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Hydrological Gradients Dominate Spontaneous Herbaceous Plant Community Assembly in Urban River Corridors: Evidence from Six Rivers in Changchun, China

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Abstract

The accelerated pace of urbanization has significant effects on the community composition, structure, regional distribution, and diversity characteristics of vegetation within urban river corridors. Spontaneous plants have strong environmental adaptability, high plasticity, and shorter life cycles; they also operate largely independently of human control. As a result, they are widely distributed throughout urban river corridors, and their ability to respond rapidly to heterogeneous habitats within these corridors makes them an ideal subject for studying the reciprocal mechanisms between rapid urbanization and riverine biodiversity. Based on a survey of 208 plots across six river corridors in Changchun, China, we found that the hydrological gradient was the strongest predictor of spontaneous herbaceous community distribution among the environmental factors examined. A total of 181 native herbaceous plant species, belonging to 55 families and 140 genera, were recorded. The Asteraceae, Poaceae, Fabaceae, Lamiaceae, and Polygonaceae families dominated. TWINSPAN classification divided the native herbaceous plant communities into 11 types, with the dominant species being predominantly low-growing perennial herbaceous plants. Canonical correspondence analysis (CCA) ordination confirmed this pattern, showing that the community distribution from aquatic to terrestrial habitats primarily aligned along the first CCA axis (defined by water depth and canopy cover), while the second axis reflected gradients in anthropogenic disturbance and slope. Thus, even in intensively managed urban rivers, natural hydrological processes remain pivotal in shaping riparian plant community composition and enhancing biodiversity. This study provides a scientific foundation for the conservation and sustainable utilization of plant resources in urban river corridors.

Keywords: urban river corridors; spontaneous plant diversity; environmental gradients; distribution patterns; canonical correspondence analysis; hydrological gradient

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1. Introduction

As natural or semi-natural ecosystems embedded in highly developed artificial environments, urban river corridors are a vital part of the ecological security framework of cities [1]. They serve multiple functions, including providing habitats for wildlife, regulating floodwater storage, moderating the climate, and offering recreational opportunities. The natural shape and ecological processes of rivers have undergone significant changes due to rapid urbanization, creating serious challenges for the mechanisms that support their

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biodiversity. Spontaneous vegetation—plant communities that colonize and regenerate through natural processes without artificial sowing or maintenance—acts as an important indicator of ecological resilience in urban river corridors [2]. They form the basis of the riparian vegetation structure and function and serve as sensitive indicators of environmental change. Therefore, determining the diversity, distribution patterns, and environmental drivers of spontaneous vegetation in urban river corridors has become a key focus in urban and restoration ecology. Understanding these drivers is a question of community assembly, which is largely governed by environmental filtering, wherein abiotic conditions select for species with suitable traits, thus shaping the community composition [3,4].

On an international level, research on spontaneous vegetation diversity in urban river corridors has developed a relatively systematic framework and methodology. To understand this ecosystem's complexity, it is essential to systematically review relevant domestic and international research progress. Early studies have mainly focused on urban parks, brownfield sites, and comprehensive green space systems, establishing the theoretical framework that "habitat heterogeneity" and "anthropogenic disturbance" are the two main factors driving urban plant distribution [5]. As research has advanced, the focus has gradually shifted to river corridors, which display more linear and connected features. European studies have shown that urbanization gradients significantly affect riparian plant diversity and that plant richness is negatively related to the percentage of surrounding impervious areas [6]. Constructing near-natural plant communities has become a trend worldwide. For example, Milan, Italy, successfully increased river biodiversity via wetland restoration and strengthened greenway networks [7]. Nature-based solutions have increased biodiversity conservation and restoration in the Netherlands by 22% [8]. These examples demonstrate that ecological restoration can effectively enhance biodiversity and ecosystem services in urban river corridors.

Substantial progress has been made in domestic research. In Harbin [9], spontaneous herbaceous layer diversity is significantly higher in areas with moderate to low urbanization than in highly urbanized zones. Research in Chengdu [10] has shown that riparian habitat diversity exceeds that of revetments and upland areas and that intensive artificial management in city centers leads to habitat homogenization. Investigations along the Hangzhou section of the Beijing–Hangzhou Grand Canal [11] have revealed that human disturbance is the primary factor affecting diversity fluctuations. These studies provide an essential scientific foundation for understanding ecological processes in urban river corridors. However, current domestic research has some limitations. In terms of perspective, most studies have focused on describing individual rivers or fragmented habitats, lacking systematic, comprehensive investigations of the environmental gradient—"water body–floodplain–green spaces"—at the regional level [9,10,12], hindering our understanding of continuous community distribution patterns and broader ecological principles. Although many studies acknowledge the significant impact of human disturbance, research on the interactions between human intervention and natural processes remains relatively limited [13,14]. Quantitative analysis of the relative importance of different environmental factors is also a weakness. These limitations in research scope and understanding of the driving mechanisms restrict our comprehension of how plant communities form and persist in urban river corridors.

However, despite this progress, several critical constraints remain in our understanding of plant community assembly along urban river corridors, particularly in the context of Northeast China. First, existing studies focus on isolated habitat patches rather than on continuous environmental gradients from water to upland. Second, the influence of human disturbance is often simplistically treated as present or absent, rather than measured along a quantifiable intensity gradient. Third, few studies jointly analyze hydrological, topographic, and socioeconomic drivers within a single, comprehensive framework to explain community assembly. To address these gaps, we investigated six river corridors in Changchun City, China, with the three following objectives: (1) document the patterns of spontaneous plant diversity along the continuous water-to-upland gradient; (2) assess how anthropogenic disturbance intensity gradients interact with natural processes to shape communities; and (3) quantify and rank the relative importance of hydrological, topographic, and socioeconomic drivers in an integrated model.

2. Materials and Methods

2.1. Overview of the Study Area

Changchun city is situated in the central region of Northeast China (43.88° N, 125.32° E). The urban area has an average elevation of 200–250 m above sea level, featuring a flat topography in the heart of the Song Liao Plain. It experiences a temperate continental monsoon climate [15]. Positioned at the core of the Northeast Asian economic sphere and the Harbin–Dalian economic corridor, Changchun is a significant manufacturing hub in China. The central urban area features a well-developed water system, with river corridors centered on the Yitong River as the longitudinal axis, forming a spatial pattern characterized by “one main channel with multiple branches” [16]. This study selected six rivers: one major trunk river (Yitong River) and five smaller tributaries (Xiaheyanzi River, Fuyi River, Yongchun River, Sijian River, and Dongxinkai River) as the principal watercourses of Changchun’s central urban area. These rivers traverse diverse orientations in the city center, encompassing varied habitat characteristics and ecological gradients. The highly heterogeneous and complex riverine habitats provide diverse ecological niches for vegetation diversity, rendering this area an ideal region for investigating plant diversity distribution patterns and their underlying causes. The study area is within the central urban built-up zone of Changchun, China. According to the *Main Data Bulletin of the Third National Land Survey of Changchun City* [17], the city’s land use is dominated by urban construction land that is primarily composed of residential, industrial, and green spaces. This land-use pattern establishes a gradient of anthropogenic disturbance. The green coverage rate of the built-up area exceeds 40%, as reported in the *Changchun Statistical Yearbook* [18], characterizing the urban ecological context.

2.2. Research Methods

Field surveys employing a systematic transect design were carried out from July to September 2023 to characterize the riparian vegetation at the study sites (Figure 1). Specifically, transverse transects were placed perpendicular to the riverbank at 1-km intervals along both sides of the river corridor, with each transect not exceeding 30 m in length (for a total of 87 transects). Within each transect, sampling followed a habitat-stratified approach.

The sampling design systematically represented the complete hydrological–anthropogenic gradient from open water to semi-artificial green space. To ensure objective and reproducible classification, we assigned plots based on observable field criteria (Table 1), integrating and refining previously established principles [11].

Using the criteria given in Table 1, we identified all habitat types present within each transect, namely aquatic (AQ, 23 plots), floodplain (FP, 24 plots), riparian edge (RE, 59 plots), and semi-natural/semi-artificial green space (SN-A, 102 plots), yielding a total of 208 plots. Consequently, each plot was an independent observation. Our analysis focused on habitat differences across the study area rather than within individual transects.

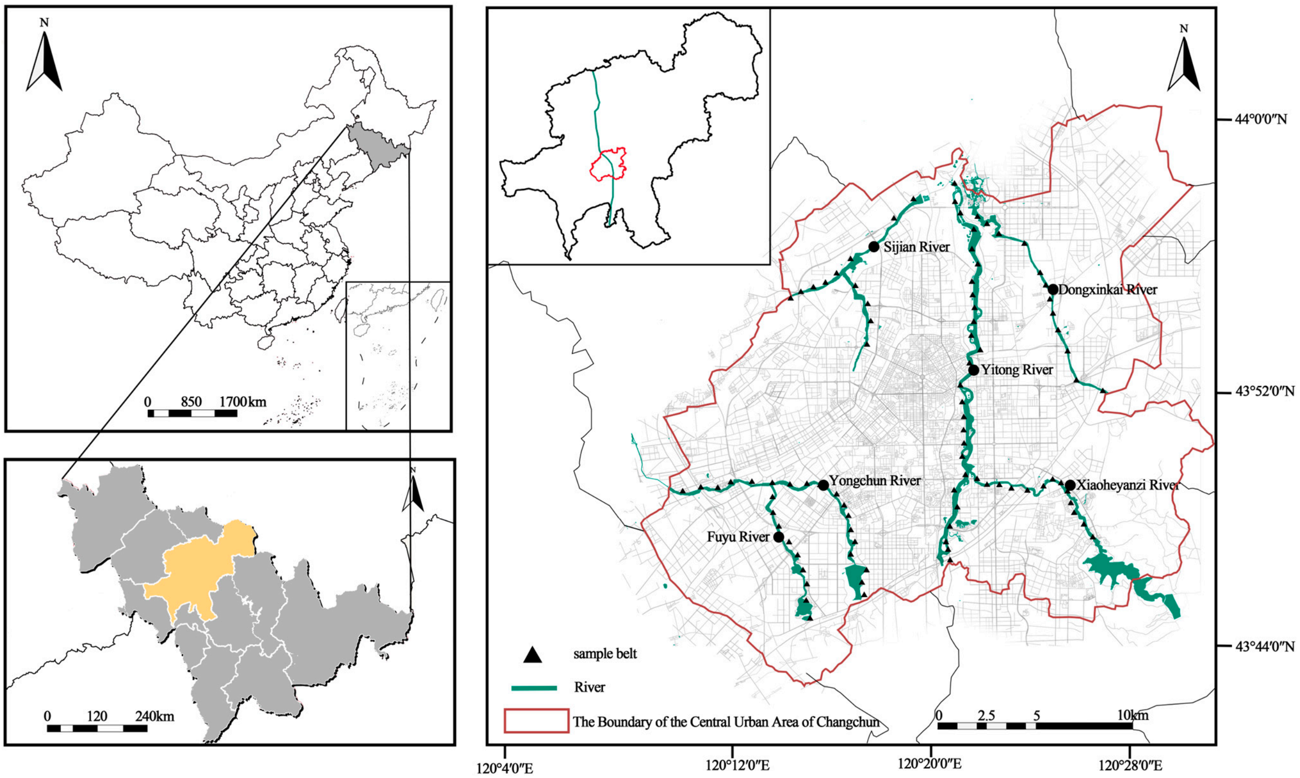

Figure 1. Location of the study area and sampling sites.

Table 1. Operational criteria for field identification of riparian habitat types.

Habitat Type	Abbreviation	Key Operational Criteria for Field Identification
Aquatic	AQ	• Persistent surface water at the time of survey. • Vegetation dominated by floating or emergent hydrophytes.
Floodplain	FP	• Flat area (slope < 5°) immediately adjacent to the water body. • Soil saturated or with clear signs of recent inundation (e.g., sediment deposits, water marks). • Vegetation dominated by hygrophytes.
Riparian Edge	RE	• Distinct slope zone (slope > 5°) connecting the floodplain to the upland. • No evidence of regular inundation. • Vegetation represents a transition from hygrophytic to mesophytic species.
Semi-natural/Semi-artificial Green Space	SN-A	• Area beyond the riparian edge slope, disconnected from direct hydrological influence. • Vegetation either visibly managed (e.g., mowed, irrigated, landscaped) or composed of spontaneous terrestrial (mesophytic/xerophytic) communities.

For each habitat type identified within a transect, a single representative 100-m^2 plot was established. As a result, the number of plots per transect (ranging from 1 to 4) directly reflected the transect's habitat diversity. To ensure that the representation of the vegetation within plots remained unbiased, random sampling was conducted inside each 100-m^2 plot. The number of herbaceous quadrats (1 m × 1 m) per plot (ranging from 2 to 5) was determined by a visual assessment of vegetation heterogeneity before random positioning.

In each subplot, all plant species were recorded, and data on species cover and height were collected for all individuals present.

The design was explicitly adapted to the linear structure of riparian ecosystems. Since habitat patches along the river (e.g., AQ, FP, and RE) are naturally elongated, the 100-m^2 plots were often configured as rectangles (e.g., 4 m × 25 m) rather than as squares, to align with the ecosystem's natural shape. Consequently, a transect length of 30 m perpendicular to the bank was sufficient to span the dominant cross-stream environmental gradient. This approach prioritized ecological representativeness over geometric uniformity, ensuring that sampling units accurately reflected the target habitats. In practice, when the natural riparian zone was narrower or truncated by infrastructure, the transect extended only to the habitat edge, and the actual surveyed length was recorded.

The specific content of the plot survey included:

(1) Species characteristics and identification: Plant species names, coverage, height, and growth status were recorded within each plot. Plant species identification was based on *Flora of China* [19] and *Flora of Jilin* [20].

(2) The latitude and longitude of the plot location were recorded. Twelve environmental factors characterizing the riverine corridor habitat were measured across natural and anthropogenic dimensions. To avoid multicollinearity, the variance inflation factor (VIF) was calculated for all 12 variables. Four highly collinear factors (Aspect, Channel Width, Distance to City Center, and Population Density) were sequentially removed based on a threshold of VIF > 10, resulting in the eight factors detailed in Table 2. These included water depth (WD), canopy cover (CC), and the distance to the river (DTR), which reflect hydrological gradient variations in riparian zones [21–23]; Housing price (HP) was used as a proxy for management intensity, as higher values typically correspond to greater landscape maintenance and human disturbance in urban riparian zones; and CP, which may be correlated with plant community succession timing [24]. DIA influenced herbaceous layer species richness [25]. Collectively, these environmental factors effectively reflect the drivers of plant diversity distribution patterns.

Table 2. Environmental factors and survey methods.

Environmental Factors		Survey Methodology
Natural factor	Water depth (WD)	WD measurements were obtained using direct measurement methods alongside data published via the Changchun River and Lake Chief System Management Platform and the Northeast Institute of Geography and Agroecology's wetland database. Land-based sampling points recorded water depths as 0 cm, indicating only the absence of surface water at the time of measurement but not excluding the influence of groundwater or soil moisture.
	Canopy cover (CC)	The projected area of the woody layer in the observation plot was measured to estimate the numerical value.
	Distance to river (DTR)	The distance between the sample plot and the river channel was measured using a rangefinder.
	Slope (SLP)	The slope of the sample plot was determined using a spirit level.

Table 2. *Cont.*

Environmental Factors		Survey Methodology
Human factors	Human-induced disturbance (HID) [1]	HID was categorized into five levels based on the degree of environmental damage and management intensity.
	Housing price (HP)	Based on field surveys and data published by Changchun's property agency website Anjuke https://shanghai.anjuke.com (accessed on 20 July 2024), this variable reflects the socioeconomic gradient.
	Construction period (CP)	The building's duration of existence was calculated as the difference between the survey year and its year of construction. This metric characterized the developmental history of different urban areas and the temporal evolution of natural habitat succession.
	Distance to industrial area (DIA)	The location of industrial zones was obtained via Google Maps version 11.127.x (accessed on 20 July 2024), and buffer zones were established for these areas in ArcGIS 10.1. The distance between sample plots and industrial zones was calculated. Spatial gradients of environmental pressures (such as pollution and heat island effects) and types of anthropogenic disturbance were characterized.

[1] HID scoring rubric: Levels were assigned as follows: 1 (Minimal): natural vegetation, no visible human impact. 2 (Low): light trampling or scattered litter. 3 (Moderate): partial vegetation removal, soil compaction, or infrequent management. 4 (High): regular mowing/management, constructed paths, or significant habitat alteration. 5 (Severe): hard landscaping, pavement, or intensive regular maintenance.

2.3. Data Processing

2.3.1. Calculation of Species Frequency and Importance Values

The species frequency (F) was calculated using the following formula:

$$F = n/N \times 100\%, \tag{1}$$

where n represents the number of sample plots in which a given species appeared during the survey, and N denotes the total number of sample plots.

The importance value (IV) was employed as an indicator to evaluate the significance of each species within the community, forming a sample plot × species importance value matrix. This study selected three indicators—relative cover (C_r), relative height (H_r), and relative frequency (F_r)—to analyze herbaceous plants in the community. The important value for each species was calculated as follows [26]:

$$\text{IV} = (H_r + C_r + F_r)/3 \tag{2}$$

Iv is a standardized index between 0 and 1, averaged from three relative metrics.

The calculated importance value was used to identify dominant species (IV > 0.05) for community classification using TWINSPAN and to derive the species proportion (P_i) used in the calculation of the Shannon–Wiener and Pielou's diversity indices.

2.3.2. Calculation of Community Species Diversity Indices and Regression Analysis

The species diversity of the community was quantified by applying the following three indices:

Patrick's Richness Index (R):

$$R = S \tag{3}$$

Shannon–Wiener Diversity Index (H):

$$H = -\sum_{i=1}^{P} p_i \ln(p_i) \tag{4}$$

where P_i is the relative importance value of species i, calculated as:

$$P_i = \mathrm{IV}_i/\Sigma\mathrm{IV} \tag{5}$$

this step converts IV to a proportion of total plot importance required for diversity indices, with IV_i being the importance value of species i, and ΣIV the sum of importance values of all species within the plot.

Pielou's Evenness Index (J):

$$J = \frac{H}{\ln S} \tag{6}$$

where H denotes the Shannon–Wiener index and S represents the total number of species.

Each diversity index was compared across the four habitat types using one-way analysis of variance (ANOVA), with Tukey's HSD post hoc tests applied for pairwise comparisons when the ANOVA was significant ($p < 0.05$). The Tukey method controls the family-wise error rate. All tests used an alpha level of 0.05, and the results are reported with the corresponding F-statistic, degrees of freedom, and adjusted p-values.

2.3.3. Quantitative Classification and Ranking of Communities

A total of 89 dominant plant species (total IV > 0.05 and frequency > 0.05) were used as clustering objects to reduce noise from rare species and highlight the major, ecologically interpretable patterns in community composition. A 208 × 89 matrix of relative importance values was constructed, with importance categorized into four levels: 0.05–0.1, 0.1–0.2, 0.2–0.3, and >0.3. The TWINSPAN classification method in PC-ORD5 was employed for quantitative community classification, with results shown as a dendrogram. The habitat factor matrix included two major environmental factor categories, totaling eight factors (Table 1) and forming a plot–environment matrix. Prior to DCA and CCA ordination, species importance values were log-transformed. Species data were analyzed with detrended correspondence analysis (DCA), which produced a maximum axis gradient length of 7.29 (above the 3 threshold). Therefore, univariate CCA was used to examine vegetation–habitat relationships, highlighting how environmental factors influence plant patterns. DCA and CCA were performed using CANOCO 5.0 [27]. Environmental factors were chosen by forward selection. The significance of factors was tested using 999 Monte Carlo simulations, with a significance threshold of 0.05.

2.3.4. Spatial Autocorrelation Analysis

To determine whether spatial proximity among sampling plots influenced the observed patterns of plant diversity, we tested for global spatial autocorrelation in the plot-level Shannon–Wiener diversity index (H') using Moran's I [28]. A distance-based spatial weights matrix was constructed across multiple scales. The primary threshold was set at 1000 m, which corresponds to the systematic spacing between adjacent transects in our sampling design. To account for potential scale dependence, we also tested additional thresholds of 250 m, 500 m, and 750 m [28]. For each threshold, the statistical significance of the observed Moran's I was determined using a Monte Carlo permutation test with 999 randomizations. The outcome of this test provided a decision rule for subsequent ordination modeling: if significant spatial autocorrelation was detected ($p < 0.05$) at any scale, spatial predictors (e.g., principal coordinates of neighborhood matrices vectors) would be incorporated into the CCA to account for spatial structure. A non-significant result across all scales ($p \geq 0.05$) would justify the use of conventional CCA without explicit spatial terms.

3. Results

3.1. Compositional Characteristics of Spontaneous Herbaceous Plants in River Corridors

This survey recorded 181 spontaneous herbaceous plant species, belonging to 55 families and 140 genera. The flora comprised 2 ferns (1.43%), 34 monocots (18.78%), and 145 dicots (80.11%). In terms of origin, there were 137 native (75.69%), 13 non-native (7.18%), and 31 invasive species (17.13%), among which 11 (35.48%) were classified as Level 1 malignant invaders.

The six most frequent invasive taxa exhibited distinct habitat preferences (Figure 2), forming two groups. *Ambrosia trifida* (IV = 6.35), *Bidens frondosa* (IV = 3.40), and *Ambrosia artemisiifolia* (IV = 2.17) were predominantly associated with RE habitats, and *Sonchus oleraceus* (IV = 4.05), *Galinsoga quadriradiata* (IV = 3.02), and *Conyza canadensis* (IV = 2.83) prevailed in SN-A habitats. Given that RE and SN-A are spatially correlated with urban zones experiencing stronger anthropogenic disturbance and lower property values, the aggregation of these dominant invaders indicates a clear association with areas of heightened human pressure and reduced socioeconomic investment.

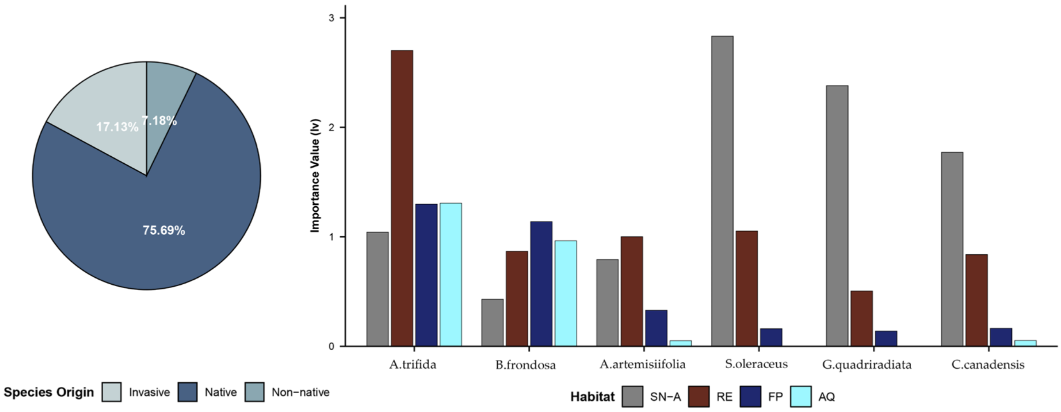

Figure 2. Composition and habitat distribution of invasive species in Changchun's river corridors. Note: SN-A: semi-natural/semi-artificial green spaces; RE: riparian revetment; FP: floodplain; AQ: aquatic.

The overall invasion pressure in this watershed was notable. The 31 recorded invasive species accounted for 17.13% of the total flora. This proportion is significantly higher than that reported for the water system of Guilin [29], a tourist city in southern China (approximately 13%) but comparable to findings from northern cities, such as Harbin (18.54%) [9] and Zhengzhou (18.22%) [30]. Notably, the invasive plant proportion in Nanchang's river corridors was reported as high as 28.33% [31], underscoring substantial regional variation in invasion pressure across China. Collectively, these comparisons place the invasion rate of the river corridors in Changchun City at a medium–high level among Chinese urban waterways, indicating widespread and persistent pressure from alien species. This macro-scale pattern reinforces the micro-scale finding that dominant invaders are clustered in disturbed areas, indicating urbanization-driven habitat disturbance as a key driver of local biological invasions and biotic homogenization.

To quantitatively assess the relationship between invasion patterns and environmental gradients, we calculated the total invasive species importance value for each plot and tested its correlation with all eight environmental factors using Spearman's rank correlation. Invasive species abundance was most strongly correlated with human-induced disturbance (HID: $\varrho = -0.426$, $p < 0.001$) and also significantly correlated with water depth (WD: $\varrho = -0.178$, $p = 0.010$). No significant correlations were found with the remaining factors (all $p > 0.05$).

The spontaneous herbaceous layer was dominated by the families Asteraceae (43 species, 23.76%), Gramineae (18 species, 9.94%), Fabaceae (12 species, 6.63%), Labiatae (11 species, 6.08%), and Polygonaceae (11 species, 6.08%). In terms of life form, the riparian zone in Changchun supported 168 terrestrial (92.82%) and 13 aquatic species (7.18%), including 33 xerophytes (18.23%), 102 mesophytes (56.35%), 33 hygrophytes (18.23%), and 13 emergent plants (7.18%). The most frequently encountered species were *Setaria viridis*, *Taraxacum mongolicum*, *Geranium wilfordii*, *Glycine soja*, *Plantago asiatica*, *Sonchus oleraceus*, *Poa annua*, and *Chenopodium album*.

3.2. Variations in the α Diversity of Spontaneous Herbaceous Plants in Different Habitat Types

As shown in Figure 3, Shannon diversity varied significantly among habitat types (ANOVA F = 51.7, df = 3, $p < 0.001$). Post hoc comparisons showed that AQ (median H = 1.09) had significantly lower diversity than RE (H = 2.34, $p < 0.001$), FP (H = 2.30, $p < 0.001$), and SN-A (H = 2.34, $p < 0.001$). Differences among these three habitats were not significant (all pairwise $p > 0.15$).

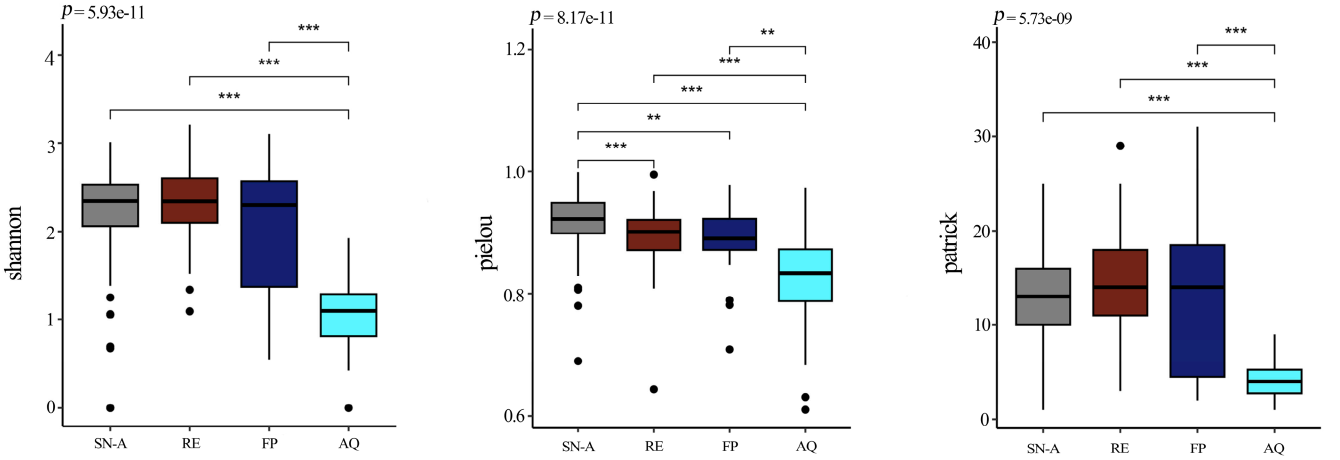

Figure 3. Variations in species diversity indices of spontaneous herbaceous plants across habitats. Note: SN-A (n = 102); RE (n = 59); FP (n = 24); AQ (n = 23) *** $p < 0.001$; ** $p < 0.01$.

Species richness (Patrick index) displayed the same pattern (ANOVA F = 51.9, df = 3, $p < 0.001$), with AQ (median R = 4.0) supporting fewer species than RE (14.0), FP (13.5), and SN-A (13.0), all with $p < 0.001$.

Evenness (Pielou index) showed the order (SN-A > RE > FP > AQ), although the difference between RE and FP was not significant ($p > 0.15$). Together, these results indicate a two-tier structure, with AQ forming a distinct low-diversity group and the remaining habitats (SN-A, RE, and FP) forming a higher-diversity cluster, rather than a smooth four-level gradient.

3.3. Differences in Spontaneous Herbaceous Plant Species Composition Across Habitat Types

3.3.1. Differences in the Dominant Species Composition

To gain a deeper understanding of the role of habitat type in shaping plant communities, we analyzed the top 10 dominant species in four habitat types (AQ, FP, RE, and SN-A), which collectively encompassed 23 species. This analysis focused on the distribution of importance values (IV) for each habitat (Figure 4), revealing variations in the dominant species composition across these habitats.

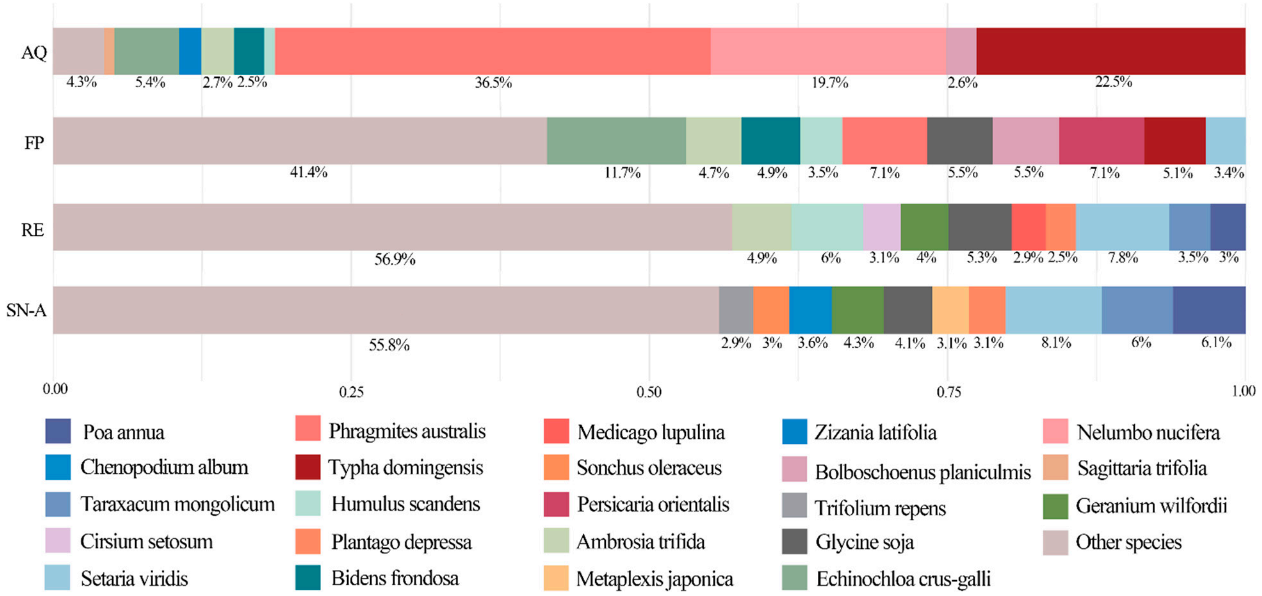

Figure 4. Differences in dominant species across habitats.

Setaria viridis and *Glycine soja* emerged as shared dominant species in SN-A, RE, and FP habitats, indicating functional or environmental overlaps among these habitats. *Humulus scandens* and *Ambrosia trifida* were identified as dominant in RE, FP, and AQ habitats, suggesting that these species thrive in a range of habitats with certain ecological commonalities. There were distinct dominant assemblages in each habitat. In SN-A habitats, *Setaria viridis* was accompanied by *Poa annua* and *Taraxacum mongolicum* as key dominant species, reflecting the unique vegetation structure of this habitat. In RE habitats, *Setaria viridis* maintained its dominance alongside *Humulus scandens* and *Glycine soja*, forming a characteristic species complex. In FP habitats, *Echinochloa crus-galli*, *Persicaria orientalis*, and *Phragmites australis* predominated, highlighting their adaptability to the specific environmental conditions of the FP habitat. In AQ habitats, *Phragmites australis*, *Typha domingensis*, and *Nelumbo nucifera* stood out, representing the typical aquatic and semi-aquatic vegetation dominant in such habitats.

These findings collectively highlight that habitat type acts as a pivotal determinant of dominant species composition. The differential distribution of these 23 species across AQ, FP, RE, and SN-A habitats reflects their evolutionary and ecological adaptations to soil moisture, nutrient availability, light conditions, and other abiotic factors inherent to each habitat type.

3.3.2. Community Quantification Classification and Dominant Types

A TWINSPAN quantitative classification of spontaneous herbaceous plant importance values across 208 sample plots in river corridors of Changchun's central urban district divided the study area into 11 communities (Table 3; Figure 5). The sample sizes among these communities were highly uneven. Four communities—II (*Trifolium repens–Poa annua*, $n = 35$), III (*Setaria viridis–Taraxacum mongolicum*, $n = 39$), V (*Glycine soja–Setaria viridis*, $n = 46$), and VI (*Echinochloa crus-galli–Ambrosia trifida*, $n = 32$)—were represented by 32 or more plots each and were therefore considered dominant and well-characterized communities. The remaining seven communities (I, IV, VII, VIII, IX, X, and XI) contained between 4 and 16 plots each. The environmental characteristics reported for these smaller groups should be interpreted as descriptive indicators; their statistical robustness was limited by the small sample sizes. These communities were named based on the nomenclature principles of "Vegetation of China" and the dominant species of each stratum [32].

Table 3. Environmental factor variable ranges and mean values of river corridor communities in the central urban area of Changchun.

Community Type	Community Name	n	SLP (°)	CC (%)	DTR (m)	WD (m)	HID	HP (CNY 10 k/m^2)	CP (yr)	DIA (km)
I	*Chenopodium album–Solanum nigrum*	6	0–23	0–98	20–25	0	4–5	0.46–0.75	13–20	0.1–5.0
II	*Trifolium repens–Poa annua* ★	35	6.3	55.9	14.3	0	4	0.73	17	2.5
III	*Setaria viridis–Taraxacum mongolicum* ★	39	6.8	50.5	13.8	0	3	0.84	14	2.5
IV	*Glycine soja*	16	6.9	21.8	10.6	0	2	0.91	9	3.3
V	*Glycine soja–Setaria viridis* ★	46	14.2	12.7	5.6	0	3	0.82	13	1.6
VI	*Echinochloa crus-galli–Ambrosia trifida* ★	32	12.3	4.8	5.7	0	3	0.76	12	3.3
VII	*Ambrosia trifida*	6	0–35	0–94	0–5	0.00–0.22	2–3	0.46–1.06	13–20	0.3–5.0
VIII	*Typha domingensis–Phragmites australis*	4	0–35	0	0–0.5	0.05–0.62	3–4	0.46–1.06	8–13	0.2–8.0
IX	*Typha domingensis*	9	0	0	0–0.5	0.01–0.81	4–5	0.66–1.06	8–16	0.2–5.0
X	*Phragmitesaustralis*	9	0–3	0	0–0.5	0.01–0.72	1–5	0.46–1.06	13–27	0.3–5.0
XI	*Phragmites australis*	6	0	0	0	0.00–0.83	3–4	0.46–1.06	8–20	0.3–1.0

Note: ★ Communities with relatively robust sample sizes ($n \geq 32$). SLP: slope; CC: canopy cover; DTR: distance to river; WD: water depth; HID: human-induced disturbance; HP: housing price; CP: construction period; DIA: distance to industrial area.

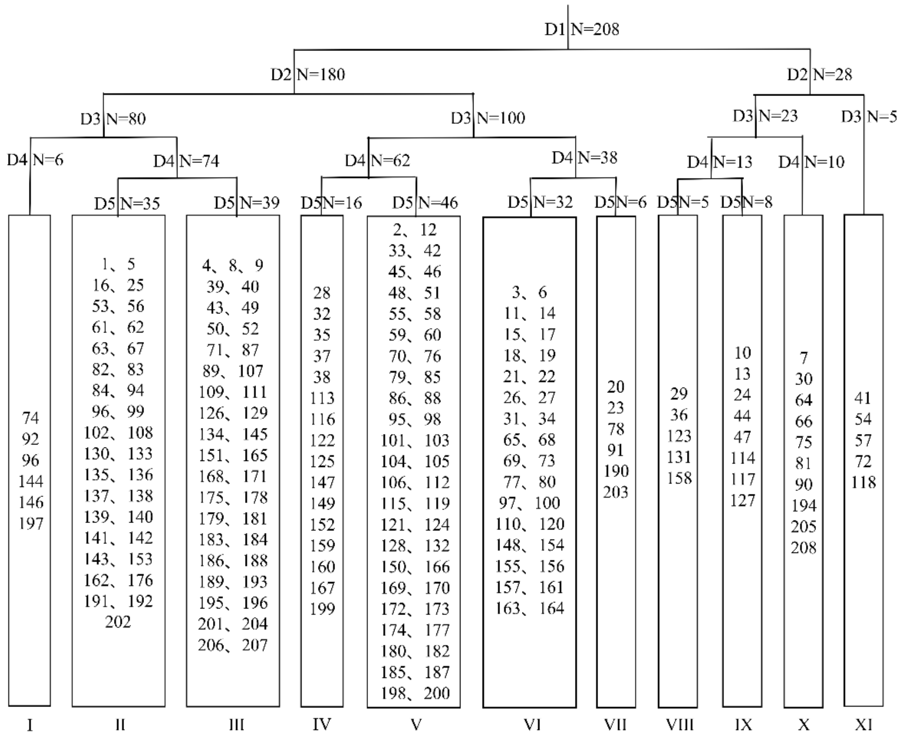

Figure 5. TWINSPAN classification tree diagram of 208 sample plots in central Changchun city. Note: Dk: Division number; N: Total number sample; 1–208: Sample number; I–X, VII: Community number.

The classification revealed two dominant environmental filters:

1. Hydrological Gradient (Aquatic ↔ Terrestrial): The communities were arranged along a moisture gradient. At the aquatic extreme (Communities VIII–XI), wetland species, such as *Typha domingensis* and *Phragmites australis*, dominated in frequently inundated habitats (mean WD: 0.18–0.42 m). At the terrestrial extreme (Communities I–IV), xerophytic species, such as *Chenopodium album* and *Setaria viridis*, prevailed in dry, upland sites (WD: 0 m). Intermediate communities (V–VII) occupied the riparian transition zone.
2. Anthropogenic Disturbance Gradient: A secondary gradient reflected human influence. Highly disturbed urban interfaces (Communities I–III, mean HID: 3–5) supported disturbance-tolerant generalists and cultivated species. Moderately disturbed areas (Communities IV–VI) exhibited the highest community-type diversity. Near-natural habitats with minimal disturbance (Communities VIII–XI) were dominated by hydrophytes.

This dual-filter process (hydrology primary and disturbance secondary) creates a predictable community sequence from aquatic to urban upland habitats.

3.4. Relationship Between Spontaneous Herbaceous Plant Communities and Environmental Factors

3.4.1. Spatial Autocorrelation Analysis of Shannon Diversity Index

Multi-scale spatial autocorrelation tests (250 m, 500 m, 750 m, and 1000 m) revealed no significant spatial dependency in Shannon diversity (all $p > 0.38$, Table 4). Moran's I values ranged from 0.042 at 250 m to 0.022 at 1000 m, with mean neighbors increasing from 0.4 to 1.2. The absence of significant spatial autocorrelation across all scales confirms sampling unit independence and justifies conventional CCA without spatial correction.

Table 4. Multi-scale spatial autocorrelation results.

Distance (m)	Moran's I	*p*-Value	Mean Neighbors
250	0.042	0.394	0.4
500	0.032	0.394	0.7
750	0.025	0.393	1.0
1000	0.022	0.382	1.2

3.4.2. Detrended Correspondence Analysis Sorting of Plant Community Plots

Based on DCA results for plot–species data and the principle that the first ordination axis length must exceed 4, this study used a unimodal model to ordain 208 plots (Figure 6). The first two DCA axes had gradient lengths of 5.46 and 7.29 standard deviations (Table 5) and explained 68.24% of the total variation in species composition (Axis 1: 44.52%; Axis 2: 23.72%). Based on TWINSPAN classification, we grouped the plant communities from the 208 plots into 11 types. These communities showed spatial differentiation on the DCA ordination plot (Figure 6): from left to right, they reflected an ordered transition of AQ, FP, RE, and SN-A habitats. This habitat gradient pattern directly supports the strong link between plot community composition and environmental conditions, confirming the scientific validity and rationality of the TWINSPAN classification results.

Table 5. DCA ordination of plant community distribution.

Content	Eigenvalue	% of Total Inertia	Gradient Length
Axis 1	0.5216	44.52	5.46
Axis 2	0.2779	23.72	7.29
Axis 3	0.2020	17.24	3.20
Axis 4	0.1701	14.52	2.80

The gradient distribution of riverine habitats was correlated with the gradient variation in hydrological conditions. AQ habitats maintained prolonged high moisture levels, favoring moisture-loving plant growth. FP habitats experienced cyclical water fluctuations due to alternating flood and low-water periods. RE habitats at the water–land interface endured frequent water level variations. SN-A habitats exhibited relatively stable moisture conditions through artificial irrigation regulation. These differing hydrological regimes directly induced gradient transitions in the plant community type and distribution pattern.

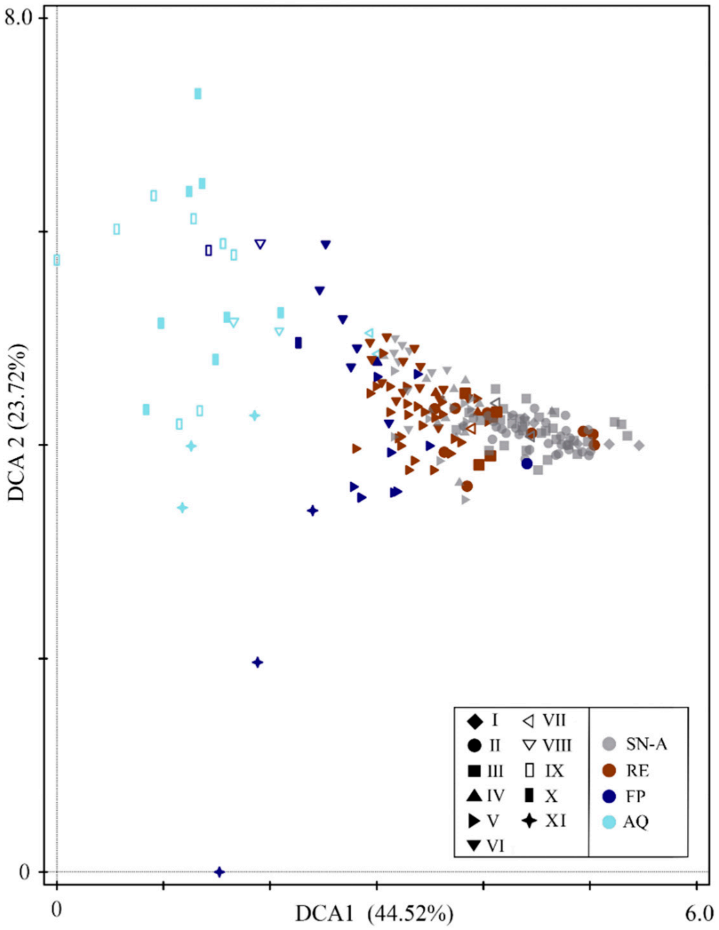

Figure 6. Sample plot DCA ordination.

3.4.3. Canonical Correspondence Analysis Ordination of Survey Plots

To elucidate the relationships between the community distribution and environmental factors, canonical correspondence analysis (CCA) was performed. Prior to ordination, VIF analysis was conducted to screen for multicollinearity among all measured environmental variables. Using a threshold of VIF > 10, four highly collinear factors (Aspect, Channel Width, Distance to City Center, and Population Density) were sequentially removed. The remaining eight uncorrelated variables were retained in the final CCA. The analysis used the importance values of 89 spontaneous herbaceous species and the 8 environmental factors from the 208 surveyed plots (Figure 7).

As shown in Table 5, the eight environmental variables together explained 13.3% of the total variation (inertia) in species composition. Of this explainable portion (the constrained inertia), the first CCA axis accounted for 40.05%, and the first two axes cumulatively accounted for 65.01%. Thus, while the measured environmental factors explain a modest fraction of total variation, the hydrological gradient (Axis 1) and anthropogenic disturbance gradient (Axis 2) are the dominant structuring forces within that explainable component. The interpretation of these axes was informed by the ordination plot (Figure 7) and correlation statistics (Tables 6 and 7). The first CCA axis accounted for 40.05% of the species–environment relationship and represented the hydrological gradient, with WD showing a strong positive association and CC and DTR showing strong negative associations. WD was significantly positively correlated with this axis ($p < 0.002$), whereas CC was significantly negatively correlated ($p < 0.004$). The strength of the correlation with the first axis decreased in the following order: WD, CC, HP, DTR, and DIA. The second axis captured anthropogenic and topographic variation, with HID and HP positively related and SLP negatively related. HID and CP were significantly positively correlated with the second axis ($p < 0.002$), and SLP was significantly negatively correlated ($p < 0.002$). The correlations with the second axis, in descending order of magnitude, were HID, HP, SLP, and CP.

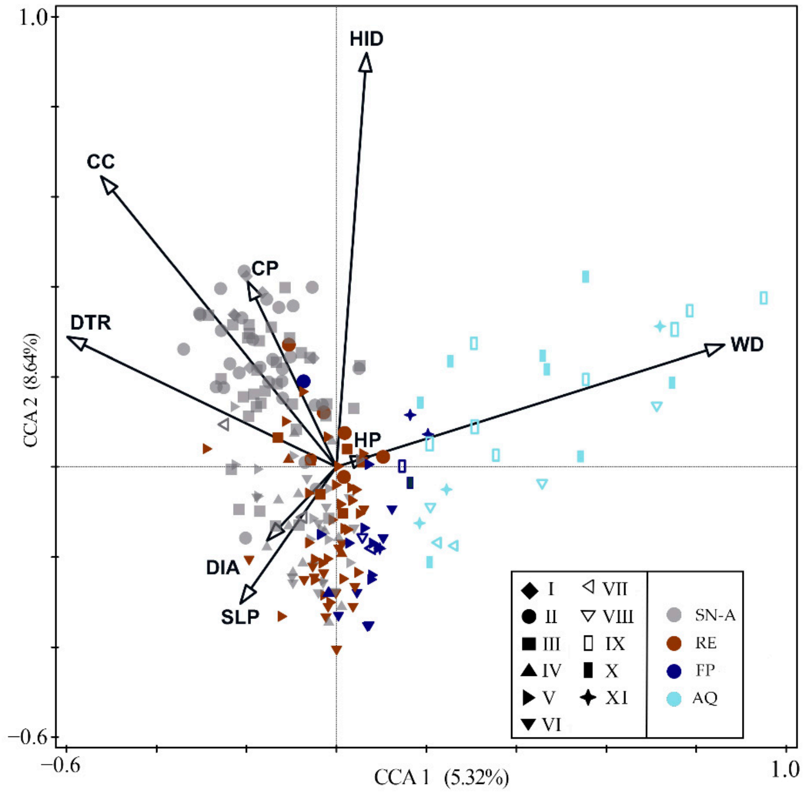

Figure 7. CCA ordination of sample plots. Note: Communities II, III, V, and VI had larger sample sizes and greater statistical robustness. The remaining communities were based on relatively fewer plots but are included to represent the full range of vegetation types observed.

Table 6. CCA ordination statistics of vegetation communities and environmental factors in river corridors of central Changchun city.

	Eigenvalues	% of Total Inertia	Canonical Correlation Coefficient	% of Constrained Inertia	Cumulative % of Constrained Eigenvalue
Axis 1	0.5442	5.32	0.8574	40.05	40.05
Axis 2	0.3391	8.64	0.8821	24.96	65.01
Axis 3	0.1695	10.30	0.7191	12.47	77.48
Axis 4	0.0932	11.21	0.5528	6.86	84.34

Note: % of Total Inertia is the proportion of the total variance in the species data explained by each axis. % of Constrained Inertia is the proportion of the variance explained by the environmental variables (the constrained variance, which is 13.3% of the total inertia; see Table 6) that is captured by each axis.

The distribution of the 11 TWINSPAN-classified communities within the CCA ordination space was consistent with their observed habitat affiliations (Figure 7; Table 3). Communities predominantly found in AQ habitats (IX, X, and XI) plotted on the positive end of Axis 1 (high WD). The community characteristics of SN-A habitats (I, II, and III) clustered on the negative end of Axis 1 (low WD, high CC). Communities associated with RE and FP habitats (IV, V, VI, VII, and VIII) occupied intermediate positions along Axis 1 and varied along Axis 2. This spatial arrangement within the ordination confirmed the major compositional gradients identified by the TWINSPAN classification and demonstrated continuous variation in the community composition along the hydrological (Axis 1) and anthropogenic (Axis 2) gradients.

Table 7. CCA ordination relating environmental factors to vegetation communities in river corridors of central Changchun city.

Environmental Factors		Marginal Explained Variance (%)	Contribution	Pseudo-F	*p*
Natural factors	WD (m)	4.3	32.7	9.4	0.002
	CC (%)	1.6	12.2	3.6	0.002
	DTR (m)	0.8	5.8	1.7	0.004
	SLP (°)	0.8	5.7	1.7	0.002
Human factors	HID	2.8	20.9	6.1	0.002
	HP (CNY 10 k/m^2)	1.5	11.6	3.5	0.002
	CP (year)	0.8	5.8	1.8	0.002
	DIA (km)	0.7	5.3	1.6	0.002

4. Discussion

4.1. Hydrological Gradient as the Dominant Filter in Community Assembly

Our results indicate that, among the environmental variables measured, the hydrological gradient emerged as the most important predictor of community composition in Changchun's urban river corridors. This is most clearly demonstrated by the first axis of the CCA ordination, which accounted for 40.05% of the explainable species–environment relationship and was strongly associated with WD, CC, and DTR (Tables 6 and 7). This axis represents a fundamental moisture availability gradient from permanently or frequently inundated areas to dry, upland sites.

It is important to acknowledge that the eight environmental variables measured in this study explained only 13.3% of the total variation in species composition (Table 6). The remaining ~87% of unexplained variance may be attributed to factors not captured by our sampling design, such as dispersal limitation, unmeasured soil properties (e.g., nutrient content, pH), stochastic colonization events, or biotic interactions (e.g., competition, facilitation). Despite this relatively low total explained variance—which is typical for community-level studies in complex urban environments—the consistent alignment of community composition with the hydrological gradient across multiple independent analyses (DCA, TWINSPAN, CCA) provides robust evidence that moisture availability is a primary ecological filter in this system.

The spatial manifestation of this gradient was evident across multiple analyses. DCA showed an ordered transition of habitats from AQ to FP, then to RE, and finally to SN-A areas (Figure 7). This sequence aligned with the moisture gradient defined by the CCA. The TWINSPAN classification revealed a continuous shift in community composition along this gradient: from AQ communities dominated by *Typha domingensis* and *Phragmites australis* (Communities VIII–XI), through communities adapted to periodic flooding (e.g., *Echinochloa crus-galli–Ambrosia trifida* in FP/RE, Community VI), to terrestrial communities dominated by xerophytic and mesophytic species, such as *Setaria viridis* and *Chenopodium album* (Communities I–V).

The observed peak in species diversity in RE and FP habitats (Figure 3) reinforces the role of dynamic hydrology as a structuring force. These intermediate zones experience periodic disturbances from water level fluctuations, which enhance habitat heterogeneity and resource availability, supporting higher species richness—a pattern consistent with the intermediate disturbance hypothesis [33,34]. This supports the concept of environmental filtering [35], in which abiotic conditions select for species with suitable functional traits, with hydrology being the key filter in this riparian system [3,36]. Although hydrological filtering acts as the dominant assembly mechanism, anthropogenic modification in urban river corridors does not act independently but overlays and modifies the natural hydrological template, reshaping the community structure along the aquatic–terrestrial gradient.

4.2. Anthropogenic Modification Reshaping the Hydrological Template

Although hydrology provides the foundational template, human activities act as a pervasive secondary filter, significantly altering community composition. The second CCA axis, which was correlated with HID, HP, SLP, and CP, captured this anthropogenic dimension. A high HID consistently led to biotic homogenization and reduced community complexity. In frequently used parklands and trails, management practices, such as mowing, trampling, and waste disposal, favor a limited set of disturbance-tolerant generalists (e.g., *Setaria viridis* and *Taraxacum mongolicum*), simplifying the community structure. This aligns with findings on herbaceous plant responses to disturbance in other urban riparian zones [37].

Conversely, areas associated with higher socioeconomic investment—indicated by a higher HP and longer CP—often exhibited distinct communities. These areas typically had a higher CC, resulting from intensive landscaping and maintenance, and were often enriched with cultivated species, such as *Hosta plantaginea* and *Medicago sativa*. This reflects a “luxury effect”, in which greater economic resources lead to more managed, less natural vegetation [38,39]. Engineering interventions, particularly the construction of steep, hardened revetments (high SLP), create novel habitats that are prone to erosion. SLP also had a significant relationship with the community distribution. By influencing habitat moisture levels and soil stability, SLP indirectly determines the composition of adapted plant communities, aligning with findings by Shen Peixin et al. [9]. DIA introduced a pollution filter, reducing species richness and selecting for pollution-tolerant taxa, as observed in the *Chenopodium album*–*Solanum nigrum* community (Community I) [40–42]. The interactive effect of altered hydrology and intensive anthropogenic disturbance creates specific habitat niches in urban river corridors, driving the invasion dynamics of alien species and forming the spatial pattern of invasion hotspots.

4.3. Invasion Dynamics and Implications for Corridor Management

The significant presence of invasive species (17.13% of total flora) and their aggregated distribution are direct consequences of the interplay between altered hydrology and anthropogenic pressure observed in Changchun’s central urban river corridors. Invasive species were not randomly distributed but concentrated in specific habitats created by human modification. Dominant invaders, such as *Ambrosia trifida* and *Echinochloa crus-galli*, formed near-monocultures (Communities VI and VII) primarily in urban fringe RE zones characterized by a high HID, moderate to low HP, and altered, unstable hydrology. These habitats represent “invasion hotspots” where natural hydrological filters are weakened or circumvented by disturbance, creating open niches and resource opportunities for highly competitive alien species [43,44]. This pattern suggests that urbanization-driven habitat alteration is a key factor influencing local biotic homogenization within the study area.

Our statistical analysis revealed that invasive species abundance was significantly correlated with HID ($\varrho = -0.426$, $p < 0.001$), but the nature of this relationship is nuanced. The negative correlation reflects a duality: while high-disturbance areas (RE and SN-A habitats, HID 3–5) harbor greater invasive species richness (Figure 2), the highest total importance values occur in low-disturbance sites (HID 1–2) where highly competitive invaders such as Ambrosia trifida form near-monocultures. This suggests that disturbance facilitates invasion by creating opportunities for multiple species to establish, but once established, strong competitors can dominate even under low-disturbance conditions, potentially excluding natives and other invaders alike. The significant but weaker correlation with WD ($\varrho = -0.178$, $p = 0.010$) indicates that hydrological stress (e.g., frequent inundation in AQ and FP habitats) suppresses invasion, consistent with the environmental filtering role of hydrology documented in Section 4.1.

These findings have actionable implications for the management of Changchun's urban river corridors:

1. Prioritize the Protection of Natural Hydrological Processes: In habitats where natural dynamics persist (e.g., FP and RE) within the study area, management should focus on maintaining or restoring hydrological connectivity and natural flood regimes. This strengthens the inherent environmental filter against invaders and supports native diversity.
2. Adopt Differentiated Strategies in Managed Areas: In highly artificial and intensively used zones (SN-A), the management goal should shift from simple disturbance control to the active design of resilient landscapes. This involves creating stable, diverse plantings using stress-tolerant native species to preempt invasion and reduce long-term maintenance [45].
3. Target Control in Invasion Hotspots: Invasion hotspots in Changchun's river corridors manifest in two forms that require differentiated management strategies. High-disturbance areas (e.g., urban fringe zones, areas near industrial sites) harbor high invasive species richness and act as potential dispersal epicenters; here, monitoring and early intervention should be prioritized to prevent spread. Conversely, low-disturbance areas where highly competitive invaders (e.g., *Ambrosia trifida*) form near-monocultures represent sites of high ecological impact; in these areas, active removal and restoration with native competitive species may be necessary. This dual-target approach addresses both invasion sources and established dominant invaders.

In conclusion, the vegetation mosaic in Changchun's urban river corridors is the product of a dominant hydrological filter overlain and modified by a secondary anthropogenic filter. Their interaction correlates with the distribution of native communities and the success and spatial patterning of invasive species in this specific urban ecosystem. Effective management must recognize the dual-factor framework to develop spatially explicit strategies that conserve ecological function while enhancing the resilience of these vital urban green–blue infrastructures.

5. Conclusions

Both natural and human factors influenced plant diversity in the river corridors of central Changchun; however, the effects of individual factors differed among habitats and plant functional groups. Among the environmental variables measured, the hydrological gradient—represented collectively by WD, CC, and DTR—was the strongest predictor of community distribution in this urban ecosystem, with HID as a secondary contributor. This study provides a scientific foundation for the conservation and sustainable utilization of plant resources in Changchun's urban river corridors. The extent to which these patterns can be generalized to other temperate cities, climate zones, and river management regimes remains to be established through comparative multi-city studies spanning multiple growing seasons.

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Abbreviations

WD: water depth; CC: canopy cover; DTR: distance to river; SLP: slope; HID: human-induced disturbance; HP: housing price; CP: construction period; DIA: distance to industrial area; AQ: aquatic habitats; FP: floodplain habitats; RE: riparian revetment habitats; SN-A: semi-natural/semi-artificial green space habitats.

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