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Urban Plant Diversity in Relation to Land Use Types in Built-up Areas of Beijing

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Abstract: Urban plants provide various ecosystem services and biodiversity for human well-being. It is necessary to examine the plant species and functional traits composition and the influencing factors. In this study, a field survey was conducted using the tessellation-randomized plot method to assess the plant species and functional traits variability in greenspaces across eight land use types (LUTs) in the built-up areas of Beijing, China. Results showed that the woody plants in the built-up areas of Beijing comprised 85 non-native species (57%), 21 pollen-allergenic species (14%), and 99 resistant species (67%). Residential areas, community parks and institutional areas had higher woody plant species richness than other LUTs. Native and extralimital native species were more widespread than exotic species. Proportions of species with resistances were low except for cold- and drought-resistance; consequently, a high intensity of management and maintenance is essential for survival of plants in this urban area. Caution should be exerted in selecting plant species with resistance to harsh conditions in different LUTs. Housing prices, distances from the urban center, years since the establishment of LUTs and greening rate were strongly correlated with the plant functional traits and species diversity. Urban forest managers should consider plant functional traits and LUT-specific strategies to maximize both forest and human health.

Keywords: functional trait; native species; extralimital native; exotic; resistant species; Beijing

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1 Introduction

Urban plants offer a wide range of direct and indirect ecosystem services in urbanized areas, including environmental improvement, aesthetic enhancement, ecological enrichment, and economic and social benefits for residents (Gaffin et al., 2012; Jim and Zhang, 2015). Additionally, urban vegetation contributes to human health and psychological well-being (Hanski et al., 2012). There is a growing consensus that functional diversity, or the value and range of species traits, rather than species numbers per se, strongly determines ecosystem functioning (Díaz and Cabido, 2001). Plant functional traits refer to the characteristics of an organism that are considered relevant to its response to the environment and its effects on ecosystem functioning (Díaz and Cabido, 2001). The higher the species richness in a community, the higher the probability of the presence of species with particularly important traits (Crawley et al., 1999). And, ecosystem resilience and resistance are strongly influenced by the traits of the dominant plant species (Aerts, 1995). However, this

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knowledge has rarely been incorporated into plant diversity studies.

In the past decade, urban plant biodiversity has been widely investigated by researchers, environmental planners and policy-makers (Jooss et al., 2009). Biodiversity patterns in urban settings are deeply affected by human-driven mechanisms that lead to habitat changes and determine the species composition by setting filters for plant selection and management of urban green spaces (Alberti et al., 2003; Grimm et al., 2008; Kowarik, 2011). The introduction of non-native plant species combined with unintended extirpation of plant species intolerant of urban environmental conditions alters the species composition in an urban area.

It is reported in Beijing, China that plant species composition in built-up areas are significantly different from those of the natural habitats (Zhao et al., 2010a). A few analyses of changes in urban flora over long periods of time revealed a significant turnover in species composition, an increase in total species richness, and a decline in rare native species and archaeophytes (pre-1500 aliens), while the number of neophytes (post-1500 aliens) markedly increased (Bassuk et al., 2009). In practice, urban foresters also can affect species composition, as they balance the need for plant diversity with human aesthetic preferences and species' ecological tolerances. For example, foresters select species that require minimal maintenance, tolerate a variety of urban stressors (e.g., high-soil compaction, low oxygen availability to roots, drought and salinity), and will grow to a size appropriate for their location in the landscape (Bassuk et al., 2009).

Urbanization increases the fragmentation of habitats (Alberti et al., 2003) and changes urban climate, hydrology, and soils upon which urban plants live (Pickett et al., 2001). As urban areas and population increase, vegetation composition in urban areas changes strongly, as does the functional composition (presence of certain plant functional traits), which was found to be more consistently associated with rates and magnitudes of ecosystem processes than species richness changes. Recent research has increasingly adopted urbanization gradient and neighborhood socioeconomic approaches to explore patterns of tree species (Berland, 2012). Williams et al. (2015) synthesized the results of 29 studies that specifically examined plant traits or niche indicators (e.g. Ellenberg numbers) of urban floras, and found some relationships between plant traits and urbanization. Wang et al. (2012) found that socioeconomic variables are related to at least one plant diversity variable (species richness of trees, shrub and grass) in the Beijing built-up areas. Urban land use types (LUT, i.e. residential area, commercial area, etc.) are the most important composition of urban landscapes, and most likely associated with different urban forest conditions (Bourne and Conway, 2014). Knapp et al. (2008) found that shifts in land use can change the trait state composition of plant assemblages, and emphasized the need to concentrate on both species traits and effects of different LUTs to assess species frequency (Knapp et al., 2009). A study focused on household yards in an urban setting found that yards had more species per hectare in densely built regions than in lower-density regions, but functional composition of plant traits did not change with housing density (Knapp and Kühn, 2012). The different purposes of LUTs mean there is variation in available planting sites, general landscaping goals, and the types of people making decisions (i.e. residents, commercial property managers, municipal parks departments). These distinctions potentially contribute to different functional traits and species compositions across LUTs. However, the plant functional traits and the potential effects of urban LUTs were understudied in China. Knowledge of similarities and differences between LUTs is needed to better understand the mechanisms driving plant functional traits and species diversity, and can provide guidance for developing successful management plans.

The goals of this study were to: 1) determine what differences in plant species and functional traits (life form, pollen-allergenicity and resistance) composition among different LUTs in built-up areas of Beijing; 2) identify the main factors that influence the composition of woody plants in the urban areas; and 3) provide advice for vegetation management, planning and protection in the urban forests.

2 Study Site and Methods

2.1 Study site

The study was conducted within the fifth ring road of the built-up areas (39°45′N–40°2′N, 116°11′E–116°33′E) in China's capital, Beijing, which is situated in the north of the country (Fig. 1). The study area has a flat terrain (average elevation approximately 50 m) and an area of 670 km^2. The city has a warm temperate semi-humid climate in which the mean annual temperature is 11℃ and annual precipitation is 500 mm. The permanent resident population was 2.15 × 10^7 in 2014. The development pattern in Beijing is typical of concentric expansion, with distinct ring-shaped urbanization from the inner center to the outskirts (Li et al., 2006).

2.2 Sampling design and field investigation

The tessellation-randomized plot method (Hope et al., 2003) was used to investigate the urban vegetation. The eight primary LUTs were defined as institutional, residential, commercial, community park, municipal park, woodlot, roadside and riverside (Table 1). We established 2 km × 2 km grids as tessellation within the fifth ring road of Beijing. Within each grid cell, 1–3 sample plots (each 400 m^2 or 20 m × 20 m) were randomly chosen using SPOT remote sensing imagery (10-m resolution, acquired in 2002). The total number of plots for each LUT was determined according to its percentage reported by 'Compilation of Census Data of Urban Landscaping in Beijing 2005' (Beijing Municipal Bureau of Landscape and Forestry, 2006). The Google Earth image of 2014 was used to verify the LUT of sample plots. We used a Garmin 60CXs GPS (Garmin International, Inc., Olathe, KS, USA) to locate the plot centers. The plots were surveyed from June to August 2014 and all woody plants were identified and recorded. A total of 300 sample plots were surveyed (Fig. 1).

Table 1 Definitions of eight land use types (LUTs) in built-up areas of Beijing

LUTs	Definition or interpretation
Institutional	Mainly referred to universities, research institutions, old people's homes, town halls, workers' unions, etc.
Residential	High-density low-rise districts, apartment complexes and old town centers with mixed residential and commercial use
Commercial	Business districts in any scale, including central business districts, commercial plaza, shopping mall and stores
Community park	Small parks surrounded by residential areas, providing fitness facilities, and mainly used by nearby residents
Municipal park	Parks and other recreational areas comprising public parks, sports fields, cemeteries and semi-natural recreational areas
Woodlot	Small scale forests or green spaces in vacant lands with no definite use
Roadside	Green spaces associated with roadways and parking lots
Riverside	Green spaces along rivers, mainly refers to riparian zone greenbelt

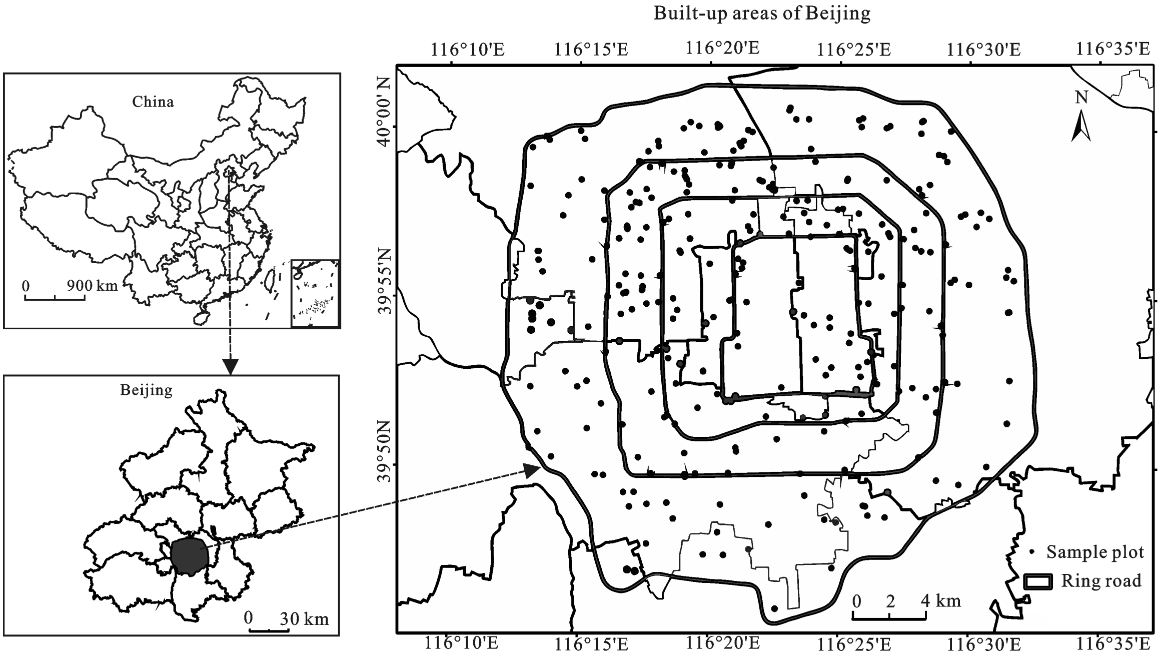

Fig. 1 Location of study site and distribution of sample plots in built-up areas of Beijing

2.3 Plant functional trait categories

2.3.1 Plant life form

The term 'plant life form' is a general term that groups plants according to their functions in ecosystems and their use of resources. Plant life form characteristics refers to such things as broad morphology characteristics (e.g., trees, shrubs, lianas, etc.) or more specific properties, such as leaf shape (needleleaf, broadleaf) and seasonality of leaves (evergreen, deciduous). Surveyed plants were grouped into eight categories (evergreen coniferous trees, evergreen broadleaf trees, deciduous coniferous trees, deciduous broadleaf trees, evergreen coniferous shrub, evergreen broadleaf shrub, deciduous broadleaf shrub and deciduous ligneous liana) according to specific properties of their leaves.

2.3.2 Species origin

Plant species were categorized into two classes: native and non-native. The non-native species was further classified based on the place of origin, i.e., whether originating from within or outside China. Each plant species was then placed into one of three origin classes: 1) species that were native within the Beijing area (native); 2) species that were native to China but non-native to Beijing (extralimital native); and 3) species that were non-native to China (exotic).

2.3.3 Pollen-allergenic species

species releasing pollen that could cause allergenic effects in humans is recognized as pollen-allergenic species.

2.3.4 Plant resistance

We used 'plant resistance' to refer to the characteristic of tolerance or resistance of plants to cold, drought, poor soil, air pollution, salt and pruning.

2.4 Determination of species with specific functional traits

The life form of each species was determined by reference to the *Flora of China* (Compilation Committee of the Flora of China, 1959–2004), the *Beijing Flora* (He et al., 1993), and online databases (e.g. eflora.cn and Scientific Database of China Plant Species).

Pollen-allergenic plant species were determined based on the reference 'An Investigation on Airborne and Allergenic Pollen Grains in China' (Investigational Team on Airborne and Allergenic Pollen Grains in China, 1991).

The resistances of each species were determined if these were reported in journal papers, books (He et al., 1993; Chen, 2003; Compilation Committee of the Flora of China, 1959–2004) or databases (eflora.cn; landscape plant net (http://plant.cila.cn/); Scientific Database of China Plant Species). At first, we searched papers on species resistance to stress and determined the species resistances. Then we examined books for each species to see if there were reports on the resistances of the species. If not, we searched websites using keyword species name plus stress factor (e.g., air pollution or salt resistance) for reports of the species. If we found no reports in either books or websites, the species was judged not to be a tolerant one.

2.5 Socioeconomic variables

For each sample plot, data were collected that identified the year of construction, house prices, distances from the urban center, and greening rate and these were used as representative socioeconomic variables. House prices and greening rate data were derived from websites reporting housing information (e.g., http://beijing.anjuke.com). Other greening rate data were obtained from the '*Beijing Statistical Yearbook 2014*' (Beijing Municipal Bureau of Statistics, 2015)

2.6 Data analysis

Woody plant diversity was compared among eight LUTs. A total of seven variables across the eight LUTs were analyzed using MS Excel 2010 (Microsoft Corp., Redmond, WA, USA), including species richness and frequency of all woody plants, native, extralimital native, exotic, and species richness of different life forms, pollen-allergenic plants and resistant plants. One-way ANOVA and LSD (least significance difference test) were used to compare species richness among different LUTs, and for P-values less than 0.05, the difference between LUTs was considered to be significant. Statistical tests were conducted using SPSS 20 (IBM Corp., Armonk, NY, USA). Canonical correlation analysis (CCA) of species richness and socioeconomic variables were conducted using Canoco4.5 (ter Braak and Smilauer, 2002).

3 Results

3.1 Diversity of woody plant species

The woody plant species richness was 148 (including 92 tree species and 56 shrub species) (the plant lists are available at http://www.bjurban.rcees.cas.cn/ydhz/swjc/201710/t20171009_4868539.html), and there were 6 ± 2 species per plot on average. Woody plant species richness per plot was higher in residential areas, community parks and institutional areas than in riverside, municipal park and woodlot LUTs ($P < 0.05$) (Fig. 2). Of the 148 species that were surveyed, 33% were found in plots of only one LUT. Of those, woody plant species in the municipal park showed the highest proportion of 65%, followed by 63% in residential green spaces. Only five species were observed in all eight LUTs (*Sabina chinensis, Sophora japonica, Ginkgo biloba, Populus tomentosa,* and *Euonymus japonicus*) (Table 2). All LUTs shared common shrubs in similar hedge plantings; i.e., *E. japonicus, Ligustrum vicaryi,* and *Buxus sinica*. The most common species present in the plots were those used to create visual barriers (i.e., *E. japonicus*) and historically popular street trees (i.e., *S. japonica*). The four most common tree species (*S. japonica*, *S. chinensis*, *Ginkgo biloba* and *Populus tomentosa*) accounted for 35% of all surveyed trees, and the species (*S. japonica*) had the largest population, accounting for 12.6% of all trees.

3.2 Life forms and origins of woody plants

The life forms of woody plant species in Beijing built-up areas were composed of deciduous broadleaf trees (49%), deciduous broadleaf shrubs (30%), evergreen coniferous trees (13%), evergreen broadleaf shrubs (5%), as well as by small populations (1% each) of evergreen coniferous shrub, deciduous ligneous liana and deciduous coniferous trees.

The non-native species (extralimital native and exotic) numbered 85 and accounted for 57% of all surveyed species. Most (68%) evergreen species were non-native. Among evergreen coniferous tree species, extralimital native species accounted for larger proportions in woodlots (100%), institutional areas (50%), municipal parks (50%), roadside (50%) and residential areas (44%) than others. For evergreen coniferous trees, riverside areas and commercial green spaces were mainly dominated by native species. For deciduous broadleaf species, the native species proportion was higher than both extralimital native and exotic species for all LUTs (Table 3). The evergreen broadleaf shrub was mainly comprised of extralimital native and exotic species, e.g. *B. sinica* and *E. japonicas*, often used as hedgerows, and appeared in all LUTs except for woodlots. *Rosa chinensis*, a deciduous flowering shrub, also appeared in all LUTs except for woodlots. Most of the deciduous broadleaf shrubs were native species, e.g. *Lonicera maackii*, *Amygdalus triloba*, *Weigela florida*, and existed in higher proportions than other species in all LUTs. Only one exotic species of deciduous broadleaf shrub (*Berberis thunbergii*) was detected, and it comprised the smallest population. Ligneous liana showed no exotic species, and only one native species (*Campsis grandiflora*), and one extralimital native species (*Wisteria sinensis*). One species of deciduous coniferous tree (*Metasequoia glyptostroboides*) was observed in residential LUT, and another species (*Albizia julibrissin*) was found in the municipal park and riverside green space LUTs.

3.3 Pollen-allergenic plants

A total of 21 pollen-allergenic species were observed in the survey and accounted for 14% of all species surveyed. Species appearing in the highest frequency were *S. japonica, P. tabulaeformis, S. chinensis, P. tomentosa, G. biloba, A. altissima, P. bungeana, C. deodara* and *S. matsudana*. In plots where pollen-allergenic species were found (96%), 1–6 species existed per plot, but most commonly (83% of all plots) 1–3 species were found. With two exceptions, the highest proportion of plots in most LUTs contained two pollen-allergenic plant species. The exceptional LUTs were community parks and roadside areas, in which 38% and 40% of plots, respectively, contained three pollen-allergenic

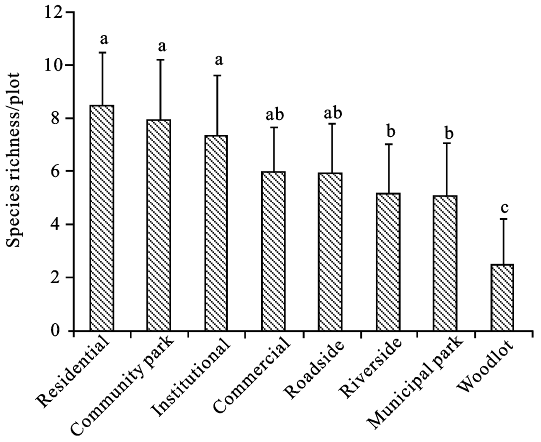

Fig. 2 Woody plant species richness in different land use types. Different letters above columns indicate statistically significant differences ($P < 0.05$)

Table 2 Frequency of primary plant species in different LUTs (%)

Species	Institutional (*n* = 28)	Residential (*n* = 61)	Commercial (*n* = 14)	Community park (*n* = 14)	Municipal park (*n* = 90)	Woodlot (*n* = 8)	Roadside (*n* = 59)	Riverside (*n* = 26)
Evergreen species								
Sabina chinensis	35.7	16.4	21.4	28.6	34.4	25.0	35.6	23.1
Euonymus japonicas	32.1	67.0	35.7	42.9	21.1	12.5	33.9	19.2
Pinus tabuliformis	17.9	21.3	14.3	21.4	24.4	0	32.2	15.4
Cedrus deodara	35.7	16.4	35.7	14.3	4.4	0	6.8	0
Buxus sinica	28.6	13.1	7.1	14.3	3.3	0	18.6	7.7
Pinus bungeana	25.0	11.5	0	0	7.8	12.5	6.8	3.8
Platycladus orientalis	0	3.3	7.1	7.1	15.6	0	0	11.5
Juniperus formosana	10.7	3.3	0	14.3	3.3	0	0	0
Picea wilsonii	10.7	4.9	7.1	0	2.2	0	0	0
Pinus armandii	14.3	1.6	0	0	1.1	0	6.8	0
Deciduous species								
Sophora japonica	32.1	49.2	21.4	64.3	34.4	37.5	54.2	23.1
Ginkgo biloba	32.1	16.4	64.3	14.3	28.9	12.5	16.9	7.7
Populus tomentosa	21.4	14.8	7.1	7.1	15.6	25.0	27.1	30.8
Salix matsudana	14.3	23.0	0	14.3	16.7	25.0	18.6	34.6
Prunus davidiana	10.7	14.8	21.4	50.0	6.7	0	15.3	11.5
Ligustrum vicaryi	17.9	21.3	28.6	0	10.0	0	18.6	3.8
Prunus Cerasifera	14.3	21.3	7.1	7.1	10.0	0	18.6	19.2
Fraxinus chinensis	0	11.5	14.3	21.4	17.8	0	25.4	3.8
Koelreuteria paniculata	7.1	26.2	14.3	35.7	0	0	6.8	3.8
Salix babylonica	3.6	8.2	0	21.4	6.7	12.5	5.1	34.6
Malus micromalus	3.6	14.8	14.3	21.4	12.2	0	6.8	11.5
Platanus acerifolia	10.7	19.7	21.4	0	6.7	12.5	13.6	0
Ailanthus altissima	0	14.8	14.3	0	5.6	12.5	8.5	11.5
Toona sinensis	7.1	31.1	7.1	7.1	1.1	0	6.8	0
Robinia pseudoacacia	0	6.6	0	14.3	13.3	0	1.7	23.1

Note: '*n*' represents number of plots

plant species. The richness of pollen-allergenic species in each plot within roadside areas was significantly higher ($P < 0.05$) than in plots within municipal parks and woodlot LUTs (Fig. 3).

3.4 Resistant plants

A total of 99 resistant species were recorded, accounting for 67% of all surveyed species. The proportions of species having cold and drought resistance were significantly higher than those of other types of resistance in all LUTs except for woodlots ($P < 0.05$) (Fig. 4). Cold-resistant species numbered 99, accounting for 67% of all species. Furthermore, 89 drought-resistant species (60%) were found, and 64 species (43%) were found that were resistant to poor soil. Species with resistance to air pollution numbered 48 (32% of all surveyed plants), while salt-resistant species totaled 28 (19%), and species with resistance to pruning numbered 13 (9%). Species that had pruning resistance were the least common among all statistically relevant resistant species. Plots that contained cold- and drought-resistant species accounted for 97% and 95% of all plots, respectively. In residential areas, species with cold, drought and salt resistance were most common, and accounted for 44%, 41% and 13% of all surveyed species, respectively. The proportions of species with resistance to poor soil (28%) and air pollution (24%) in community parks were the highest among all eight LUTs. The municipal park LUT had the largest number of species with resistance to pruning (6% of all surveyed species).

3.5 Relationship between species richness and socioeconomic variables

Canonical correlation analysis resulted in a bi-plot of ordination space showing plant species richness in relation to socioeconomic variables (Fig. 5). Species richness

Table 3 Proportions of species origins of different life forms among land use types (%)

	Institutional	Residential	Commercial	Community park	Municipal park	Woodlot	Roadside	Riverside
Deciduous broadleaf tree								
Native	53.7	55.6	47.4	50.0	55.6	77.8	54.8	58.3
EN	34.1	26.7	42.1	33.3	31.1	11.1	29.0	20.8
Exotic	12.2	17.8	10.5	16.7	13.3	11.1	16.1	20.8
Deciduous broadleaf shrub								
Native	63.6	44.8	45.5	53.8	45.5	66.7	40.9	53.3
EN	22.7	34.5	27.3	30.8	42.4	0	40.9	33.3
Exotic	13.6	20.7	27.3	15.4	12.1	33.3	18.2	13.3
Evergreen coniferous tree								
Native	25.0	33.3	66.7	42.9	33.3	0	33.3	60.0
EN	50.0	44.4	16.7	42.9	50.0	100.0	50.0	40.0
Exotic	25.0	22.2	16.7	14.3	16.7	0	16.7	0
Evergreen broadleaf shrub								
Native	20.0	20.0	20.0	20.0	20.0	0	20.0	20.0
EN	40.0	40.0	40.0	40.0	40.0	0	40.0	20.0
Exotic	40.0	40.0	40.0	40.0	40.0	100.0	40.0	60.0
Evergreen coniferous shrub								
Native	0	0	0	0	0	0	0	0
EN	0	0	0	0	0	0	0	0
Exotic	100.0	100.0	100.0	100.0	100.0	0	100.0	100.0
Deciduous ligneous liana								
Native	0	50.0	0	0	0	0	50.0	0
EN	100.0	50.0	0	100.0	100.0	0	50.0	0
Exotic	0	0	0	0	0	0	0	0
Deciduous coniferous tree								
Native	0	0	0	0	0	0	0	0
EN	0	100.0	0	0	100.0	0	0	100.0
Exotic	0	0	0	0	0	0	0	0

Note: EN represents extralimital native

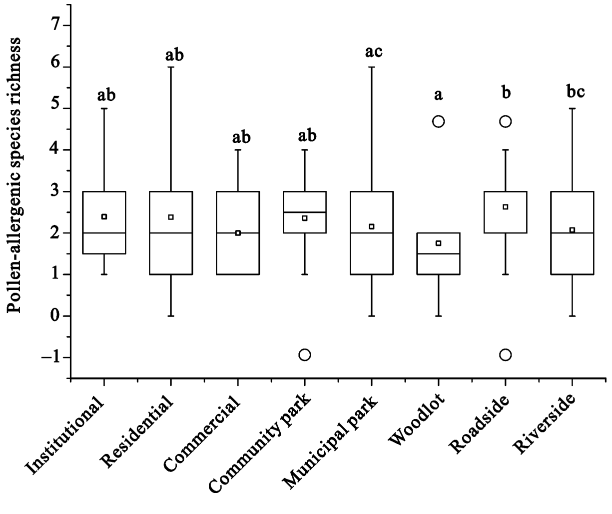

Fig. 3 Pollen-allergenic woody plant species richness of each plot in different land use types. Different letters above columns indicate statistically significant differences ($P < 0.05$)

of evergreen broadleaf shrubs, deciduous broadleaf trees, exotic species and woody plants were all correlated positively with house prices. The extralimital species richness was correlated positively with years since the establishment of LUTs, and correlated negatively with distances from the urban center. The richness of species with resistance to cold, drought, poor soil and salt were positively correlated with greening rate.

4 Discussion

4.1 Patterns of woody plant diversity

In this study, the most abundant tree species *S. japonica* accounted for 12.6% of all trees. The four most abundant species comprised 35% of the population, which was a higher proportion than in Hong Kong where the four most common species comprised 28% of the tree

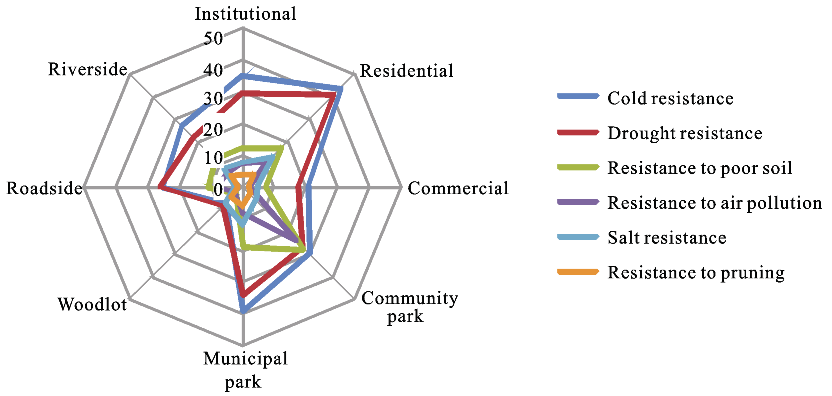

Fig. 4 Proportions (%) of species having various types of resistance in different land use types

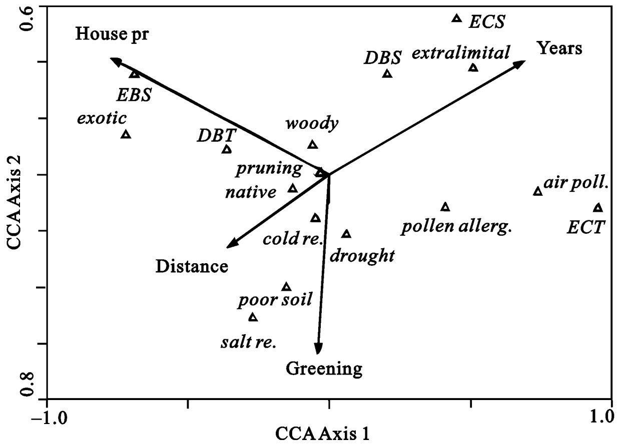

Fig. 5 Canonical correspondence analysis (CCA) of the relationships between species richness and socioeconomic variables. Triangles represent species diversity variables (*native*: native species richness; *exotic*: exotic species richness; *extralimital*: extralimital native species richness; *cold re.*: species richness with cold resistance; *drought*: species richness with drought resistance; *air poll.*: species richness with resistance to air pollution; *salt re.*: species richness with salt resistance; *poor soil*: species richness with resistance to poor soil; *pruning*: species richness with resistance to pruning; *pollen-allerg.*: pollen-allergenic plant species richness; *DBT*: Deciduous broadleaf trees' richness; *DBS*: Deciduous broadleaf shrubs' richness; *ECT*: Evergreen coniferous trees' richness; *EBS*: Evergreen broadleaf shrubs' richness; *ECS*: Evergreen coniferous shrubs' richness); Arrows represent socioeconomic factors (*House pr*: house price; *Years*: years since the establishment of LUTs; *Distance*: Distances from the urban center; *Greening*: Greening rate)

population (Zhang and Jim, 2014). Some researchers indicated that no single species should account for more than 10% of the entire tree population in an urban forest (Miller and Miller, 1991). Large contributions by a few species to the total tree population could cause an uneven species distribution. Thus, the number of native species *S. japonica* should be controlled to increase the proportions of other species and develop a more diverse and healthy ecosystem.

In this study, woody plant species richness was higher in residential areas, community parks and institutional areas than in the other LUTs. This is related to stakeholder characteristics and management of land use in the urban environment.

In Beijing urban areas, residential land was mostly covered by multistory apartments with about 10%–30% of land reserved for greening. There are companies responsible for planting and management. High investment in establishment and intensive management of green space provide bases for more diverse plant species. Community parks are generally small areas and less intensively managed. Woody plants are rich in native species and have grown widely for many years. Thus, the high species diversity can be sustained. This observation is different from that in a previous report that the number and diversity of trees in community parks may be lower than in municipal parks (Johnson and Swan, 2014). In Beijing, most public institutions had green spaces that were clearly planned and managed professionally. More species were introduced for beautifying the landscape. In contrast, the green spaces in the municipal park LUT frequently were covered by large areas of grass and relatively sparsely distributed individual trees, or by pure forest. This partly explained the species richness in municipal parks is not high in Beijing.

Cities are important centers for intentional and unintentional introduction and naturalization of exotic species (McKinney, 2006). Research showed that non-native species richness significantly increased with increasing urban land cover (Aronson et al., 2015).

Non-native species in the built-up areas of Beijing accounted for 57% of all species recorded in our survey. Less than 20 % of the woody vegetation was non-native in Chongming Island, China (Zhao et al., 2013). Alien species accounted for 44.5% of woody plant species in the built-up areas of Xi'an, China (Ouyang et al., 2015). The ratio of non-native species in Bracknell, England was 24.8% (Helden et al., 2012). Non-native species accounted for 31.1% in Chennai's urban forest (Muthulingam and Thangavel, 2012). Therefore, compared with that in other cities and sites around the world, the proportion of non-native species was significantly higher in the built-up areas of Beijing.

Socioeconomic status was a strong predictor of plant species richness in urban areas. Neighborhoods with high house prices had more exotic species than other neighborhoods, demonstrating an earnest preference for exotic plants in urban landscaping of high-income neighborhoods. Other research in Beijing also found that richness increased with increasing housing prices across all groups of species (Wang et al., 2015). These results reflected to some extent a 'luxury effect' on plant populations in which affluence was associated with species richness. Distances from the urban center were positively related to native species richness, reflecting an increase in the relative abundance of native species from the urban center to fringe areas. Studies in 2009 and 2011 found a significant negative relationship between the distance to the city center and both tree and shrub species richness, and researchers thought this trend was related to the growth history of the city (Wang et al., 2012). For Beijing, which is undergoing urbanization and expansion of built-up areas, the high ratio of non-native to native species is reasonable and is similar to findings in other studies that have shown that increased urbanization causes a decrease of native species and an increase of non-native plant species (D'Antonio and Meyerson, 2002).

4.2 Patterns of plant functional traits diversity

Plant life form was an important functional trait. It was affected by local climate, soil and other environmental conditions. In Beijing, deciduous species was the dominant life form, accounting for 79% (including deciduous broadleaf trees of 49% and deciduous broadleaf shrubs of 30%) of the richness of woody plants. The prominent proportion of deciduous species reflected obvious characteristics of Beijing's climate. Nevertheless, the introduction of extralimital native and exotic species, especially evergreen species, has changed the local plant diversity. In the urban environment, the impact of environmental stress and disturbance on the composition of plant species is not as important as in the natural environment. In urban areas, artificial management and control are the main factors influencing the life form composition.

A total of 21 pollen-allergenic species were recorded in the current study, and these species appeared in approximately 96% of the plots surveyed. The proportion was similar to the study in 2007, which showed that 94% of the plots contained pollen-allergenic species (Zhao et al., 2010a). In our study, pollen-allergenic species were distributed more intensively in community parks and roadside areas than in other LUTs, because most species in community parks and roadside areas are non-native species with high aesthetic value, and these species are often pollen-allergenic (Xin et al., 2007).

Trees in urban environments are often exposed to heat stress, low air humidity and restricted soil moisture. Harsh urban growing conditions may allow only a limited number of tolerant plant establishments in cities. In addition, plant resistant characteristics reflect the habitat condition where plants live, and consequently determine what kind of urban environment is suitable for survival. Jim and Zhang (2015) reported that the poor conditions in residential areas (environmental stresses, limited habitat dimensions, and improper care and abuses) have been shown to determine survival of plants having certain resistance.

In this study, residential green space had high proportions of species that were cold-, drought- and salt-resistant. The proportions of species with resistance to poor soil and air pollution in community parks were the highest among all eight LUTs. However, roadside greenspace had low proportions of species with resistance to poor soil and air pollution. The municipal park LUT had the largest number of species with resistance to pruning, mainly due to landscaping requirements. In general, urban environments (characterized by poor soil nutrients, high soil salinity, and air pollution) are not suitable for the survival of intolerant plants, making high-intensity management and maintenance essential for their survival in urban areas.

In this study, resistant species richness increased with higher greening rate (Fig. 5). Obviously, in areas with lower greening rate, the high proportion of impervious surfaces (e.g. building or pavement surface) provides few lands for planting. For the purpose of landscape aesthetic, some non-native species were often selected (e.g. exotic evergreen species) (Zhao et al., 2010b; Aronson et al., 2015), but these species often lack the resistant characteristics that adapt to local environment (e.g. cold and drought resistance) and need intensive management.

5 Conclusions

This study focused on plant functional traits (e.g. life forms, pollen-allergenicity and resistance) of woody plants in the urban area of Beijing, and analyzed the plant diversity and the impact factors among LUTs. Residential areas, community parks and institutional green space showed particularly higher species richness than other LUTs, and the highest richness of species with resistance to air pollution was found in the community park LUT. The analysis of the relationship with socioeconomic factors showed that house prices, distances from the urban center, years since the establishment of LUTs and greening rate were strongly correlated with species richness. In addition, the different characteristics (e.g. stakeholder characteristics, management strategies and policy) and various planting maintenance practices and turnover among LUTs contributed to the heterogeneity of urban vegetation composition in the urban built-up areas.

Overall, complex patterns of spatial heterogeneity in urban plant community composition are a product of multiple drivers. Furthermore, plant selection and maintenance strategies should be tailored to plant functional traits and LUTs to maintain healthy and diverse urban forests. We selected only a few functional traits for examination in the study, but plant species have many functional traits that could affect ecosystem function. For example, species that have shallow root system are subject to lodging and have little or no resistance to drought. Further study on mechanisms such as the role of drought-resistance in plant establishment, and the effect of pollen-allergenic species on human health are needed to get a full understanding of the relationship between plant functional diversity and ecosystem processes.

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