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Plant Diversity Along the Urban–Rural Gradient and Its Relationship with Urbanization Degree in Shanghai, China

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Abstract: Urbanization is one of the major causes for plant diversity loss at the local and regional scale. However, how plant species distribute along the urban–rural gradient and what the relationship between urbanization degree and plant diversity is, is not very clear. In this paper, 134 sample sites along two 18 km width transects that run across the urban center of Shanghai were investigated. We quantified the spatial patterns of plant diversity along the urban–rural gradient and measured the relationship between plant diversity and urbanization degree, which was calculated using a land use land cover map derived from high spatial resolution aerial photos. We recorded 526 vascular plant species in 134 plots, 57.8% of which are exotic plant species. Six spatial distribution patterns of species richness were identified for different plant taxa along the rural to urban gradient. The native plant species richness showed no significant relationship to urbanization degree. The richness of the all plants, woody plants and perennial herbs presented significant positive relationship with urbanization degree, while the richness of annual herbs, Shannon-Wiener diversity and Heip evenness all exhibited a negative relationship to urbanization degree. Urbanization could significantly influence plant diversity in Shanghai. Our findings can provide insights to understand the mechanism of urbanization effects on plant diversity, as well as plant diversity conservation in urban areas.

Keywords: spatial pattern; gradient analysis; plant diversity; urbanization degree; shanghai

1. Introduction

Urbanization has been accelerating for several decades at an alarming rate around the world. The world's population was nearly 7.6 billion as of mid-2017, and it was projected that 70% of the world's population increase would be concentrated in urban areas [1]. The urbanization level in China exceeded population by 54% at the end of 2018 (National Population Development Strategy Report). Cities have become increasingly important habitats for preserving biodiversity and homes for threatened and rare species [2,3]. However, urbanization associated with the habitat degradation and fragmentation, intense human activities and disturbances has led to biodiversity loss even extinction [4]. The urbanization impact on plant diversity is bringing about more and more concerns and has become a hot topic in urban ecology [5–8].

Urban–rural gradient manifests from the outer edge of a city towards the city's center, and it has been widely used to measure the variations of physical variables, habitat types, and biodiversity of cities and towns [9,10]. Spatial distribution patterns of plant species along the urban–rural gradient varies with different taxon in different cities: Some studies showed that non-native plant richness was higher in urban areas than that in rural areas [11], while some other studies found that total plant richness, native plant richness, and non-native species richness are lowest in urban areas [12,13]. Meanwhile, there also exists a phenomenon of a peak of weed richness between urban and rural areas [14,15], which tends to follow the intermediate disturbance hypotheses [16,17]. These results suggest that the distribution pattern of different plant taxon is not consistent along the urban–rural gradient. Therefore, how the plant species diversity of different taxon (e.g., life form, origin) vary along the urban to rural gradient needs further study.

Although urbanization is known to influence the distribution of plant diversity [18,19], the patterns of the plant diversity distribution vary significantly from study to study. Some studies found that the richness of total plants, including trees, shrubs and herbs are all highest in the areas with a moderate urbanization degree [20–22]. Wang et al. [23] found that the number of total species, native species and exotic species were all lowest in the areas with mid-urbanization degree, while the number of total and native plants are all highest in lowest urbanization degree, and exotic plant richness is highest in the areas with high urbanization degree. Other studies found that the total species richness and native species richness are all the highest in highly urbanized areas [24,25]. McDonnell and Hahs [26] reviewed studies on gradient analysis and summarized that there were at least six patterns of organism distribution along the urbanization gradient, i.e., no response, negative, punctuated, intermediate, positive, and bimodal responses, respectively (Figure 1). However, these are conceptual models derived mainly from the taxon of arthropods, insects, amphibians, birds, etc., and have seldom quantitatively been tested. There are relatively few studies showing only a linear relationship between urbanization degree and plant diversity. For instance, the richness of native plant and exotic plant species were shown to be positively related to urbanization degree [27,28]. However, Burton and Samuelson [29] found that woody plant species richness is negatively related to urbanization degree. Therefore, how different plant species diversity responds to urbanization needs further study.

As the largest and most urbanized city in China, Shanghai experienced huge landscape transformation and drastic land use/cover change in the past three decades [30]. Therefore, it is an ideal place to study the impacts of urbanization on plant diversity. In this paper, we aim to address the following questions: (1) What is the distribution pattern of plant species richness along the urban–rural gradient? (2) What is the relationship between plant diversity and urbanization degree?

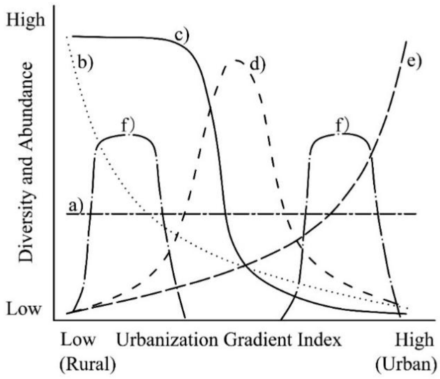

Figure 1. Responses of organisms to urbanization gradient. (**a**) no response, (**b**) negative response, (**c**) punctuated response, (**d**) intermediate response, (**e**) positive response, and (**f**) bimodal responses (Redraw from McDonnell & Hahs [26]).

2. Materials and Methods

2.1. Study Area

Shanghai lies in the eastern part of the Yangtze River Delta region and borders the East China Sea, located between 30°40′–31°53 N and 120°52′–122°12′ E with a territory area of 6340.5 km^2 and average elevation of 4 m above sea level (Figure 2). The registered population was 24.19 million by the end of 2016 [31]. Shanghai has a typical north subtropical monsoon climate with an annual mean air temperature of 16 °C and precipitation of 1200 mm. The original natural vegetation in shanghai is mixed forest composed of subtropical evergreen and deciduous broad-leaved trees, but it has been destroyed due to long-term intense human activities. Only a few remnant natural forest patches were left and distributed on hills such as Sheshan, Tianma, etc., and the offshore island of Dajinshan [32,33]. The current vegetation is mainly artificial forest and urban green spaces [34]. According to "*the plants of Shanghai*" summarized in 1999, there are 500 native plant species and 350 non-native species distributed in the city. However, in the past few decades, the non-native plant species has increased greatly due to the introduction of alien species into urban green spaces, while the number of native species has reduced rapidly, which can be attributed to urbanization [35].

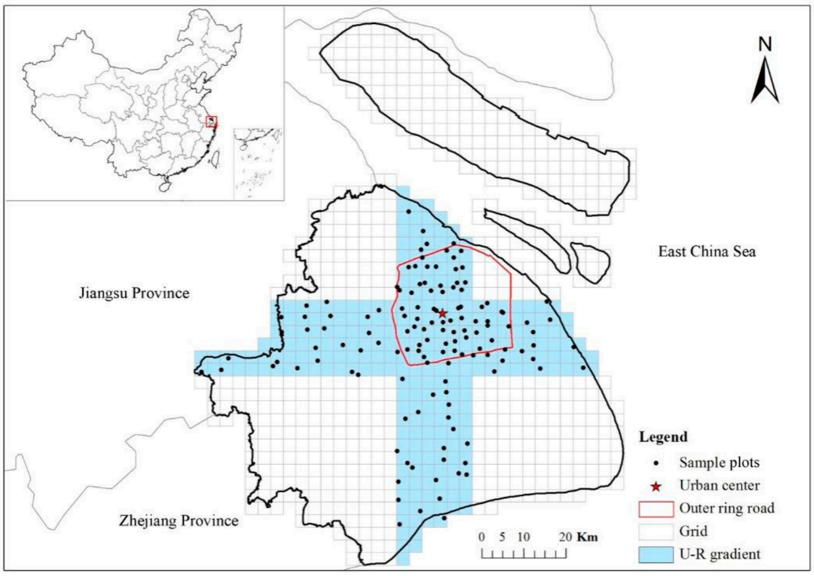

Figure 2. Study area, urban-rural transects and the distribution of sampling plots. The two transects are oriented east–west and oriented north–south, both cutting across the urban center (People Square).

2.2. Sampling Design and Plant Field Survey

To get spatially well represented and unbiased samples, the dual-density, randomized, tessellation-stratified design was used to obtain the samples [36], consisting of a grid of 3 km × 3 km squares. To the tessellation, the outer ring road as the boundary was superimposed to divide shanghai into high and lower developed urban areas. Considering the greater landscape heterogeneity within the urban core area, we use a sampling density of 3:1 inside/outside the urban core area, i.e., a random sample taken in every square inside and one sample in every third square outside the urban core area along two 18 km-width transects that run across the urban center in north–south and east–west directions, respectively. A total of 134 plots were sampled, of which 68 samples were inside and 66 samples were outside the urban core area (Figure 2).

A plant field survey was conducted from July to October 2014 using a further modified Whittaker sample plot on each sample site [37] (Figure 3). For those sample sites where there is less, even no vegetation to satisfy the minimum sample area (20 m × 50 m), we found another similar site to replace them within a 500 m radius circle. In the heterogeneous urban landscape, especially in the dense residential urban core area, it is not easy to find a place to set a sample plot with suitable size, such as 30 m × 30 m, 20 m × 20 m, or a 12 m radius circular plot [38], so we employed the modified Whittaker sample plot proposed by Stohlgren et al. [37], which was widely used to investigate plant diversity [39,40]. To make it more flexible in the dense residential urban area, we further modified the plot design to split the central subplot of 5 m × 20 m into two subplots of 2.5 m × 20 m (Figure 3). Each sample plot was located using a portable GPS; once the plot was set, it was fixed onto the high spatial resolution aerial photos to ensure the revisit. Species richness and their abundance or coverage of all vascular plants founded in each plot were recorded. Plant species was identified in reference to the Flora of shanghai [34], the Checklist of Shanghai Vascular Plants [41] and Flora of China [42]. When the records of plant species were not the same in different plant reference books, the Flora of China was used as the standard reference. Plant species were categorized into different taxa, i.e., woody and herbaceous plant, and the herbaceous was further classified into annual and perennial species in terms of life form, and native and exotic species according to their origin.

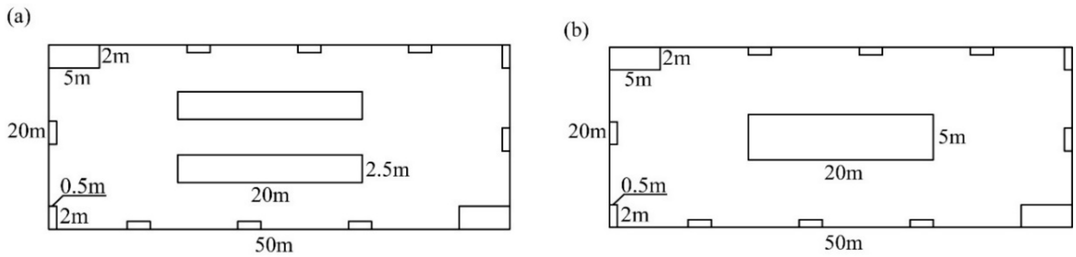

Figure 3. Modified Whittaker Sampling plot. (**a**) Our further modified plot based upon Stohlgren et al.'s modification; (**b**) Stohlgren et al. [37] modified Whittaker plot.

2.3. Plant Diversity Index Calculation

Three plant diversity indexes were calculated for each sample plot including species richness, Shannon-Wiener diversity and Heip evenness. The Shannon-Weiner index is a widely used measure of diversity [43]. Wilsey and Stirling [44] suggested that evenness and richness could be affected by different ecological processes and suggest that both indices should be measured in plant diversity studies. Meanwhile, Heip evenness index measures how well the abundance distributed among species within a community [45,46], especially in highly heterogenous urban areas. As suggested by Jost [47], the value of Shannon-Wiener diversity gives uncertainty. So the exponential conversion of Shannon-Wiener diversity was calculated to intuitively measure the effective numbers of species in this paper. Further, Heip evenness was also exponentially transformed. The Shannon-wiener diversity indices and the Heip evenness of plant species were calculated using the following formulations [47,48]:

$$H' = \exp(-P_i \ln P_i) \tag{1}$$

where, H' is Shannon-Wiener diversity, and P_i is the relative abundance of each species.

$$E_{heip} = \frac{H' - 1}{S - 1} \tag{2}$$

where, E_{heip} is Heip evenness, and S is the sum of the total species abundance.

2.4. Urbanization Degree Calculation

Urbanization degree can be measured by the percentage of urban population or the proportion of total urban land use types, such as traffic road, residential areas, industrial land, public facilities, etc. Here we used the latter as the indicator of urbanization degree in Shanghai. To calculate the urbanization degree of each sample site, we used a 1km-radius circle to overlap upon the land use land cover map, which was derived from high spatial resolution aerial photos of Shanghai in 2013, according to the land use land cover classification system proposed by Li et al. [30]. We combined the land use types of industry, traffic road, public facilities, residential, and the construction site into the type of urban land use; and finally five land use land cover types were obtained (Table 1) and used to calculate the urbanization degree (UD) around each sample site using Equation (3):

$$\text{UD} \frac{S_{urban\ land}}{S} \tag{3}$$

where, $S_{urban\ land}$ is the area of urban land use type, and S refers to the total area of the 1 km radius circle around each sample plot.

Table 1. Classification of land use land cover (LULC) type.

LULC Type	Subtype of LULC
Urban land	Industry land, traffic land, public facility land, residential land, in construction land, etc.
Green land	Park, botanic garden, zoo garden, forest
Agriculture land	Farmland, orchard, nursery
Water	River, lake, pond and wetland
Other land	Unused land and Wasted land

2.5. Data Analyses

Gradient analysis, which was proposed by Whittaker and Niering [49], has been widely used to investigate the effect of urbanization on plant distribution [50], ecosystems characteristics [51], and landscape patterns [30,52]. In this paper, gradient analysis was employed to examine the distribution pattern of plant species diversity along the four rural-to-urban transects. Regression analysis was used to explore the relationship between urbanization degree and plant diversity. When several fitting models existed, to well quantify the relationship between urbanization degree and plant diversity, the minimum Akaike information criterion (AIC) was used to select the best one. This was calculated in R 3.4.1 [53]. The figures were produced using the SigmaPlot (version 12.5) and Origin (version 8.0).

3. Results

3.1. General Plant Species Composition

We recorded 526 vascular plant species that belong to 114 families and 364 genera in our 134 sample plots. There were 183 woody plants and 343 herbaceous plants, among which annual and perennial herbs were 192 and 151, respectively. Among these vascular plants, there are 222 native species, and 304 exotic species including the cultivated plant species, accounting for 44.4% and 93.4% of the total native and exotic species in Shanghai, respectively. The exotic plant species exceeds the native ones and accounts for 57.8% of the total recorded species.

3.2. The Distribution Pattern of Plant Diversity along the Urban to Rural Gradient

For easy comparison, polynomial curve fitting was utilized to quantify the spatial distribution patterns of plant species of different taxa along the urban–rural gradient. Urbanization degree showed approximately a symmetric pattern along the west–east and the south–north urban-rural transects where the urbanization degree peaked in the urban center and decreased gradually from urban to rural areas, except for a little valley near the east and south rural end, respectively (Figure 4).

Plant species richness of different growth forms exhibited different patterns along the four urban–rural transects (Figure 4). For the total plant species richness, there are no significant changes along the urban–rural gradient on the west, south and north parts of the transects, respectively, only a bimodal pattern exhibited along the eastern urban–rural gradient and a fourth-order polynomial were presented (Figure 4A,a). The woody plant species richness presented a cubic polynomial and linear decreasing pattern from the urban to rural area along the west, east and south transects, but no particular quantitative patterns along the north transect (Figure 4B,b). The annual herbaceous species richness showed up as a unimodal spatial pattern along the western and eastern urban–rural transects, and as a linear increasing pattern from urban to rural on the northern transect (Figure 4C,c). The perennial herbaceous species richness exhibited a linear, quadratic and fourth-order distribution pattern on the western, southern and eastern transects, respectively (Figure 4D,d). All the fitting equations of the spatial pattern are presented in Table 2.

Table 2. The fitting equation's spatial patterns of different plant growth forms along the urban–rural gradient.

Variables	Equation	Parameters
Urbanization (W - E)	$y = 73.81 - 3.71x - 0.81x^2 + 0.07x^3 + 0.006x^4 - 2.35e^{-4}x^5 - 1.54e^{-5}x^6$	$R^2 = 0.89$, $p = 2.08e^{-07}$
Urbanization (S - N)	$y = 74.47 + 0.68x - 0.59x^2 - 0.002x^3 + 0.002x^4$	$R^2 = 0.86$, $p = 3.80e^{-08}$
All plant - E	$y = 54.85 + 11.64x - 4.95x^2 + 0.68x^3 - 0.03x^4$	$R^2 = 0.79$, $p = 0.032$
Woody plant - W	$y = 23.07 + 3.87x + 0.37x^2 + 0.01x^3$	$R^2 = 0.74$, $p = 0.005$
Woody plant - E	$y = 22.15 - 2.41x + 0.13x^2$	$R^2 = 0.50$, $p = 0.015$
Woody plant - S	$y = 20.50 + 1.11x$	$R^2 = 0.48$, $p = 0.002$
Annual herb - W	$y = 13.54 - 3.55x - 0.2x^2$	$R^2 = 0.54$, $p = 0.020$
Annual herb - S	$y = 14.60 - 4.11x - 0.20x^2$	$R^2 = 0.56$, $p = 0.003$
Annual herb - N	$y = 12.82 + 2.54x$	$R^2 = 0.71$, $p = 0.004$
Perennial herb - W	$y = 15.31 + 0.53x$	$R^2 = 0.67$, $p = 0.0006$
Perennial herb - E	$y = 14.52 + 6.60x - 2.77x^2 + 0.35x^3 - 0.01x^4$	$R^2 = 0.79$, $p = 0.032$
Perennial herb - S	$y = 17.37 + 0.84x + 0.04x^2$	$R^2 = 0.36$, $p = 0.046$

W: West; E: East; S: South; N: North.

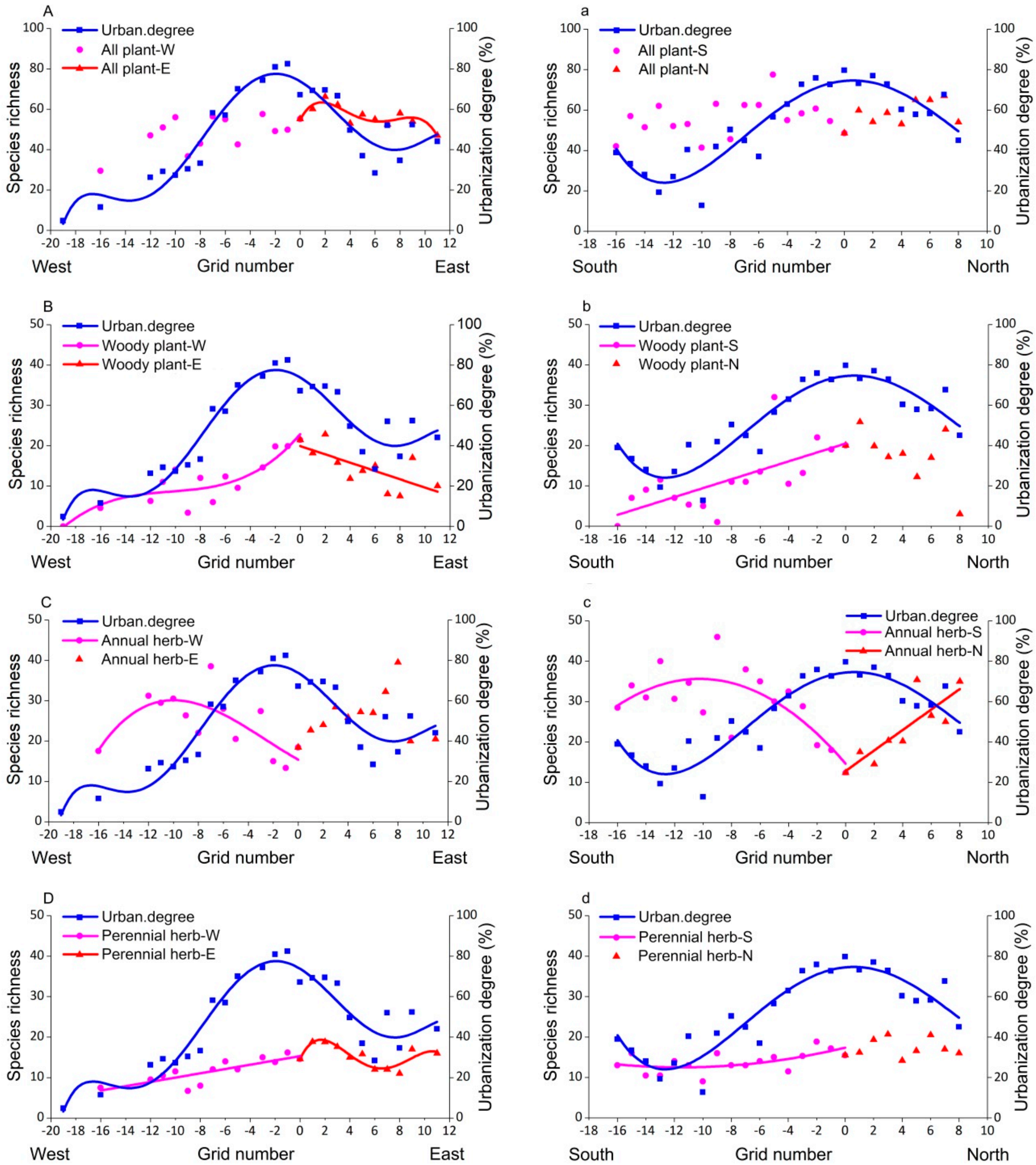

Figure 4. The spatial pattern of plant species richness along the urban–rural gradient. (**A**,**a**) All plants, (**B**,**b**) Woody plant, (**C**,**c**) Annual herb, (**D**,**d**) Perennial herb.

The native plant species richness did not show an evident pattern along any of the four urban–rural transects (Figure 5A,a). The exotic plant species richness showed a cubic and four-order pattern along the west and east urban–rural transect, respectively, but not any significant pattern along the south and north transects (Figure 5B,b). The fitting models are shown in Table 3.

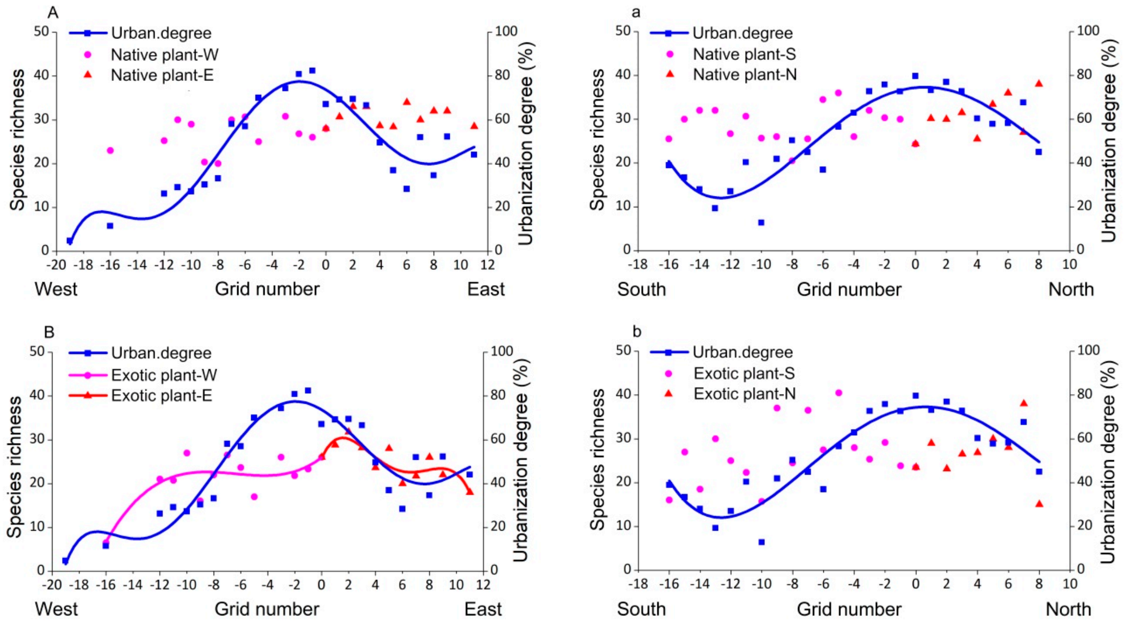

Figure 5. The spatial patterns of native and exotic plant species richness along the urban–rural transects. (**A**,**a**) Native plant, (**B**,**b**) Exotic plant.

Table 3. The fitting models of native and exotic along the urban–rural gradient.

Variables	Equation	Parameters
Exotic plant - W	$y = 25.93 + 2.29x + 0.4x^2 + 0.02x^3$	$R^2 = 0.67$, $p = 0.016$
Exotic plant - E	$y = 25.73 + 6.95x - 3.14x^2 + 0.43x^3 - 0.02x^4$	$R^2 = 0.75$, $p = 0.047$

3.3. The Relationship between Plant Diversity and Urbanization Degree

The relationship between plant diversity and urbanization degree show that the species richness of total plants increased linearly with urbanization degree ($R^2 = 0.0321$, $p < 0.05$); however, the urbanization degree has very limited capability to explain the variation of the total species richness (Figure 6a). Woody plant species richness quadratically increases with urbanization degree ($R^2 = 0.3596$, $p < 0.01$) and urbanization degree explains nearly 36% of the variations of woody species richness (Figure 6b). Among the herbaceous plants, the annual herb species richness quadratically decreases with the increase of urbanization degree ($R^2 = 0.2499$, $p < 0.01$) (Figure 6c). On the contrary, the perennial herb species richness linearly increases with urbanization degree ($R^2 = 0.2805$, $p < 0.01$) (Figure 6d). There is a positive quadratic relationship between exotic plant species richness and urbanization degree ($R^2 = 0.0896$, $p < 0.01$), but no significant relationship exists between native species richness and urbanization degree (Figure 6e,f). The Shannon-Wiener diversity index declines quadratically with urbanization degree ($R^2 = 0.0699$, $p < 0.01$), while the Heip evenness decreases linearly with urbanization degree ($R^2 = 0.1463$, $p < 0.01$) (Figure 6g,h).

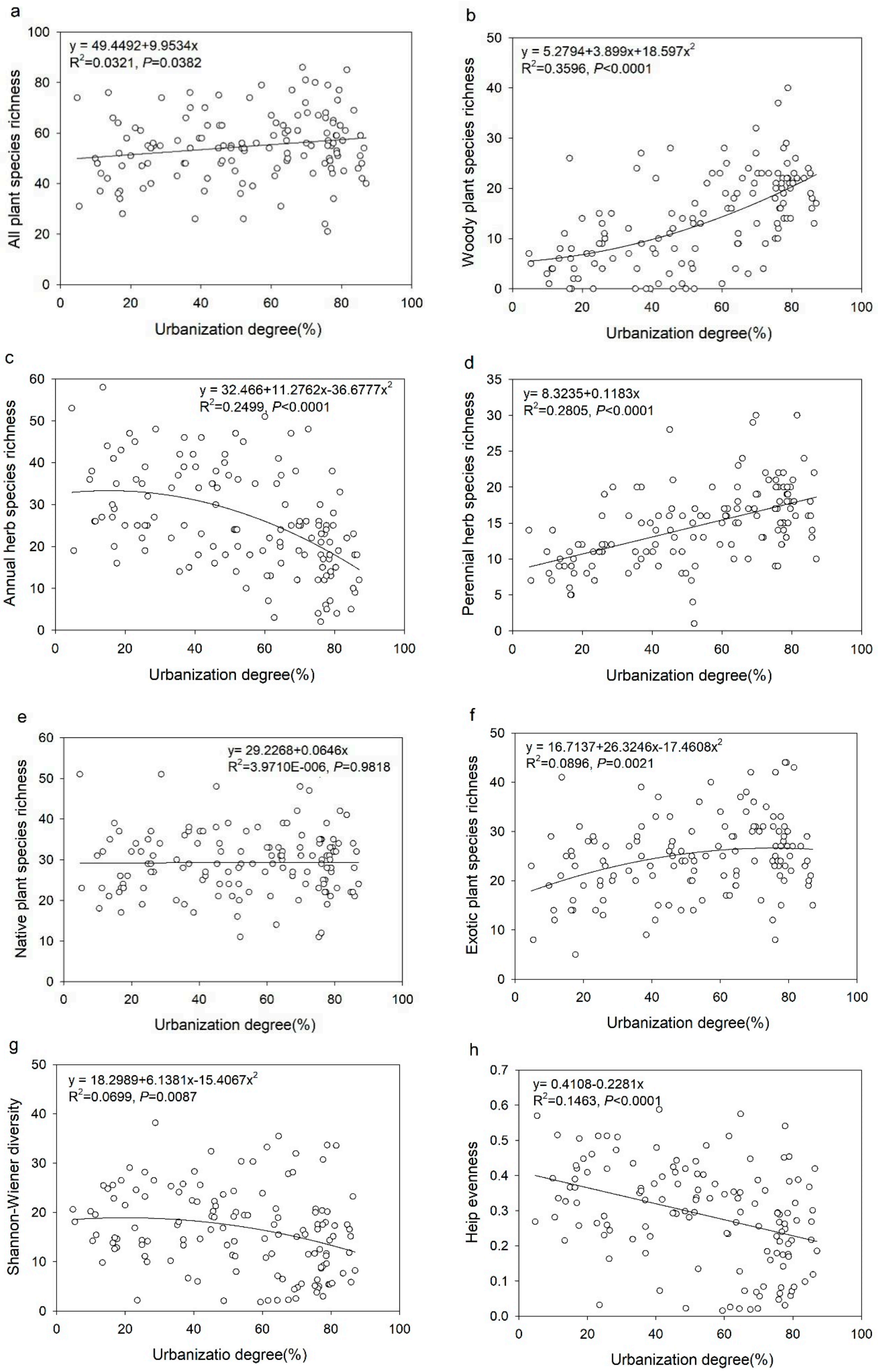

Figure 6. The relationship between urbanization degree and plant species richness. (**a**) All plants, (**b**) Woody plants, (**c**) Annual herb, (**d**) Perennial herb, (**e**) Native plant, (**f**) Exotic plant, (**g**) Shannon-Wiener diversity, (**h**) Heip evenness.

4. Discussion

4.1. Multiple Patterns of Plant Species Diversity along the Urban-rural Gradient

Our study reveals several spatial distribution patterns of plants, i.e., no responses, linear increasing, linear decreasing, unimodal, bimodal, and punctuated increasing co-existed for different plant taxon along the rural–urban gradient in Shanghai, which has never been reported before. This coexistence of multiple spatial patterns of plant diversity along the urbanization gradient may be due to the following reasons: First, Urban landscape is of high heterogeneity, which provides numerous habitats for various plant species [30,54–56]. Second, urban areas, especially along the urban–rural transect, usually have diversified land use land cover types, and the diverse land use land cover types and their spatial compositions undoubtedly enhance plant diversity [57–60]. Third, urban socioeconomic conditions, cultural diversity and land use management are important factors that influence plant diversity patterns along the urban–rural gradient [36,61–65]. All these factors may simultaneously function to determine plant diversity [66]. Fourth, the heterogeneous urban areas could have a hierarchical filtering effect on plant diversity [67], which could occur on plant functional, taxonomic, and polygenetic levels [68] through various mechanisms, such as land use and habitats, and even landscape [69–71] and environmental factors [72–74].

There is a general trend that plant species richness is higher in areas with higher urbanization degrees than rural areas in our study. This may due to the pre-existing biodiversity hotspots in the city [75] and/or intentional or unintentional import of exotic plants in the central urban areas throught urban landscape management [11,76,77]. Each plant taxon exhibited a specific spatial distribution pattern along the urban–rural transect in Shanghai. The woody and perennial herbaceous plants exhibited highest species richness in the central urban area (Figure 4), which is similar to what was found in Beijing [78]. Compared to the rural area, the urban green spaces usually dominated by artificial vegetation in Shanghai, and similarly more woody plant species and perennial herbs have been found in European cities because of the human and landscape architect's preference and landscape designs [79,80]. The annual herbaceous plants exhibit unimodal distribution with the peak occurring in urban to rural transition zones, the so-called ecotone where intermediate disturbances and highly fragmented and heterogeneous landscape existed [30]. This is similar with the previous report where ruderal species presented highest richness in the transition areas between urban and rural interfaces in the same city of Shanghai due to high diversity of habitat and environmental factors [14]. Furthermore, many annual herbs are crop species, which were mainly recorded in agriculture land in the suburbs, while the majority of annual herbs in central urban areas are weed and exotic flowers, which are frequently removed by intensive green space management activities, resulting in lower species richness. We found no evident spatial pattern for native plants in shanghai probably because native plant species have evolved and proved to be more adaptive and competitive than the non-natives which colonized or were artificially introduced in the urban areas [81]. In addition, the exotic plant species along the north and south urban–rural gradient also exhibited no distinct patterns. This may be due to a decades old landscaping policy in Shanghai that allows the new green to utilize both the indigenous plant and the introduced alien plant species [82].

4.2. The Impacts of Urbanization on Plant Diversity

Urbanization could influence plant diversity, such as reduce native plant species richness, increase exotic plant species richness, structural and functional alteration [83–86], etc. at local, regional and global scales [87,88], ultimately leading to biota homogenization [25,89–91]. This study showed how the urbanization degree influences plant diversity of different taxon. It is very necessary and important to understand the underlying process of urbanization on plant diversity, which was less well addressed before. Previous studies founded a positive linear relationship [27] and negative linear relationship between urbanization and plant diversity. We found a diversity of relationships (linear model, quadratic polynomial model, and no relationship) between urbanization and plant diversity in this study, which deeply enriches the theory of plant responses to urbanizations.

Our study reveals that spatial relationships existed between urbanization degree and a diversity of different plant taxa except for native plant species. The relationship between woody plant species richness and urbanization degree follows a binomial pattern. The richness of woody plant increased sharply with the increase of urbanization degree. This is mainly due to a high demand for urban greenspaces, where big woody plants are preferred by planners or local governments to quickly create greening landscapes. This was a very common phenomenon during urban greening in other cities in China in the past decades. Perennial herbaceous species richness increased with urbanization degree and may be due to the following mechanisms: (1) perennial herbs' survival strategies are more adaptive and persistent to the highly disturbed urban environment, and (2) some of the perennial herbs are ornamental species preferred by landscape managers in urban residential areas in Shanghai. The annual herb richness quadratically changed with urbanization degree and the highest value occurred at the moderate urbanization degree. This can be explained by intermediate disturbance hypothesis or other urban-related disturbances, similar to previous studies in Chinese cities [14,92,93]. In addition, the majority of the annual herbs we recorded are ruderal species, which evolve with different survival strategies to diverse habitats and multiple disturbances [94–96]. Exotic plant species richness exhibited a slightly negative quadratic relationship with urbanization degree, which means the introduction of an exotic plant could increase the total plant species richness associated with the urbanization process, which was also demonstrated by previous studies [75,97]. All these patterns of different plant taxa work together to result in a weak but significant linear increase of total plant species richness with urbanization degree. The Shannon-wiener diversity and evenness that both decreased with urbanization degree may be due to landscape fragmentation [30]. A similar result was reported by Lopez et al. [68] who utilized the structural equation model to analyze and found that most diversity indices decline with urbanization, which could be explained by four biodiversity filters of habitat transformation, fragmentation, the urban environment, and human preference. However, further study is needed to compare the situation in Shanghai with the Lopez et al.'s work in the Research Triangle area of North Carolina, USA.

Many previous studies, which aim to quantify the impacts of urbanization on urban plant diversity, have encountered the question of how to quantitatively measure the urbanization degree. For example, Hahs and McDonnell [98] selected four indices, i.e., combined Index, the ratio of people per unit urban land area, landscape shape index, and dominant land-cover from 17 commonly used variables of covering demographic, physical and landscape variables, to capture and quantify the urbanization patterns along Melbourne's urban–rural gradient. Some studies only coarsely divided urbanization into three levels of urban, suburban and peri-urban based on landscape composition in Strasbourg, eastern France [24], or into urban, suburban and exurban using human density and a proportion of the built-up area by Wang et al. [23] in Beijing, China. Some other studies used the surrogate index, such as distance from urban center [11,99] or ring road surrounding urban areas [14,22] to indirectly measure the urbanization degree. All these indices are an indirect representation of urbanization degree. However, the most frequently used measurement of urbanization is quantified by the urban population percentage and/or urban land use proportion, which also reflects the percent of impervious surface in the city. The former mainly links to the socio-economic dimension of urbanization and the latter focuses more on urban biophysical and environmental factors. These two kinds of indices are more straightforward and easily obtained from urban census data or retrieved from remotely sensed data, which have been widely utilized to study urbanization and their relationships to, or impacts on urban biodiversity [72,100–103]. Compared with most of the previous studies, our study directly used the urban land use proportion to quantify the urbanization degree and established a quantitative relationship to plant species diversity that can help easily understand and predict the influences of urbanization on plant diversity; therefore, this study can provide insight to optimize ecosystem services in future urban green space planning and design [104–106]. Apart from urbanization degree, several mechanisms such as social-economic factors (e.g., population density) [66]; landscape factors, such as land use types [107] or the type of building, especially for residential use (high-rise buildings, city blocks, attached or individual houses, etc.) [82]; and environmental factors, such as climate variables [108] or soil conditions [109] could have a considerable influence on both the distribution pattern and plant species richness, and even the relationship between the plant diversity and urbanization degree; therefore, future studies are still needed to quantitatively explore the underlying mechanisms.

5. Conclusions

We investigated 134 plots along four urban–rural transects in Shanghai to explore the spatial patterns of plant diversity and their relationship with urbanization degree. We recorded 526 vascular plant species from these plots, nearly 60% of which are exotic species. We found that six kinds of spatial distribution patterns of different plant taxa co-existed along the urban–rural gradient. The total plant, woody, perennial herbs, and exotic plant richness positively increase with urbanization degree, while annual herb richness, measured by Shannon-Wiener diversity and Heip evenness, decreased with urbanization degree. The relationships can be classified into linear, quadratic polynomial, or random for different plant taxa. These findings could provide insights for urban green space planning and plant biodiversity conservation in urban areas in Shanghai. However, the underlying mechanisms of the urbanization degree and plant diversity need further study.

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