees; (b)-shrubs, and (c)-herbs), number of plant taxa ((d)-families; (e)-genus; (f)-species) and ISA percentage. The R^2 and p values are shown in each panel. Significant relationships ($p < 0.05$) are denoted with solid red lines, and gray areas indicate the 95% confidence interval of the fit.

species was oftentimes regarded as "wildflowers and weeds" due to their perceived low aesthetic (Iuliana et al., 2011). Higher diversity of "wildflowers and weeds" depending on the less maintenance practices performed in urban areas, such as urban villages and vacant lands (Hayasaka et al., 2012). Therefore, due to the deliberate eradicated the existence of "wildflowers and weeds" closer the city center and higher ISA, many greenspaces use a single lawn species, such as carpet grass (*Axonopus compressus (Sw.) Beauv.*), to facilitate tourists to rest, which is more convenient to manage and resistant to trimming and trampling (Cervelli et al., 2013; Li et al., 2019).

4.2. The effect of GSA percentage on plant diversity

In our study area, the GSA percentage of each grid ranges from 8.85% to 68.53%, mainly concentrated in 9–35% (93.36%). However, the GSA percentage does not significantly impact plant diversity and taxa (Fig. 4), reflecting the neglect of plant diversity in urban greening and management. As noted in the most recent 2016–2035 urban master plan, Beijing sought to increase the coverage of areas within a 500-m buffer to a park from 67.2% in 2016 to 85% in 2020 (Beijing Municipal Bureau of Land and Resources, 2017). Diverse types of parks, the Million-Mu (666 km^2) plain afforestation, and new ways of using green space have been developed in Beijing during the last two decades to mitigate environmental degradation and provide spaces for increasing demand for outdoor leisure activities (Yao et al., 2019). However, more attention to improving green areas rather than biodiversity conservation led to urban green spaces being relatively simply structured (Wang et al., 2014). Although habitat fragmentation caused by urban expansion has

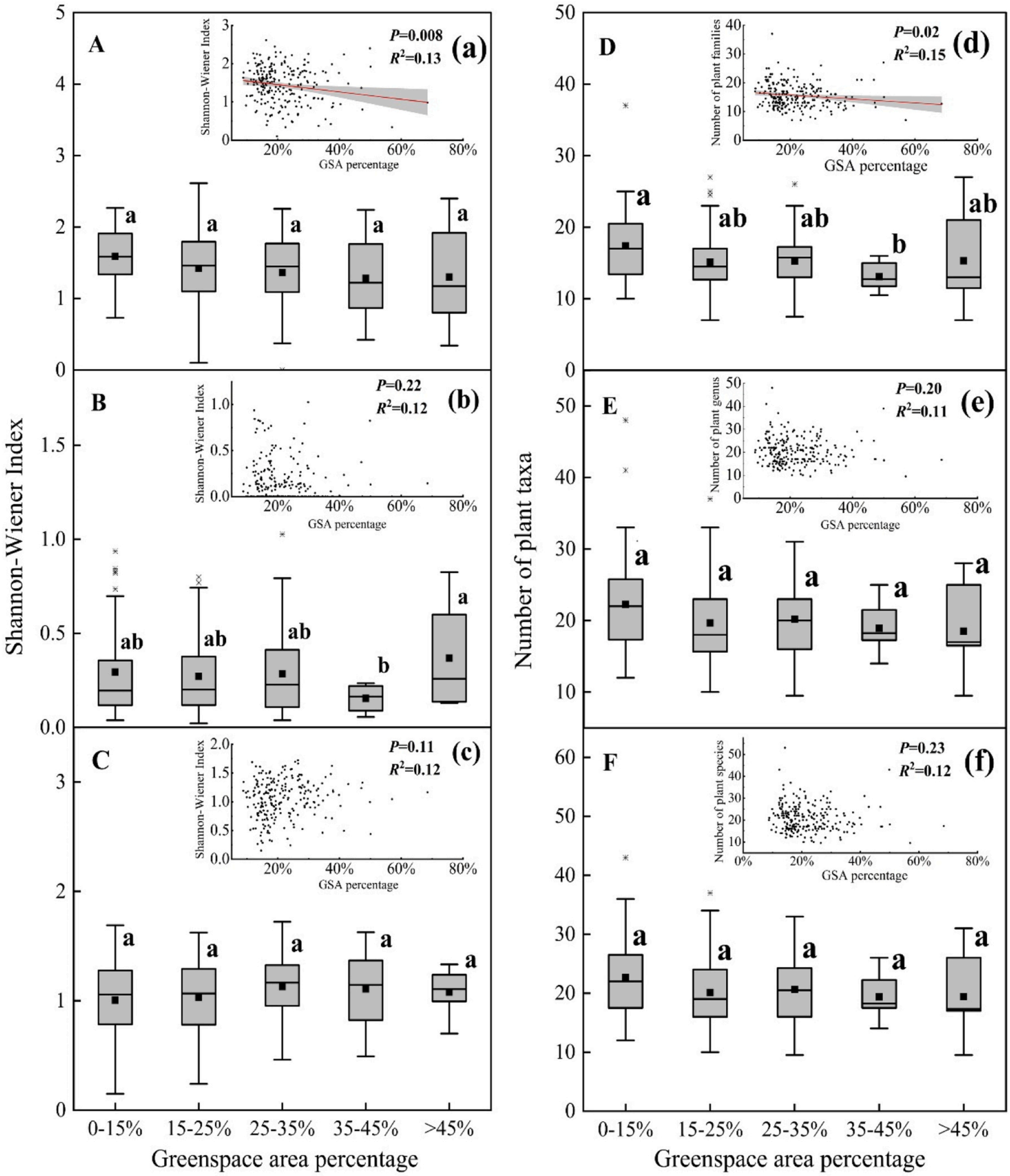

Fig. 4. Different GSA percentages against plant diversity (A-trees, B-shrubs, and C-herbs) and the number of plant taxa (D-families; E-genus; F-species). Boxplots show the mean (black square), median (black line in the box), inter-quartile range (25–75% in the box), and outliers (the whisker). Mean values sharing different letters are significantly different ($p < 0.05$), and mean values sharing the same letters are not significantly different ($p > 0.05$). Inserted panels are relationships between plant diversity ((a)-trees; (b)-shrubs, and (c)-herbs), number of plant taxa ((d)-families; (e)-genus; (f)-species) and GSA percentage. The R^2 and p values are shown in each panel. Significant relationships ($p < 0.05$) are denoted with solid red lines, and gray areas indicate the 95% confidence interval of the fit.

been reduced, and the urban forest connection within the city has been preserved and strengthened, the ecological function potential brought by plant diversity has yet to be tapped.

The quantity and quality of GSA is of prime concern for planners and city administrators (Gupta et al., 2012; Wu and Rowe, 2022). The larger GSA in cities can be used as the core habitat of urban organisms, and the proper improvement of plant diversity and rational allocation can bring more ecological and social benefits into full play (Jalkanen et al., 2020). The GSA and plant diversity across many cities in other countries reflect the urban social-ecological complexity of various concerns (Cilliers et al., 2013; Faeth et al., 2011; Gupta et al., 2012; Immergluck and Balan, 2018; Jo and McPherson, 1995; Millard, 2008). For example, above-average values for GSA and plant richness in Northern EU cities related to the natural forest richness in their surrounding landscape areas (Kabisch et al., 2016). However, our study found few remaining natural forest patches in the 6th of Beijing, and the management of the larger GSA may not have entirely performed its ecological function.

4.3. Variation of plant diversity in low urbanization intensity areas

Our study found that plant diversity increased against the increase in ISA percentage and 50% is the threshhold in the city (Fig. 3). Other

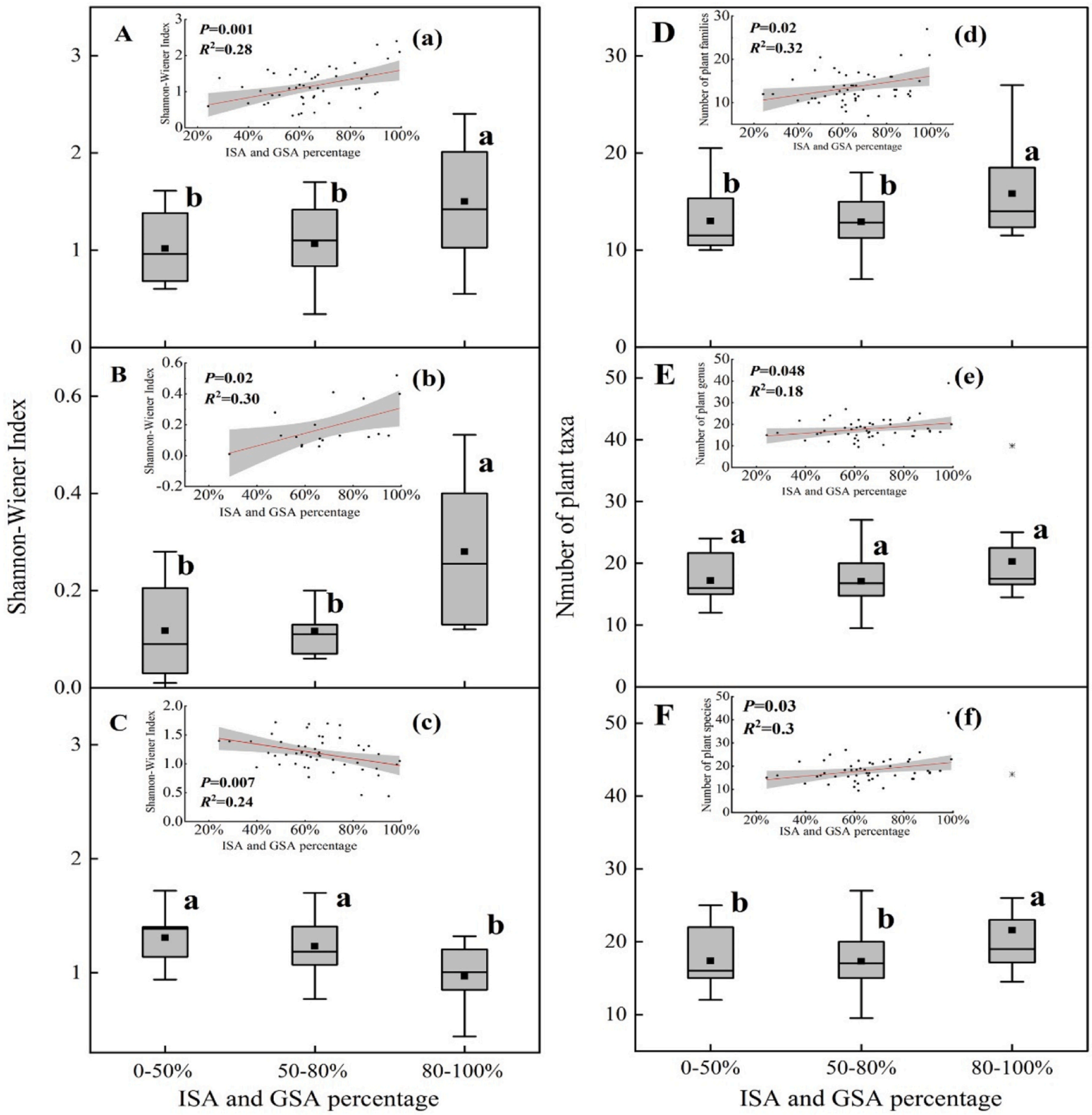

Fig. 5. In low urbanization intensity (ISA percentage<50%), different total percentages of ISA and GSA against plant diversity (A-trees; B-shrubs, and C-herbs) and the number of plant taxa (D-families; E-genus; F-species). Boxplots show the mean (black square), median (black line in the box), inter-quartile range (25–75% in the box), and outliers (the whisker). Mean values sharing different letters are significantly different ($p < 0.05$), and mean values sharing the same letters are not significantly different ($p > 0.05$). Inserted panels are relationships between plant diversity((a)-trees; (b)-shrubs, and (c)-herbs), number of plant taxa ((d)-families; (e)-genus; (f)-species) and the total percentage of ISA and GSA in low urbanization intensity grids. The R^2 and p values are shown in each panel. Significant relationships ($p < 0.05$) are denoted with solid red lines, and gray areas indicate the 95% confidence interval of the fit.

researchers also found that 40–60% ISA percentage is the threshold for the significant effect on plant diversity (Yan et al., 2019). We have analyzed the reasons why ISA promotes plant diversity in 4.1. We further found that within 50% ISA, the higher total ISA and GSA can also promote plant diversity (Fig. 5). The diversity increase may be explained by the "green space paradox" (GSP), which suggests that urban greenspaces planned to benefit more people end up serving a smaller spectrum of the total population (Wu and Rowe, 2022). Larger GSA with high biodiversity provides multiple benefits to residents (Immergluck and Balan, 2018; Pearsall and Eller, 2020; Wolch et al., 2014). In addition to spatial arrangement, measuring GSA at neighborhood level also is important for application of plant diversity and greening strategies (Gupta et al., 2012). Neighborhood Green Index aims to identify action areas for improving the green quality, and some researchers found that area of high rise neighborhood requires more amounts of good quality properly distributed green as compared to low-rise neighborhood (Gupta et al., 2012; Wu and Rowe, 2022). The GSP leads to gentrification of the neighborhood by increasing the value of the nearby real estate and will change other land-use types such as cultivated land and wasteland into ISA (Immergluck and Balan, 2018; Pearsall and Eller, 2020; Wolch et al., 2014). GSP or gentrification increases the cost of living nearby, forcing marginalized people who cannot afford to live in these areas to move further away from areas with higher ISA and GSA (Wu and Rowe, 2022). Therefore, not only the ISA percentage increase will promote people to pay more attention to the plant diversity around their living environment, but also the higher plant diversity in large GSA will also increase ISA percentage around the region. When the total ISA and GSA percentage decreased and the proportion of other land-use types increased (such as cultivated land and wasteland), the plant diversity in the region decreased significantly (Fig. 5). Low ISA and GSA have less population and social resources due to the deficiency of impervious surface area for residential and industrial or commercial and

Table 2
Mean DBH, height, and canopy breadth of urban trees pooled by urbanized degree ISA and GSA percentage, respectively.

Variable	Ranges	DBH (cm)	Height (m)	Canopy breadth (m)
ISA(%)	0–50(low urbanization intensity)	17.83 ± 0.58b	6.25 ± 0.27b	2.88 ± 0.09b
	50–80(medium urbanization intensity)	19.08 ± 0.36b	6.34 ± 0.18b	3.14 ± 0.07b
	80–100(heavy urbanization intensity)	23.69 ± 0.92a	8.29 ± 0.35a	4.21 ± 0.40a
GSA(%)	0–15	21.58 ± 0.84a	7.19 ± 0.30a	3.73 ± 0.40a
	15–25	19.99 ± 0.49ab	6.69 ± 0.23a	3.29 ± 0.09ab
	25–35	18.47 ± 0.57ab	6.52 ± 0.25a	3.15 ± 0.09ab
	35–45	18.27 ± 1.16ab	6.59 ± 0.52a	3.01 ± 0.16ab
	45–100	16.28 ± 2.12b	6.46 ± 1.53a	2.56 ± 0.40b

Note: mean values for different levels (a, b, & c) of DBH (cm), height (m), and canopy breadth (m) in classified impervious surface area percentage and greenspace area percentage are significantly different ($p < 0.05$)

high quality green resources, which fails to attract people to pay more attention on plant diversity in these areas (Gupta et al., 2012; Wu and Rowe, 2022). The finding indicates that higher ISA, and GSA with high plant diversity contribute to more social resources and high population density, which in turn promote plant diversity and both supplement each other (Wu and Rowe, 2022).

However, other cities in the world don't always have high plant diversity in larger ISA and GSA, which related to "specific urban processes", such as the more stressful environmental conditions and human preferences (Williams et al., 2009). Compared with western cities, the remaining natural forest patches within the 6th ring road of Beijing are almost entirely converted to impervious surface area and farmland. However, cities in countries such as Europe still have extensive original urban forests in the city center, which retain high plant diversity (Korhonen et al., 2021). Unlike greening decision-makers in Beijing are mainly from the Landscape Management Bureau, real estate property companies, and public units, citizens also involved to design urban plant species in Western and African countries, such as the household garden can significantly increase plant diversity in urban areas (Jha et al., 2019; Yan et al., 2019).

4.4. *Implications of urban plant management and urban planning*

Based on the abovementioned results, we make several recommendations for improving Beijing's conservation and sustainable management of plant diversity. Our first recommendation is that plant diversity needs to be increased in low ISA and GSA areas and away from the city center. Higher plant diversity can exert more significant ecological

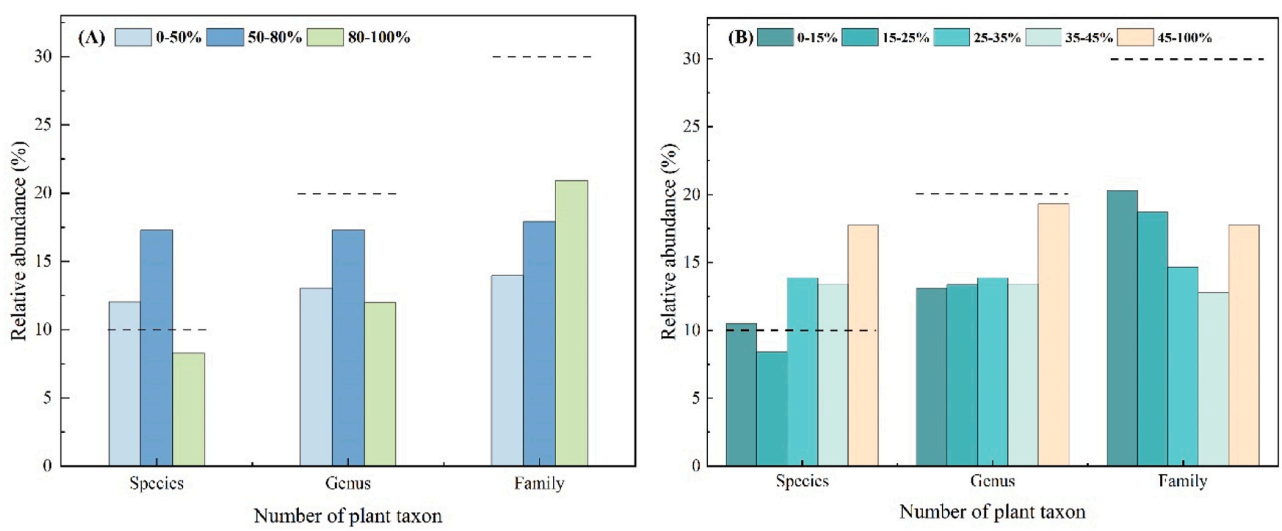

Fig. 6. The relative abundance of trees according to species, genus, and family is between different ISA percentages (A) and GSA percentages (B). The dotted lines are 10%, 20%, and 30% of species, genus, and family, respectively.

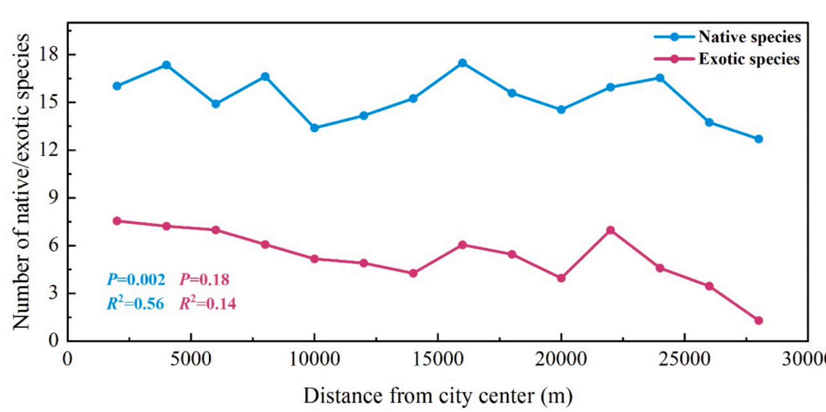

Fig. 7. The relationship between the distance from the city center and the number of exotic and native species. The R^2 and p values are shown in the figure.

Table 3
Mean number of species, the ratio of exotic/ native, mean number of exotic and native species, the mean number of trees exotic and native, the mean number of shrubs exotic and native, the mean number of herbs exotic and native (± *S.E.*) of different percentage of ISA and GSA in urban areas of Beijing, China.

Variable	Ranges	Mean number of species	Ratio of exotic/ native	Number of exotic	Number of native	Number of trees exotic	Number of trees native	Number of shrubs exotic	Number of shrubs native	Number of herbs exotic	Number of herbs native
Impervious surface percentage	0–50%	17.85 ± 0.79b	28.67%	3.95 ± 0.67b	13.79 ± 0.59b	1.14 ± 0.16b	3.48 ± 1.64b	0.95 ± 0.25c	0.73 ± 0.12c	1.11 ± 0.14b	10.54 ± 0.36a
	50–80%	21.49 ± 0.56a	35.29%	5.62 ± 0.28a	15.93 ± 0.39b	2.05 ± 0.13a	4.34 ± 2.1a	1.88 ± 0.14b	1.26 ± 0.1b	1.58 ± 0.12a	10.43 ± 0.28a
	> 80%	22.38 ± 0.91a	42.07%	6.63 ± 0.45a	15.75 ± 0.64a	2.15 ± 0.2a	4.37 ± 1.85a	2.81 ± 0.29a	2.01 ± 0.18a	1.62 ± 0.18a	9.38 ± 0.54a
Green space coverage percentage	0–15%	22.93 ± 1.05a	40.35%	6.59 ± 0.57a	16.32 ± 0.72a	2.02 ± 0.24a	4.53 ± 0.26a	2.29 ± 0.25a	1.68 ± 0.19a	1.92 ± 0.19a	10.42 ± 0.53a
	15–25%	20.39 ± 0.55a	33.70%	5.14 ± 0.29a	15.25 ± 0.38a	1.86 ± 0.12a	4.09 ± 0.19a	1.86 ± 0.17ab	1.27 ± 0.11a	1.42 ± 0.12a	9.87 ± 0.3a
	25–35%	20.42 ± 0.79a	30.44%	4.76 ± 0.41a	15.65 ± 0.54a	1.86 ± 0.19a	3.81 ± 0.25a	1.70 ± 0.24ab	1.03 ± 0.13a	1.18 ± 0.16a	10.84 ± 0.40a
	35–45%	19.15 ± 2.05a	24.10%	5.58 ± 3.20a	16.60 ± 1.80a	1.60 ± 0.37a	4.40 ± 0.77a	0.75 ± 0.25b	1.45 ± 0.37a	1.65 ± 0.39a	10.75 ± 0.63a
	> 45%	20.31 ± 4.72a	37.92%	5.58 ± 3.2a	14.72 ± 1.8a	1.56 ± 0.93a	4.75 ± 1.12a	2.75 ± 1.75a	1.39 ± 0.4a	1.28 ± 0.61a	8.59 ± 1.14a

Values followed by the same letter within columns are not significantly different at $p < 0.05$.
Note: mean values for different levels (a, b, & c) of Mean number of species, Ratio of exotic/ native, Number of exotic, Number of native, Number of trees exotic, Number of trees native, Number of shrubs exotic, Number of shrubs native, Number of herbs exotic, and Number of herbs native in classified impervious surface area percentage and greenspace area percentage are significantly different ($p < 0.05$)

benefits and could attract more people and social resources to improve social and economic benefits (Li et al., 2020).

Our second recommendation focuses on increasing the proportion of GSA and plant diversity. GSA can be estimated as 100 minus ISA of each grid in our study. Our study showed that the ISA< 50% grid account for 21.83% of all grids, but the GSA > 50% grid only accounts for 1.32% of all grids (Fig. 1d, e). Due to the proportion of cultivated land and wasteland increased away from city center and compressed the GSA. Therefore, there is a large space (such as wasteland) for the improvement of GSA.

Our study found a relationship between distance, ring road, ISA, GSA, and plant diversity. However, a caveat exists to demonstrate that urbanization gradient studies simplify the complex patterns of species diversity distribution. Although socio-economic factors still firmly guide Beijing greening decision-makers to plan plant composition, ISA and GSA as effective quantitative indicators can replace these other complex social factors to predict plant diversity in Beijing. Compared with other factors affecting urban plant diversity, such as socio-economic factors, history, and traditions, it is feasible to include ISA and GSA restrictions in urban planning and design because ISA and GSA are tangible and easy to measure, thus can be enforced (Yan et al., 2019). Although we found that plant diversity increase significantly with increases ISA percentage in Beijing, the biodiversity would not be maximized by 100% ISA percentage. What is the threshold of ISA percentage for the improvement of urban plant diversity needs further exploration. Although our conclusion based on the urbanization gradient of Beijing, distance from city center, impervious surface area and greenspaces are indicative of conservation and improvement of urban plant diversity applies to many cities around the world.

5. Conclusion

Urbanization has created a landscape that is fundamentally different from the natural ecosystem. We found that tree plant diversity, DBH, height, canopy breadth, and exotic plant species increases significantly against the increase in urbanization intensity while herb plant diversity decreases significantly. However, the GSA percentage has no significant impact on plant diversity and taxa. In addition, the results show the higher woody plant diversity and lower herb plant diversity in ISA's with a percentage> 50% and the larger ISA and GSA area (ISA+GSA percentages (i.e., >80%), and with ISA percentage < 50%. Based on the 10/20/30 "rule of thumb", the large proportion of single species in urban trees is unreasonable. In Beijing, our study found the relationship between ISA, GSA, and plant diversity. Therefore, ISA and GSA percentages can be used to predict urban plant diversity conservation and management. We suggest that the plant diversity should be increased in low ISA and GSA areas and away from the city center area, which exert more significant ecological benefits and attracts more people and social resources to improve social and economic benefits.

CRediT authorship contribution statement

Dingjie Zhao: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Qimeng Yang:** Investigation. **Mingqi Sun:** Investigation. **Yawen Xue:** Investigation. **Baohua Liu:** Investigation. **Baoquan Jia:** Resources. **Steven McNulty:** Writing – review & editing. **Zhiqiang Zhang:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2023.128119.

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