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Drivers of Spontaneous Plant Communities in Urban Parks: A Case from Nanjing, China

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Abstract: Urban plant diversity is one of the key elements for sustainable urban development. Urban plant landscapes not only create a variety of experiences for residents but also have a positive effect on their physiology and psychology. In order to better introduce nature into urban green spaces, this study conducted a field survey in Nanjing, China, to analyze the current situation of spontaneous plants in Nanjing's urban green spaces and propose a plant planning strategy that takes into account both ecology and residents' well-being. This study surveyed the herbaceous plant resources in 96 sample plots in nine typical urban parks in Nanjing, and recorded 284 plant species in 192 genera and 78 families. The research results show that the differences in plant diversity, richness, and evenness among urban parks in Nanjing are significant; combined with cluster analysis and ranking results, the total area of urban parks, green space construction time, lighting conditions, and management frequency have an impact on plant communities. Further analysis of the species composition of plant communities showed that moderate management frequency in urban parks can increase plant diversity. With the advantages of both high ecological benefits and low management costs, a model of "artificial plants + native spontaneous plants" was finally proposed for the planting of herbaceous plants in sustainable urban green spaces.

Keywords: biophilic city; plant diversity; spontaneous plant community; sustainability

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1. Introduction

Rapid urban expansion has led to problems such as urban green space loss and fragmentation [1] and ecological degradation [2]. In the previous urbanization process, due to the lack of overall ecological planning, urban green spaces were gradually divided into small areas by hard spaces such as residential, commercial, and industrial areas. This has resulted in environmental injustice and green gentrification [3,4], which have a negative impact on the well-being of urban residents and sustainable urban development. To address the various problems caused by urbanization and make cities sustainable, experts and scholars have proposed biophilic urbanism [5,6], nature-based solutions [7], urban rewilding [8,9], and other urban regeneration strategies that pay more attention to the ecology of cities and communities from different perspectives.

The aim of biophilic urbanism is to integrate as much nature as possible into the human living environment [10,11], emphasizing the impact of nature on citizens, including psychological feelings [12,13], physical health [14,15], well-being [16], etc. This theory was initially widely used in the design of urban buildings, and later, this perspective was introduced into urban and community planning. Despite the rapid development of science and technology, sustainable cities can combine various smart means to influence the citizens' experience, but nature has always been the most irreplaceable component of sustainable cities. Meanwhile, the concepts of "urban wilderness" and "rewilding" have become popular in China. Strictly speaking, true "wilderness" cannot exist in urban areas [17]; however, elements of wilderness can be integrated into urban and peri-urban areas through natural processes [18,19], thereby enhancing human health and quality of life. From this perspective, "rewilding" is consistent with biophilic urbanism. Introducing "wilderness" into the city can increase the diversity of urban green habitats and avoid the homogenization of urban plant landscapes, which has positive implications for landscape planning under sustainable development [20].

Many studies have shown that there is some correlation between the characteristics of urban green spaces and the mental health of residents. The size of green spaces is positively correlated with the mental health of residents [14]. Landscape heterogeneity can also effectively influence tourists' perception of green spaces [21]. Although few studies have proposed a direct link between biodiversity and residents' well-being [15,22], some studies have also mentioned that increasing urban biodiversity can effectively improve the well-being of some residents [22,23], and herbaceous plants in urban green spaces are more attractive to tourists than fountains and other features [12,13]. Increasing plant diversity can therefore help to improve urban residents' perception of living things and their positive perception of urban green spaces.

Spontaneous plants are a major contributor to urban plant diversity. Studying the diversity and community composition of urban spontaneous plants can provide material for plant planning in biophilic city design and become one of the measurement indicators of a biophilic city. Spontaneous plants are those that can self-sow and thrive in urban environments [24]; these plants are not directly affected by urban construction and artificial planting activities [25], often referred to in studies as spontaneous flora [26], spontaneous plants [27], and spontaneous vegetation [28]. The category of spontaneous plants often overlaps with that of native and wild plants, with the narrow definition of spontaneous plants emphasizing the spontaneity of plant growth and the urban habitat's specificity of the growing environment.

Spontaneous plant landscapes offer the advantages of low maintenance and low cost; hence, they have been extensively researched and practiced worldwide [29,30]. Research on spontaneous plants has been ongoing for many years, with common research methods including field surveys or measuring spontaneous plant areas based on remote sensing technology to construct ecological models [31]. Numerous scholars have conducted in-depth studies and discussions on the diversity of spontaneous plants and environmental impact factors across different regions, proposing multiple environmental conjectures. The variation in species, apart from human disturbances within the patches, may be related to urbanization [32,33]. Urbanization is often a complex process; under the mutual interaction between spontaneous plants and urban environments [34], green patches in cities are interconnected to form a dynamic ecological network [35]. Beyond large areas of remaining mountains and bodies of water [36,37], even small green spaces can provide temporary habitats for certain species [38–40].

Currently, the research methods for studying the diversity and community composition of spontaneous plant species often resemble those used in plant diversity [41–43] and community ecology [44,45]. The study of plant diversity involves many influencing factors, such as soil conditions [46], altitude [47], green space patches [48,49], canopy closure [50], and the process of urbanization. Beyond examining the driving factors affecting plant diversity [51–53], constructing a landscape evaluation system for plant communities has also become a research focus. In complex urban ecosystems, some species with distinct characteristics find it hard to adapt to new habitats, resulting in decreased opportunities for their emergence [54]. Human management practices directly affect plant growth; hence, the level of diversity of spontaneous plants varies between different types of green spaces. Research on spontaneous plants in Nanjing's urban green spaces primarily focuses on highly human-disturbed sites such as urban road green spaces, urban vacant lands, residential areas, universities, and on the city's remaining mountains [55], bodies of water [56], and historical relics [57], with fewer studies reported on urban parks. Driven by human interference and changes in urban biology, urban plants have formed new combinations [58]. Investigating the types and compositions of spontaneous plants in urban parks can help us understand how artificially planted plants and spontaneous plants recombine to form new communities within urban environments.

To explore the relationship between the herbaceous spontaneous plant communities and urban green areas, this study, based on field surveys of nine urban parks in Nanjing, records the data of spontaneous plants in various habitats within these parks. The recorded herbaceous spontaneous plants include herbaceous plants and woody plant seedlings within the sample plots. Unlike existing studies on spontaneous plants in Nanjing's urban parks [59], this paper adopts an ecological perspective to study the community of spontaneous plants in the herbaceous layer of urban parks. The Unweighted Pair Group Method with Arithmetic Mean (UPGMA) cluster analysis and Canonical Correspondence Analysis (CCA) ordination methods are used to analyze the species composition, diversity characteristics, and community classification of spontaneous plants in the herbaceous layer of Nanjing's urban parks. Furthermore, the relationship between park features and the communities of spontaneous plants in the herbaceous layer of urban parks is explored, providing references for planning strategies for plant landscapes in sustainable cities.

2. Methods

2.1. Study Area

The study area is located in Nanjing City, Jiangsu Province, China (118° 22′~119° 14′ E, 31° 14′~32° 37′ N). Nanjing is the provincial capital of Jiangsu Province, with a maximum east–west span of about 70 km and a maximum north–south length of about 150 km; the municipal area is elongated from north to south and narrower from east to west. The northern and central regions are characterized by yellow–brown soils, while the southern region bordering Anhui Province consists of red soils. It is located in the north subtropical zone and has a north subtropical monsoon climate, with distinct seasons, abundant rainfall, and a significant annual temperature difference, and it is one of the richest regions in plant resources in southeastern China [60].

Besides climatic advantages, Nanjing is characterized by low mountains, hills, and hillock terrains, which account for 65% of the city's total area, and the Yangtze River runs through the city, forming a pattern of two main urban areas, south and north of the river. Under the current trend of rapid urbanization, Nanjing, as one of the few cities in China with a century-long planning history, still retains some of its historic urban green spaces in the main urban area. These urban green spaces, beloved by city residents and mostly open in the form of city parks, have witnessed the modern development of Nanjing while preserving habitats for various urban species.

According to the green space planning of Nanjing City [61], the selection of sample sites was confined to urban central parks. By integrating the catalog and current status of urban parks in Nanjing City, a list of main urban district parks divided by administrative regions was compiled. Parks were classified based on their location and size, and from each category, nine representative and evenly distributed parks were selected using a systematic sampling method (Figure 1, Table 1).

The total area of the nine parks studied (Table 1) is approximately 6.70 km^2. As of 2023, five of these parks were constructed within the last 10 years, while two parks have been around for nearly 100 years. Parks that have been established for more than ten years are distributed in a ring around the area of Nanjing's ancient city wall, while those built within the last ten years are mainly located on the outskirts of the ancient wall area, close to the remaining mountains or bodies of water in the city. Overall, the older the park, the closer it is to the city center, and the higher the frequency of management.

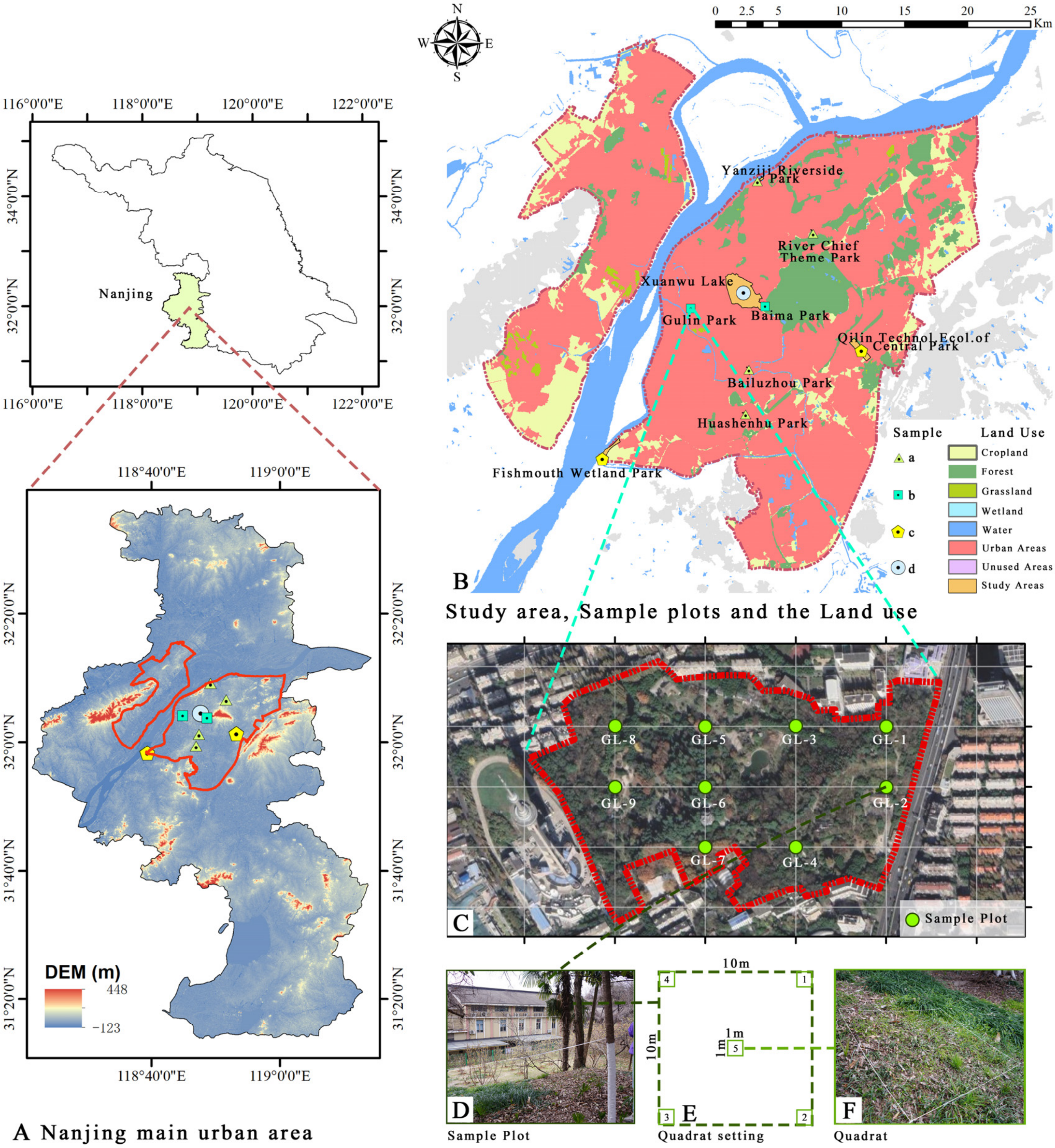

Figure 1. Study area, sample plot selection, and quadrat setting. (**A**) Boundary data of China's municipal administrative divisions derived from the Resource and Environmental Science Data Registry & Publishing System [62]. (**B**) Study area boundaries, sample plot location, and land cover class. Land cover class map from the National Geographic Information Resources Catalogue Service System (www.webmap.cn, accessed on 26 April 2024). (**C**) Boundaries based on Maps data (©2023 Google), representing the layout of sample plots in Gulin Park. (**D**–**F**) Relationships between sample plots and quadrats.

Table 1. The overall situation of the park.

Park	Abbreviation	Construction Time	Area Size (km^2)	Park Type	Number of Sample Plots	Number of Quadrats
Bailuzhou Park	BL	1929	0.12	A	8	40
Gulin Park	GL	1984	0.27	B	9	45
Baima Park	BM	2000	0.33	B	10	50
Xuanwu Lake	XW	1928	4.68	D	30	150
Yanziji Riverside Park	YJ	2019	0.13	A	9	45
River Chief Theme Park	HZ	2020	0.05	A	5	25
Huashenhu Park	HS	2019	0.11	A	8	40
Qilin Technol. Ecol. of Central Park	QL	2021	0.39	C	9	35
Fishmouth Wetland Park	YZ	2014	0.64	C	10	50

2.2. Data Collection

2.2.1. Sample Plot and Quadrat Setting

After identifying the nine park sample sites, we conducted a plant survey of these parks from February to August 2023. For uniformity in sample selection, we adopted a grid system sampling method, utilizing map software such as Google Earth 2023 and ArcGIS 10.6, to set grids along the true north and true south directions for dotting the park areas. Due to the large differences in land area among the nine parks, we classified the parks according to their size and set corresponding grid scales to ensure that the number of sampling points in each park was proportionate to its area, allowing the plant data collected from the survey to be more comprehensive and representative of the habitat types. Parks with an area of 0.05~0.20 km^2; were classified as type A parks, those with an area of 0.20~0.35 km^2 as type B, those with an area of 0.35~0.65 km^2 as type C parks, and those with an area larger than 0.65 km^2 as type D parks. Finally, the grid size was set to 50~100 m for type A parks, 100~150 m for type B parks, 150~200 m for type C parks, and 200~250 m for type D parks (Table 1).

Grid intersections were selected as the central locations for the sample plots. Considering the different layouts of hard impermeabilized soil, green space, and water areas in parks, grid intersections in areas not covered by vegetation were excluded. Based on the predetermined geographical coordinates of each sample plot, locations were determined using the handheld GPS device "Zhuolin A8", adjusting the actual positions of the research sample plots as necessary. If a sample plot was inaccessible or enclosed, it was appropriately relocated within 20 m of the surrounding area or removed entirely. Sample plots were set at random grid intersections, and, after adjustments and screening, we ensured that each quadrat achieved a coverage of 50% or above; thus, each sample point could be considered as a small green patch within the park.

A quadrat survey of the plant community was conducted at each sample plot in the park, i.e., at the grid intersections. The geographical location, topography, climatic conditions, soil status, vegetation conditions, and human activity status of the sample plots (Figure 1C–F) were described qualitatively or quantitatively. Centered on the sample point, a 10 m $\times$ 10 m tree and shrub quadrat was set up, recording the species, number of individuals, height, canopy width, and diameter at breast height (DBH) of the trees and shrubs within it. Within each tree and shrub quadrat, five 1 m $\times$ 1 m herbaceous layer quadrats were placed at the four corners and the center of the sample plot. The quadrat at the center of the sample plot was designated as number 5, with the other four quadrats, located at the northeast, southeast, southwest, and northwest corners of the sample plot, numbered 1, 2, 3, and 4, respectively, in a clockwise direction. The species, height, abundance, cover, and phenological characteristics of the herbaceous layer present were recorded, serving as the base data for analysis at each sample plot. Ultimately, after excluding large water bodies and hard impermeabilized soil areas in the parks, this study surveyed 96 10 m × 10 m tree quadrats and 480 1 m × 1 m herbaceous layer quadrats. We used a 20 m tape measure and a 1 m rope to determine the extent of the quadrat.

In urban parks, artificial plant communities are often fertilized and watered, so the soil is rich in chemical fertilizers [63]. These chemicals have a negative impact on the ecosystem, but for spontaneous plants, the soil is fertile enough to support them throughout their life cycle [64,65]. These green spaces provide a temporary habitat for spontaneous vegetation until the next routine maintenance of the park (e.g., mowing of lawns, spraying of herbicides and insecticides, etc.). Due to their resilient vitality [39,66], these spontaneous plants can quickly occupy the ecological niches left vacant by artificial communities and coexist temporarily with artificially planted plants. Therefore, it is difficult to exclude artificially planted plants in the herbaceous layer when studying urban spontaneous plant communities. Apart from artificially planted herbaceous layer plants, some scholars [67] consider that trees and shrubs of the overstory layer are also significant factors affecting the species and distribution of understorey spontaneous plants; hence, the conditions of trees and shrubs at the sample sites are also included in the survey.

2.2.2. Classification and Definition of Park Features

Prior to the field survey, it is necessary to clarify the types of park features for each sample point and their definitions. This study sets influence factors on two levels (Table 2).

Table 2. Park features used in this study.

Scale	Park Feature	Description	Range
Park level	construction time	number of years from completion of the park to 2023 (y)	1–100
	park area	park type, which describes the size of the area	A/B/C/D
	park location	variable describing the park's relative distance from the city center	0–1
	distance from the park to mountain	distance to the nearest mountain in the center of the park (km)	0.00–6.00
	distance from the park to water	distance to the nearest river in the center of the park (km)	0.00–1.00
Habitat level	types of plant spatial structure	complexity of plant spatial structure	1–4
	habitats	habitat condition of sample point in the park	HR/HG/RG/GG/RR/GW/RW/HW
	slope	sample point slope grade	1–3
	human disturbance	impact of tourists on habitats	1–5
	management frequency	frequency of thinning of spontaneous plants in the herbaceous layer	1–4
	sunshine condition	lighting conditions in the habitat under the influence of buildings	1–3
	tree canopy closure	estimating the canopy cover of the tree layer	0–10

Firstly, from the overall perspective of the park, statistics such as park area [68], construction time, park location, distance from the park to mountains, and distance from the park to water bodies [46] are gathered. Secondly, at the sample point level, different habitats are classified. Parkland has four land attributes: Hard, Green, Road, and Water. Community habitats are defined by combining land attributes where they are located (HR = Hard–Road; HG = Hard–Green; RG = Road–Green; GG = Green–Green; RR = Road–Road; GW = Green–Water; RW = Road–Water; HW = Hard–Water). Besides habitat types, data on slope degree (1 = 0°–15°, 2 = 16°–30°, 3 = 31°–45°), sunshine condition, tree canopy closure [51], degree of human disturbance (1 = almost no human disturbance; 2 = only a few people passing by; 3 = a small number of people passing by; 4 = more people staying; 5 = high human traffic), management frequency (1 = cleaned monthly; 2 = cleaned once a season; 3 = cleaned once a year; 4 = no cleaning), and types of plant spatial structure (1 = herbaceous layer; 2 = shrub layer + herbaceous layer; 3 = tree layer + herbaceous layer; 4 = tree layer + shrub layer + herbaceous layer, where shrubs are defined as 1–3.5 m and trees as over 3.5 m) were also recorded.

2.2.3. Identification and Arrangement of Plant Species

Plant species identification referenced "Flora of Jiangsu" [69], "Flora of China" [70], and books and website resources such as the Catalogue of Invasive and Naturalized Plants in China, and the species found in the green spaces of Nanjing's urban parks were categorized and organized by family and genus. Photos taken during the survey were promptly organized and summarized, covering aspects such as the external appearance of the quadrats, the vertical structure of the communities, individual specimens of each species in the herbaceous layer, and various ornamental parts. The photos were archived and filed according to the survey site number and named after the quadrat number and the scientific name of the species.

2.3. Statistical Analysis

Plant and environmental data were statistically managed using Microsoft Excel 2016, in which four indices of alpha diversity were calculated. The "cluster" [71] and "stats" packages in R (v.4.2.2) [72] were used for UPGMA cluster analysis, the vegan [73] package for DCA and CCA ranking analysis, and the "ggplot2" [74] package for plotting.

ANOVA tests were utilized to examine differences in the distribution of the four alpha diversity indices among various park characteristic groups. Significant differences were denoted with '*' for *p*-values between 0.01 and 0.05, '**' for *p*-values less than 0.01, and no marking for p-values exceeding 0.05. Subsequently, cluster analysis, UPGMA, Detrended Correspondence Analysis (DCA), and CCA were conducted to investigate correlations among plant community composition and potential explanatory factors. Monte Carlo permutation tests were employed to evaluate the significance of the correlation between all park characteristics and species community composition, revealing significant differences ($p < 0.05$) in seven factors across two dimensions out of the twelve park characteristics examined.

2.3.1. Alpha Diversity

This study employed three commonly used diversity indices from ecology to validate species diversity: the Shannon–Wiener species diversity index (H), Pielou's evenness index (J), and Simpson's diversity index (D). The importance values (IV) of species at each sampling site were calculated using the following formulae:

- Importance values

Frequency refers to the percentage of quadrats in which a particular plant species appears at a sampling site. Height is the average height of a plant species observed in quadrats at a sampling site. Cover refers to the average cover of a plant species in quadrats at a sampling site.

$$\mathrm{IV} = \frac{\mathrm{relativefrequency} + \mathrm{relativeheight} + \mathrm{relativecoverage}}{3}$$

- Diversity index: Richness and evenness

The Shannon–Wiener index, Pielou's evenness index, and Simpson's diversity index for each sampling site were calculated in Excel utilizing the following formulas:

1. Patrick richness index,

$$\mathrm{R} = \mathrm{S}$$

2. Shannon–Wiener index (Magurran, 2004),

$$\mathrm{H} = -\sum \mathrm{P_i} \log \mathrm{P_i}$$

3. Pielou's (1975) evenness index,

$$J = -\frac{\sum P_i \log P_i}{\log q}$$

4. Simpson's diversity index,

$$D = 1 - \sum {P_i}^2$$

where q represents the quantity of each species in a sample plot, IVi is the relative importance value of species i, and Pi = IVi/IV, where IVi is the importance value of species i at the corresponding sample plot.

2.3.2. Cluster Analysis and Ordination Analysis of Spontaneous Plant Community

In this study, 284 herbaceous plant species were identified across 96 surveyed sites, including some rare and infrequent species. To minimize the impact of these rare species, plants with a frequency of less than or equal to two across all sites and a total importance value of less than 0.01 were excluded. Consequently, a 96 × 153 (sites × plant species) importance value matrix and a 96 × 12 (sites × park features) environmental value matrix were established as the basis for analysis. The UPGMA was utilized to group the sites with the objective of summarizing the similarity in plant composition among these sites and determining the differences between groups. This approach aimed to explore and summarize the patterns of the herbaceous spontaneous plant communities in Nanjing urban parks. To investigate the impact of park features on the composition of plant communities, a DCA was first conducted using the importance value matrix data. The analysis revealed a gradient length of 5.15 along the first axis. Subsequently, CCA was employed to analyze the relationships between site communities and influencing factors. Both UPGMA, DCA, and CCA were conducted for graphical analysis in R version 4.2.2. The species data represented the importance values of plants at each site.

3. Results

3.1. Species Composition and Diversity of Spontaneous Plants in Nanjing Urban Parks

A total of 284 plant species belonging to 192 genera and 78 families were investigated in 480 quadrats in this study. Among the 78 surveyed families, 4 dominant herbaceous families were represented with more than 10 species each: Poaceae (23 genera, 34 species), Asteraceae (22 genera, 32 species), Polygonaceae (5 genera, 14 species), and Lamiaceae (8 genera, 11 species); 35 families were represented by only 1 genus and 1 species each. The 284 plant species were categorized according to life forms: 104 perennial herbs, accounting for 36.61% of the total; 70 annual herbs (24.65%); 46 trees and shrubs (16.20%); 35 biennial or annual herbs (12.32%); 14 herbaceous vines (4.92%); nine woody vines (3.17%); and six ferns (2.11%). According to the Chinese Invasive Species Database, 45 species across 17 families identified in this survey were classified as invasive, with the Asteraceae family containing 15 species across 11 genera, the Plantaginaceae with 6 species across 2 genera, and the Poaceae with 5 species across 3 genera. These invasive species were categorized into five levels: 11 species were classified as Level 1 (most invasive), such as *Solidago canadensis*, *Symphyotrichum subulatum*, and *Alternanthera philoxeroides*; 6 as Level 2 (severely invasive); 3 as Level 3 (moderately invasive); 17 as Level 4 (less invasive); and 8 as Level 5 (monitoring required). The majority of the more aggressively invasive plants were also categorized as annual, biennial, or perennial plants, while most of the Level 5 invasive species were horticultural introductions (Figure 2).

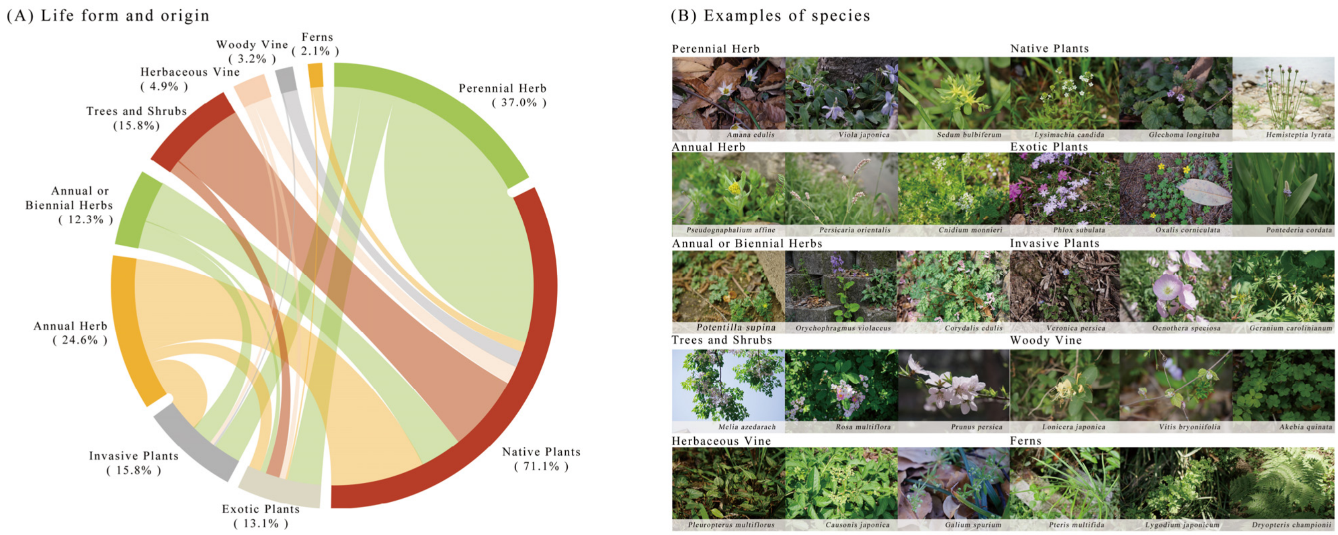

Figure 2. Comparison between plant life forms and plant origins.

In this study, among the herbaceous layers of nine parks, the highest average values for the Patrick index, Shannon–Wiener index, and Pielou evenness index were observed in the River Chief Theme Park, with values of 25.80, 3.13, and 0.96, respectively. Conversely, the lowest average values for these indices were recorded in Bailuzhou Park, with values of 14.38, 2.43, and 0.89, respectively. Significant differences were found between the different parks for the Patrick and Shannon–Wiener indices ($p < 0.01$), while significant differences were observed for the Pielou evenness index ($0.01 < p < 0.05$). A significant correlation was evident between the park area and the Patrick index; however, no significant correlation was found between the Shannon–Wiener diversity index and the Pielou evenness index.

From a habitat perspective, there were no significant differences in habitat types in relation to the three indices. The most common habitat types identified among the 96 sampling sites were RG and GG, appearing 26 and 19 times, respectively. The frequencies of RW, RR, and GW were relatively similar, appearing 14, 12, and 11 times, respectively, while HG, HR, and HW were each encountered less than 10 times, likely due to the exclusion of completely hardened patches during the grid layout process. The most common spatial structure types were tree layer + shrub layer + herb layer and tree layer + herb layer, appearing 47 and 36 times, respectively. In contrast, the spatial structures of shrub layer + herb layer, and solely herb layer in urban parks were less common, appearing only 8 and 5 times, respectively. Sites with more complex plant spatial structures exhibited higher average values for species richness and diversity indices, while the highest average values for the evenness index appeared in the simplest structures (Figure 3).

3.2. Composition of Herbaceous Spontaneous Plant Communities

To facilitate a more rational division of plant communities, a cluster analysis was conducted on 96 sampling sites based on the matrix of plant importance values. By calculating and plotting the fusion level values of the cluster dendrogram (Figure 4A), suggestions for trimming the cluster tree at ten groups were derived from the graph. To further verify the rationality of the UPGMA cluster analysis, the silhouette width plot for the number of groups k = 10 (Figure 4B) was examined, and dividing into ten groups was considered to be a reasonable final clustering outcome.

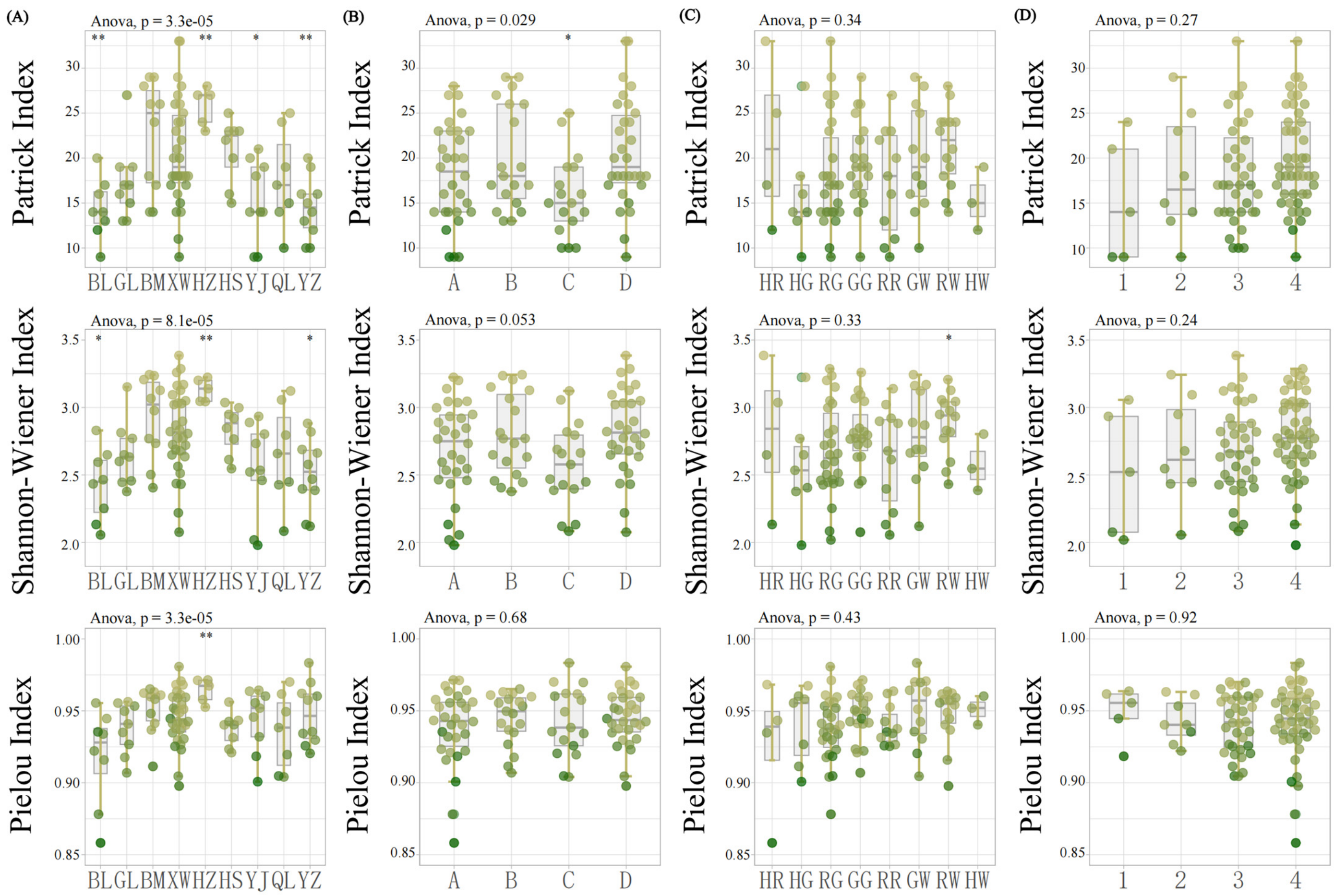

Figure 3. Comparison of plant diversity and evenness across (**A**) different parks; (**B**) different types of parks; (**C**) different habitat types; (**D**) different spatial structures (bars denote S.D.).

The final classification results from the UPGMA clustering analysis of the sampling sites are shown in Figure 4C and Table 3. Based on the grouping results of the sampling sites, the plant communities can be divided into ten types (Table 4), named after the species with the highest frequency of occurrence and the highest total importance values. Observing the types of plant communities, it was not difficult to find that in types A, B, C, E, F, and I, artificially planted plants often appeared as dominant species, while in types D, G, H, and J, the dominant species were herbaceous spontaneous plants. Types C, E, and F represented the most common artificially managed herbaceous ground covers in Nanjing urban parks, such as *Reineckea carnea*, *Ophiopogon japonicus*, and *Cynodon dactylon*, which appeared frequently in sites with high management frequency. In contrast, in groups (D, G, and J) dominated by herbaceous spontaneous plants such as *Stellaria media*, *Achyranthes bidentata*, and *Vicia cracca*, the management frequency did not significantly affect the composition of the herbaceous spontaneous plants.

3.3. Park Features Influencing Spontaneous Communities

Following a DCA of the species matrix and park features matrix of spontaneous plant communities in the herbaceous layer of the parks, the gradient length of the first axis was determined to be 5.15 (>4), indicating that a linear method would be inappropriate. Thus, CCA was chosen to further test the correlation between park features and groups of herbaceous spontaneous plant communities. In the DCA, the eigenvalues for the first four axes were 0.62, 0.45, 0.34, and 0.25, respectively; the first and second axes explained 37.15% and 27.14% of the variance, respectively. According to the DCA ordination diagram

(Figure 6), the arrangement of the sampling sites corresponded well with the community groups formed by UPGMA cluster analysis.

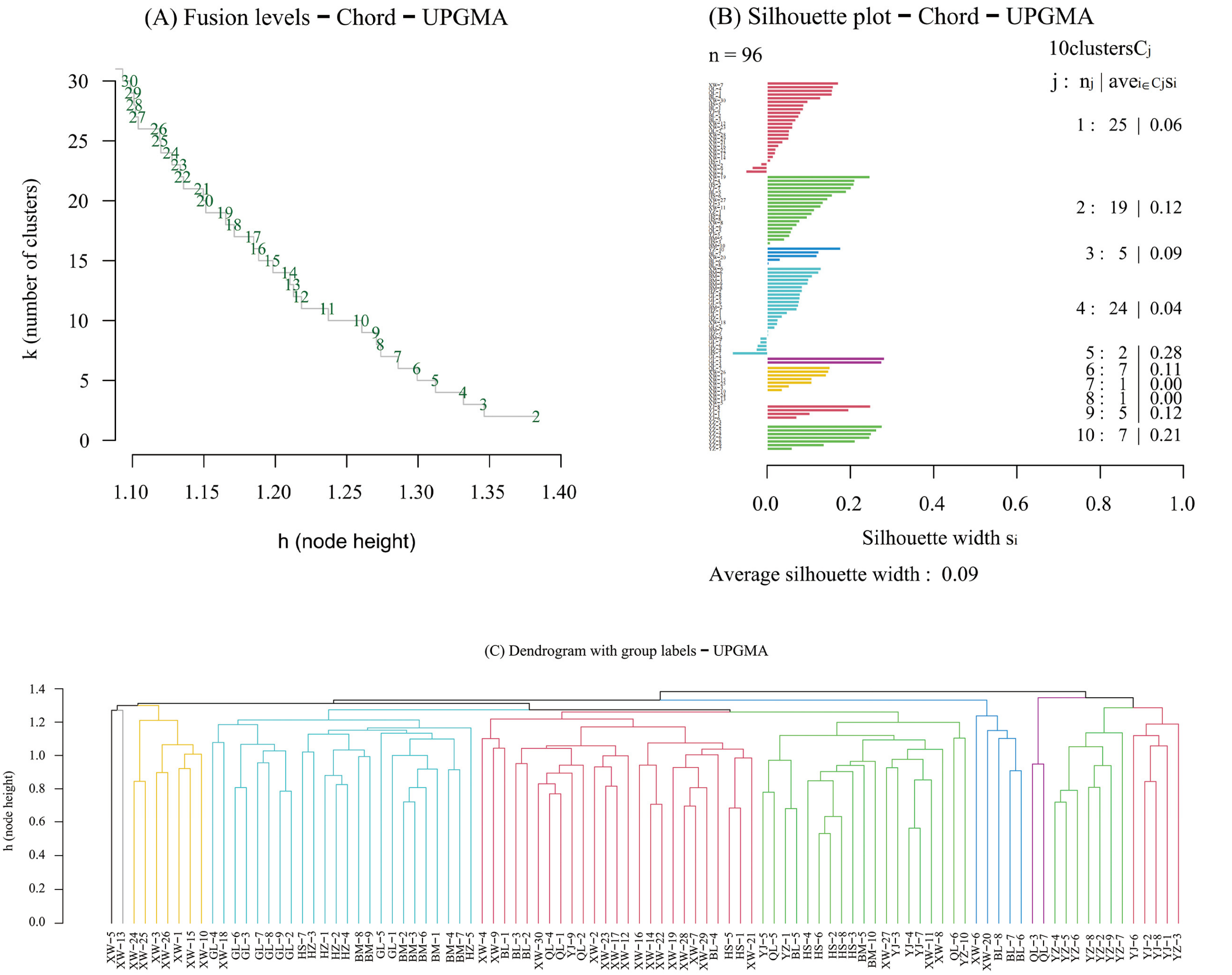

Figure 4. Cluster analysis of herbaceous spontaneous plant communities in the herbaceous layer of Nanjing urban parks. (**A**) Fusion level values graph of the cluster tree. (**B**) Silhouette width plot. (**C**) Cluster dendrogram of sampling sites classified into 10 groups.

Table 3. Results of the sample plot clustering.

Group	Sample Plot
A	XW-5
B	XW-13
C	XW-1, XW-3, XW-10, XW-15, XW-24, XW-25, XW-26
D	GL-1, GL-2, GL-3, GL-4, GL-5, GL-6, GL-7, GL-8, GL-9, XW-18, BM-1, BM-2, BM-3, BM-4, BM-6, BM-7, BM-8, BM-9, HS-7, HZ-1, HZ-2, HZ-3, HZ-4, HZ-5
E	XW-2, XW-4, XW-7, XW-9, XW-12, XW-14, XW-16, XW-17, XW-19, XW-21, XW-22, XW-23, XW-28, XW-29, XW-30, QL-1, QL-2, QL-4, YJ-9, HS-1, HS-5, BL-1, BL-2, BL-3, BL-4
F	XW-8, XW-11, XW-27, BM-5, BM-10, QL-5, QL-6, YJ-3, YJ-4, YJ-5, YJ-7, YZ-1, YZ-10, HS-2, HS-3, HS-4, HS-6, HS-8, BL-5
G	XW-6, XW-20, BL-6, BL-7, BL-8
H	QL-3, QL-7
I	YZ-2, YZ-4, YZ-5, YZ-6, YZ-7, YZ-8, YZ-9
J	YJ-1, YJ-2, YJ-6, YJ-8, YZ-3

Table 4. Community types.

Group	Occurrence Number	Community Type
A	1	*Sedum sarmentosum + Iris ensata var. hortensis + Iris pseudacorus*
B	1	*Trachelospermum jasminoides + Nephrolepis cordifolia*
C	7	*Reineckea carnea + Orychophragmus violaceus*
D	24	*Stellaria media + Poa annua + Galium spurium + Veronica persica*
E	25	*Ophiopogon japonicus + Oxalis corniculata + Poa annua*
F	19	*Cynodon dactylon + Lolium perenne + Oxalis corniculata + Poa annua*
G	5	*Broussonetia papyrifera—Achyranthes bidentata + Duchesnea indica + Causonis japonica*
H	2	*Echinochloa crusgalli var. zelayensis + Polypogon fugax + Bidens pilosa*
I	7	*Phragmites australis + Miscanthus sacchariflorus + Artemisia lavandulifolia + Aster indicus*
J	5	*Vicia cracca + Geranium carolinianum + Elymus shandongensis*

3.4. Alpha Diversity Indices of Different Spontaneous Community Types

The community classification results obtained from the cluster analysis were analyzed again with the alpha diversity indices. The Patrick index, the Shannon–Wiener index, the Pielou evenness index, and the Simpson index between different groups all showed significant differences (Figure 5). The average ranges of the Patrick index, Shannon–Wiener index, Simpson index, and Pielou index of each group were 14.29~24.50, 2.49~3.09, 0.90~0.95, and 0.92~0.97, respectively (Table 5). Among them, the top five index averages are groups H, B, C, D, and A. Unexpectedly, the four index averages of group H dominated by invasive plants are all the highest, which means that the alpha index value of the plant community cannot be completely equated with the level of its ecological benefit. The urban ecosystem should also be evaluated in combination with other park features.

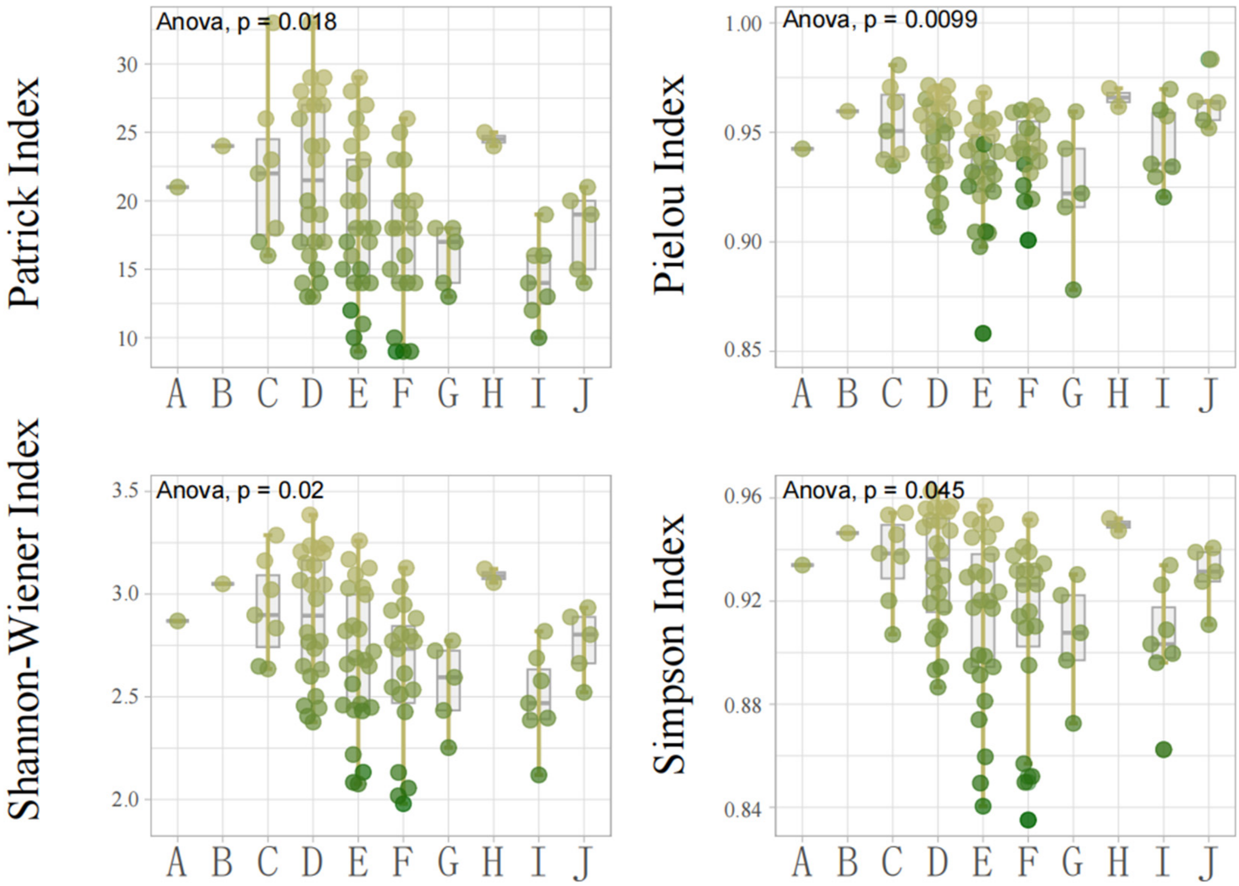

Figure 5. Comparison of alpha diversity indices across different community types (bars denote S.D.).

Table 5. Mean and standard deviation of each index for different community types.

Community Types	Patrick Index	Shannon–Wiener Index	Pielou Index	Simpson Index
A	21.00 ± 0.00	2.87 ± 0.00	0.94 ± 0.00	0.93 ± 0.00
B	24.00 ± 0.00	3.05 ± 0.00	0.96 ± 0.00	0.95 ± 0.00
C	22.14 ± 5.54	2.93 ± 0.23	0.95 ± 0.02	0.94 ± 0.02
D	21.63 ± 5.98	2.88 ± 0.31	0.95 ± 0.02	0.93 ± 0.02
E	18.48 ± 5.64	2.68 ± 0.34	0.93 ± 0.02	0.91 ± 0.03
F	16.84 ± 5.20	2.61 ± 0.34	0.94 ± 0.02	0.91 ± 0.03
G	16.00 ± 2.10	2.56 ± 0.19	0.92 ± 0.03	0.91 ± 0.02
H	24.50 ± 0.50	3.09 ± 0.03	0.97 ± 0.00	0.95 ± 0.00
I	14.29 ± 2.76	2.49 ± 0.21	0.94 ± 0.02	0.90 ± 0.02
J	17.80 ± 2.79	2.76 ± 0.15	0.96 ± 0.01	0.93 ± 0.01

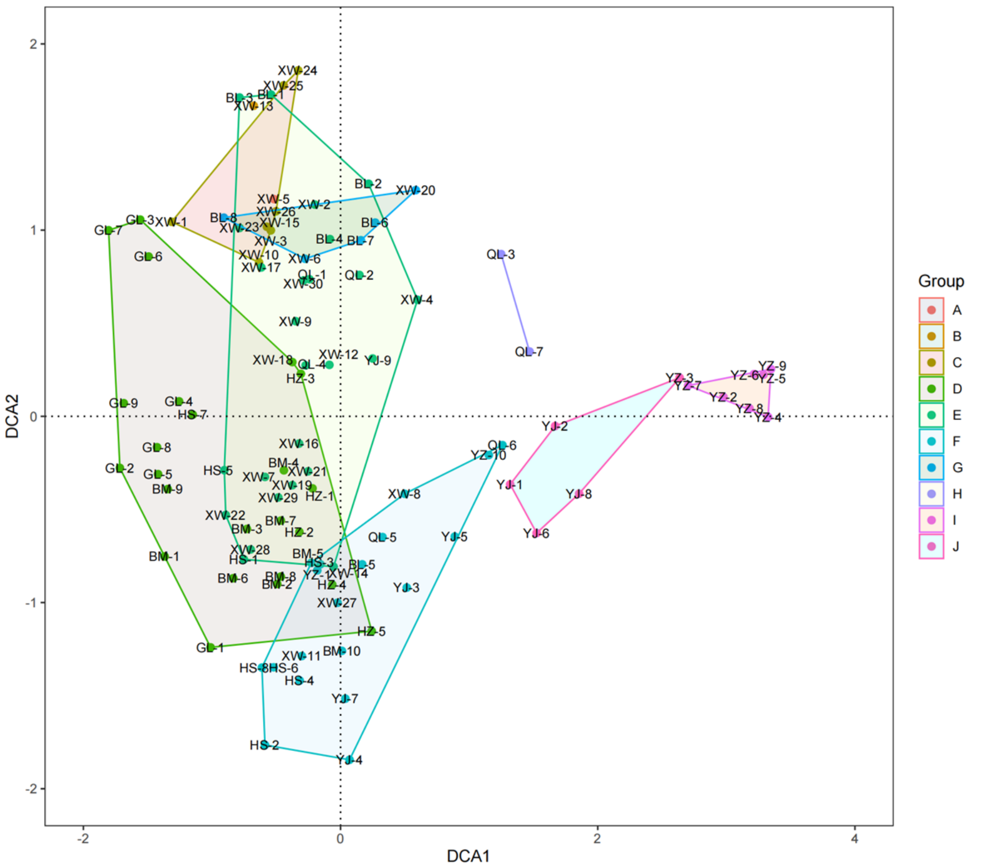

Figure 6. DCA ordination diagram for 96 herbaceous spontaneous plant community sampling sites in Nanjing urban parks.

Twelve park features were then analyzed separately from two perspectives using CCA (Table 6). Regarding the park perspective, the eigenvalues for the first and second axes in the CCA ordination were 0.54 and 0.29, respectively. The first axis was most strongly correlated with park area (0.58), followed by distance to water (−0.24); the second axis was most strongly correlated with park establishment time (0.89), followed by park area (0.71). From the habitat perspective, the eigenvalues for the first and second axes in the CCA ordination were 0.21 and 0.14, respectively. The first axis showed the strongest correlation with management frequency (−0.62), followed by light conditions (−0.45); the second axis was most strongly correlated with light conditions at the sampling sites (−0.63), followed by slope (−0.28).

Table 6. Scores of constraining variables in the CCA biplots from the perspectives of the park and the habitat.

On a Park Level					On a Habitat Level				
Park Features	**Canonical Correspondence Analysis**				**Park Features**	**Canonical Correspondence Analysis**			
	CCA1	**CCA2**	**CCA3**	**CCA4**		**CCA1**	**CCA2**	**CCA3**	**CCA4**
Time	−0.22	0.89	0.21	−0.34	ST	0.33	−0.06	−0.14	−0.72
Size	0.58	0.71	0.38	0.01	Habitat	−0.14	0.06	−0.07	0.55
Location	0.16	−0.51	−0.41	0.74	Slope	−0.10	−0.28	0.87	−0.02
DW	−0.24	−0.45	0.70	−0.21	HD	0.00	0.21	−0.53	0.16
DM	0.02	0.20	0.52	0.57	MF	−0.62	0.01	0.36	−0.30
					SC	−0.45	−0.63	−0.15	0.47
					Canopy closure	0.42	0.06	−0.19	−0.56
Eigenvalue	0.54	0.29	0.15	0.14	Eigenvalue	0.21	0.14	0.12	0.10
Proportion Explained	0.44	0.24	0.13	0.11	Proportion Explained	0.26	0.18	0.15	0.12
Cumulative Proportion	0.44	0.68	0.81	0.92	Cumulative Proportion	0.26	0.44	0.59	0.71

In the table, DW represents the distance from water; DM represents the distance from mountains; ST represents space type; HD represents human disturbance; MF represents management frequency; SC represents a sunshine condition.

The ordination results indicated that from the perspective of the park (Figure 7A), park area size had a significant impact on group E, F, and D communities; park establishment time significantly affected the communities of groups F and E; and park location and distance from water had greater impacts on group C and G communities. In parks along the Yangtze River, plant communities exhibited relatively unique combinations, such as groups I and J, with lower environmental influences from park factors, possibly related to the unique conditions along the Yangtze River banks.

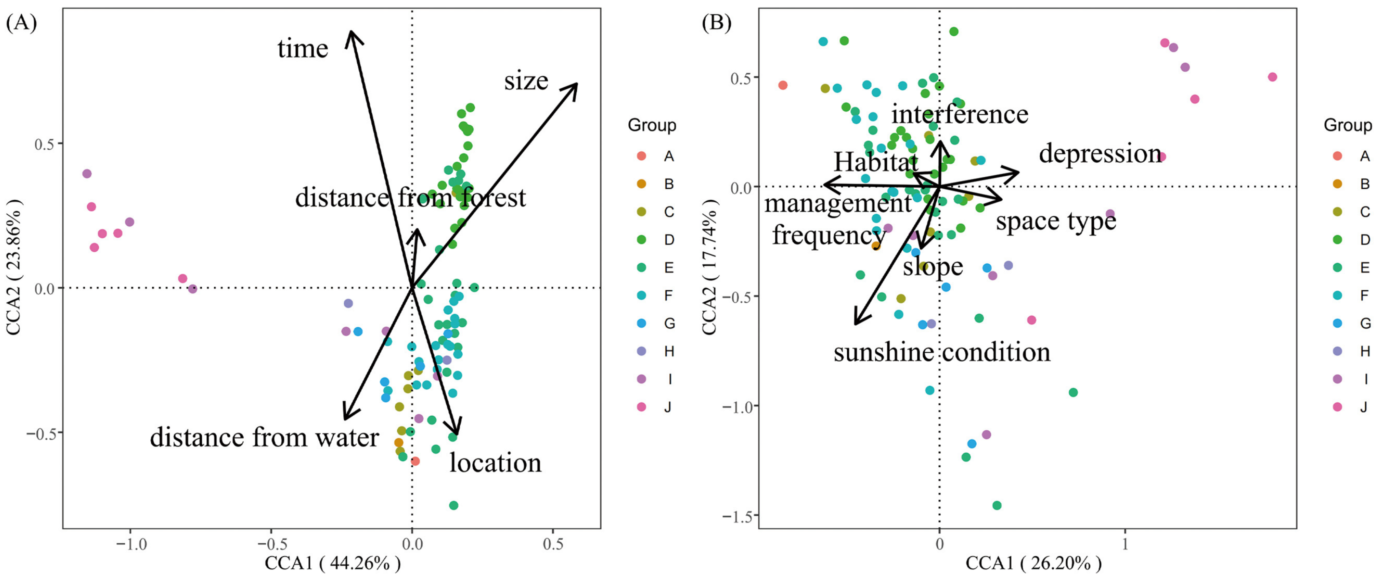

Figure 7. CCA ordination diagrams for 96 sampling sites and park features in Nanjing urban parks. (**A**) Canonical Correspondence Analysis of park features from the park perspective. (**B**) Canonical Correspondence Analysis of park features from the habitat perspective.

From the perspective of site habitat (Figure 7B), light conditions were the most crucial factor affecting plant communities; the presence or absence of building shadows could affect the composition of the communities within them. Communities of group F tended to be found in sunny, unshaded lawns, while groups B and C typically occurred in understory spaces. In this study, canopy cover was also an influential factor regarding light conditions for the herb layer, distinct from the light conditions influenced by architectural features; it describes the extent of canopy coverage at the site. In the ordination results, canopy cover scored less than light conditions, significantly influencing groups D and E. Management frequency was another significant factor affecting plant communities, especially for groups E and F. These community types were dominated by artificially planted plants, where spontaneous plants must grow and reproduce quickly in ecological niches vacated by cultivated plants before the next management cycle. Therefore, in habitats with higher management frequencies, herbaceous spontaneous plants tend to be species that can complete their life cycle in a short period, and their importance values are often second only to those of extensively cultivated plants.

4. Discussion

4.1. Urban Parks Have a Rich Variety of Spontaneous Plants

In this study, 96 sampling sites across nine urban parks in Nanjing were surveyed, recording 284 plant species. Although the study area was concentrated in the main urban area of Nanjing, the number of species recorded in this study is higher than the results of previous surveys [56,59]. The difference may be due to the fact that the range of plants recorded in this study includes some self-seeded woody plants, woody vines, and shrubs, thus broadening the range of surveyed objects. The three dominant families in terms of number of species included are Gramineae, Asteraceae, and Polygonaceae. Asteraceae and Gramineae are not only dominant families in the urban riverside zone of Nanjing [56] and urban parks [59] but are also dominant families in northern Chinese cities such as Beijing [68] and Harbin [75]. This advantage of the Asteraceae family is also reflected in 45 invasive plant species.

A grid-sampling method was used to investigate the diversity of habitats and plants. However, the surveyed plant resources only provide basic data on a small scale, and measuring the diversity of urban spontaneous plants in large areas requires in-depth research. Many studies based on large spatial scales have verified the changes in species richness with spatial scales [76–78], but there were fewer studies analyzing the alpha diversity index and urban characteristics at small spatial scales. To this end, this study used the alpha diversity index to analyze the characteristics of urban spontaneous plant diversity in Nanjing and further investigated the relationship between plant diversity and green space characteristics at small spatial scales.

Ecological methods were employed to calculate the α-diversity at each site, with ranges for the Patrick index, Shannon–Wiener index, Pielou evenness index, and Simpson index, respectively, being 9~33, 1.98~3.39, 0.86~0.98, and 0.84~0.96. The range of diversity indices for herbaceous spontaneous plants in this study is similar to that observed in small urban parks in Beijing [79]. Despite the selection of Nanjing's urban parks of various scales for this study, the overall park size in Nanjing remains smaller compared to Beijing's. Therefore, the plant diversity indices obtained from this survey are close to those of Beijing's small urban parks, yet the mean richness of the sites is higher than that of Beijing's urban parks, demonstrating Nanjing's rich plant resources and its suitability for various herbaceous spontaneous plants.

4.2. Moderate Park Management Encourages Spontaneous Plant Diversity

The amount of green space available for urban park development in Nanjing's central urban area is gradually diminishing [80], and the landscape patterns of existing parks are relatively fixed. Exploring the relationship between biodiversity and the environment in urban green spaces will help to provide better suggestions for other cities to build biophilic cities. From a park perspective, park size and establishment time are positively correlated with the alpha diversity index, which is consistent with other research [58,68,75]. For spontaneous plant communities, park area and establishment time are also the most influential characteristics. It is worth mentioning that in this study, the distance between the park and the water also significantly affects the community composition. This means that where there are rivers or lakes around urban green spaces, communities dominated by some plants such as *Achyranthes bidentata* and *Duchesnea indica* will be more affected, and the management of such green spaces may need to be strengthened.

Park features from a habitat perspective also impact the herbaceous spontaneous plant communities. In sites with higher management frequency, commonly planted understory herbaceous coverings in Nanjing include *Ophiopogon japonicus*, *Reineckea carnea*, and the increasingly popular *Orychophragmus violaceus* over the past decade, indicating a gradual increase in urban residents' acceptance of spontaneous plants. Contrary to the traditional impression of urban parks held by the public, more residents are able to accept orderly herbaceous spontaneous plant communities [9], especially those with rich colors [81]. Similarly, in park lawns with high management frequency, Nanjing commonly uses mixed planting of *Cynodon dactylon*, *Lolium perenne*, and *Poa annua*. Surprisingly, although lawns are typically synonymous with tidiness and high maintenance, we still recorded a variety of non-lawn grasses such as *Oxalis corniculata*, *Dichondra micrantha*, and *Trifolium repens*. Therefore, high management frequency in parks does not mean spontaneous plants outside the planned greenery can be completely eliminated. However, by controlling the timing and frequency of management, the composition and landscape characteristics of spontaneous plants can be artificially manipulated to provide good visual effects for the herbaceous plant landscape, thereby improving residents' experience of urban green spaces [16].

4.3. Reducing Plant Invasion Risk by Intervening in the Composition of Herbaceous Spontaneous Plant Communities

In this study, 45 invasive plant species were recorded, accounting for 15.85% of the surveyed plant species, with the dominant families being Asteraceae, Plantaginaceae, and Poaceae. The invasiveness of these families is largely associated with their modes of growth and reproduction: invasive species in Asteraceae and Plantaginaceae mostly have lightweight seeds that can be dispersed by wind, while those in Poaceae are often spread by animals [59]. According to the results of cluster analysis, group H (*Echinochloa crusgalli var. zelayensis* + *Polypogon fugax* + *Bidens pilosa*) had the highest proportion of invasive species in its community, with 11 invasive species identified, whereas group C (*Reineckea carnea* + *Orychophragmus violaceus*) had the smallest proportion, barring the occasional group B (*Trachelospermum jasminoides* + *Nephrolepis cordifolia*), with only 7 out of 78 plants being invasive. These seven invasive plants were either annual or biennial herbaceous and perennial herbaceous, with one plant each from invasion Levels 1 (malicious invasion) and 2 (serious invasion) and low total importance values. Based on the above analysis, it can be further hypothesized that in newly established park green spaces with infrequent management, invasive plants often preemptively occupy vacant ecological niches, leading to poor growth conditions for transplanted plants, whereas a controlled "artificially planted plants + native plants" herbaceous plant community combination can suppress the spread of invasive plants to some extent. This perspective coincides with the strategies of naturalistic planting practices conducted by the team of Hitchmough J.D. and Dunnett N.D. in the village green space in front of Nanjing Shishanxia village.

4.4. Using Spontaneous Plant Communities to Promote Biophilic Cities

Although the acceptance of "wilderness" by urban residents has improved, entirely unmanaged herbaceous spontaneous plant communities are inappropriate in urban parks, as the public has not yet accepted unmanaged landscapes in urban green spaces [28]. The primary duty of urban green areas remains to provide a place for daily relaxation for city residents; focusing solely on the ecological benefits of parks while neglecting the well-being of citizens contradicts the original intent of urban park design. Therefore, biophilic cities need to balance ecological benefits and human interests through innovative policy and maintenance interventions.

Nature-based planting designs that focus on ornamental qualities and the newer concept of naturalistic planting have become increasingly popular in urban green spaces in recent years due to their combined aesthetic and ecological benefits. The concepts of vegetation rewilding and new naturalistic planting designs share significant similarities, as both consider the ecological benefits, maintenance costs, and aesthetic outcomes of the plant landscape. However, their emphases differ: new naturalistic planting focuses on landscape values, incorporating non-native and artificially planted perennials to expedite the formation of landscape effects; in contrast, rewilding aims to reconstruct urban wilderness habitats. Research into suitable local herbaceous spontaneous plant community compositions aims to restore the species composition, structure, and function of severely degraded urban plant communities, emphasizing ecological benefits in landscapes. Therefore, the targeted, efficient, and aesthetically pleasing establishment of rewilded plant communities has emerged as a new need in urban vegetation rewilding. Based on the concepts of rewilding and new naturalistic planting, we propose that in urban green spaces, herbaceous spontaneous and artificially planted plants are not in opposition. In informal settings of urban green spaces, the introduction of locally spontaneous plants with desirable ornamental traits can be appropriate. Using transplanted plants as the structural framework of the landscape, the addition of local spontaneous plants can enhance the seasonal dynamics of urban plant landscapes and potentially reduce maintenance costs of park vegetation to a certain extent.

5. Conclusions

This study documented 284 species of herbaceous spontaneous plants in Nanjing's urban parks, belonging to 78 families and 192 genera. The richness and diversity of plant communities serve as crucial indicators of urban ecology, with herbaceous spontaneous plant communities contributing significantly [82]. Through cluster analysis, ten groups of spontaneous plant communities were identified, with the three most frequently occurring communities being E (*Ophiopogon japonicus* + *Oxalis corniculata* + *Poa annua*), D (*Stellaria media* + *Poa annua* + *Galium spurium* + *Veronica persica*), and F (*Cynodon dactylon* + *Lolium perenne* + *Oxalis corniculata* + *Poa annua*). We employed ecological methods to analyze the effects of park characteristics and micro-scale park features on herbaceous spontaneous plant communities. The results indicated that park size and establishment time impacted the richness and diversity of the herbaceous layer, supporting the species–area relationship [83]. Larger parks harbored more species. As cities expand outward, green spaces are increasingly fragmented into smaller patches, resulting in newly established urban parks. These nascent urban green spaces often consist of entirely rebuilt plant communities, where many non-native or invasive plants enter the park along with construction, forming community patterns significantly different from the original plant communities. In contrast, in the initial urban centers, the plant communities of urban parks have become stable after long periods of secondary succession. Urban parks are primary venues for city residents to interact with nature, making it difficult to avoid human activities' impacts on plant communities. Among the park features investigated from several habitat perspectives, management frequency and light conditions are the main factors affecting the herbaceous spontaneous plant communities, while slope, space type, and habitat have less influence.

In summary, in Nanjing's urban parks, a relative balance has been formed between herbaceous spontaneous and artificially planted plants under the influence of different park characteristics and management intensities. The existing herbaceous spontaneous plant communities are the result of selection through both human activity and the natural environment. Within a controllable range, as park management intensity decreases, the composition of the herbaceous spontaneous plant communities also changes. Short-lived spontaneous plants can form specific landscape effects within a certain period, and different types of spontaneous plants can quickly replace the previous species to become dominant, providing references for low-maintenance seasonal landscapes. Removing the herbaceous layer of spontaneous plants in highly urbanized park green spaces requires high maintenance and management costs. However, by artificially altering the composition of the herbaceous layer of spontaneous plants, artificially planted plants and spontaneous plants can be recombined to form a new plant landscape. The planning combination of "artificially planted plants + native plants" in the herbaceous layer can be applied to low-maintenance green spaces in sustainable urban landscape design and management, allowing nature to grow freely. This not only helps save on maintenance and management costs but also provides a protective space for other urban species. At the same time, it provides more opportunities for residents to get in touch with nature.

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