**FORESTED WETLANDS, FLOODPLAINS AND RIPARIAN CORRIDORS**

# Environmental Flow Increases The Riparian Vegetation Diversity And Community Similarity

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## Abstract

Environmental flow is increasingly used in restoring degraded riparian vegetation. To assess the impact of environmental flow on plant community characteristics and to provide a scientific basis for the subsequent restoration and management of the riparian vegetation at Yongding River (Beijing Section), field surveys were conducted before and after environmental flow application in 2022. Before environmental flow application, sixty-nine species were identified, and the number of species increased to ninety-six species after environmental flow application. Community similarity analysis found that riparian vegetation communities were dominated by emergent hygrophytic plants and the introduced *Xanthium italicum* had the largest contribution before environmental flow application. The environmental flow increased the proportion of submerged plants, four submerged plant species were among the top ten species contributing to dissimilarity. Canonical correspondence analysis found that soil total nitrogen and organic matter significantly influenced riparian plant richness. Non-metric multidimensional scaling analysis showed that after environmental flow application, the similarity of plant communities in the mountain and plain sections increased. However, it is worth noting that the invasive species *Bidens frondosa* became dominant in the mountain section, whereas the invasive species *Xanthium italicum* was widely distributed in the plain section after environmental flow application. The results showed that environmental flow increased mountain section's vegetation uniformity and plant species richness in the plain section, enhancing plant communities similarity in both regions. Environmental water application supports the spread of both native and invasive species; thus, future management should prioritize the timing of environmental flow to prevent invasive species' widespread dissemination.

## Introduction

The riparian zone is a transitional area between the terrestrial and aquatic environments, which is crital for local and regional biodiversity conservation (Sargac et al. 2021). It is characterized by its complex and diverse habitat structures, playing a crucial role in the flow of nutrients and energy. Vegetation in the riparian zone is an important component of the riparian ecosystem, providing basal energy for the river ecosystem and playing a key role in the maintenance of riverine ecological function (Cornejo-Denman et al. 2018; Guo et al. 2021). The diversity of riparian vegetation is the basis for riparian zone ecosystem health and ecosystem services as it helps to regulate the local microclimate (Riis et al. 2020), to maintain the flow regime of the river

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(del Tanago et al. 2021), and to provide habitats for other biota (Epaphras et al. 2007; Bennett et al. 2014).

Previous studies have demonstrated that flooding regime, elevation gradient, soil organic matter, and nutrients all affect the composition and spatial distribution of riparian vegetation, determining the composition of plant communities, species diversity, and functional traits (Dwire et al. 2006; Sirolli et al. 2022). Among these, hydrology, including the frequency, depth and duration of inundation, is a vital factor in determining the characteristics of plant communities by directly influencing the growth, reproduction, distribution, and dispersal of plants (Zhu et al. 2017). However, due to rapid economic and social development in many catchments, industrial and domestic water demands have increased rapidly, leading to flow deficits and the associated impacts on riparian vegetation communities (Ellery Mayence et al. 2010; Chen et al. 2020; Shaeri Karimi et al. 2021). River drying can lead to decreases in the richness and abundance of helophytes and submerged plants, and increases in drought-resistant plants (Datry et al. 2014; Wassens et al. 2017). It also affects the dispersal and germination efficiency of plant reproductive bodies (Kong et al. 2021). Meanwhile, drying also affects the chemical properties of sediment and regional groundwater, which can further impact the riparian vegetation community (Yang et al. 2020; Ma and Ma 2022).

Environmental flow refers to the quantity, timing of river flow required to sustain aquatic ecosystems, with the aim of maintaining ecosystem integrity (Arthington et al. 2018; Mohan et al. 2022). Previous studies found that environmental flow can effectively improve plant diversity (Ahmadi et al. 2019), increase landscape heterogeneity and ecosystem complexity (Cao et al. 2023). It can also increase inundation extent, raise groundwater level, therefore, improve the soil water conditions for plant growth (Zhang et al. 2017; Chen et al. 2020). At the same time, environmental flow accelerates the exchange rate of water between atmosphere and sediment, improving the chemical properties of sediment, increasing plant height, coverage (Zhang et al. 2022) and biomass (Wang et al. 2018). For example, Gomez-Sapiens et al. (2020) found that the vegetation coverage in the riparian zone increased by 14% after environmental flow application (Gomez-Sapiens et al. 2020). Environmental flow can also decrease the concentration of pollutants and improve local water quality (Yang et al. 2022; Chen et al. 2023). Therefore, environmental flow is an effective way to restore riparian vegetation (Xie and Li 2022). However, environmental water allocation reduces the water availability of other users, it might also promote the dispersion of invasive species (Perkins et al. 2016), such as

*Juncus ingens* (Vivian et al. 2014), *Pacifastacus leniusculus* (Mathers et al. 2020), *Cyprinus carpio* (Koehn et al. 2018), leading to changes in landscape patterns.

Therefore, this research aimed to address the following key questions: (i) how the vegetation community along the Yongding River changed after environmental flow application; and (ii) which environmental factors were associated with the changes in vegetation community structure before and after environmental flow application? The study could provide a scientific basis for improvements in Yongding River riparian vegetation management and urban watercourse management more broadly.

## Methods

### Study Area

Yongding River (Fig. 1) is about 865 km long, draining an area of 76,700 km². The basin belongs to a temperate sub-humid and semi-arid continental monsoon climate, with an annual average precipitation is approximately 450 mm (Du et al. 2023). The length of the Beijing section is about 170 km, mainly flowing through the southwest and southern parts before entering Baiyangdian in Hebei Province. The section from Guangting Reservoir to Sanjiadian Dam, termed the mountain section, has a narrow river channel, and is differentiated from the section extending from South Six Ring Road to Qujiadian Reservoir, termed the plain section. Yongding River is an important ecological asset of Beijing. Due to the increased demand of water for production and domestic consumption, the Yongding River diversion canal was built in the mid-1950s, diverting almost all the water from the Yongding River above Sanjiadian into Beijing, as a result, the riverbed below Sanjiadian was dry for most time of the year. Consequently, the prevalence of riparian plant species along the Yongding River is gradually replaced by xerophytes, resulting in a reduction in groundwater levels, decrease of landscape heterogeneity, and degradation of the river ecosystem. In the downstream area, lack of aquatic plants, severe soil erosion, and increased sedimentation promote the infilling of the river. At the same time, riparian vegetation degradation weakens the water conservation capacity, resulting in increased risks of serious floods and droughts (Ren et al. 2021). To restore the damaged ecosystem, Beijing government initiated an environmental water project using reservoir water and recycled water to assist the recovery of the riverine ecosystem (Bai et al. 2023). In September 2021, the 865 km long river channel of the Yongding River achieved bank-full flow for the first time since the cutoff in 1996, and the full flow was maintained in
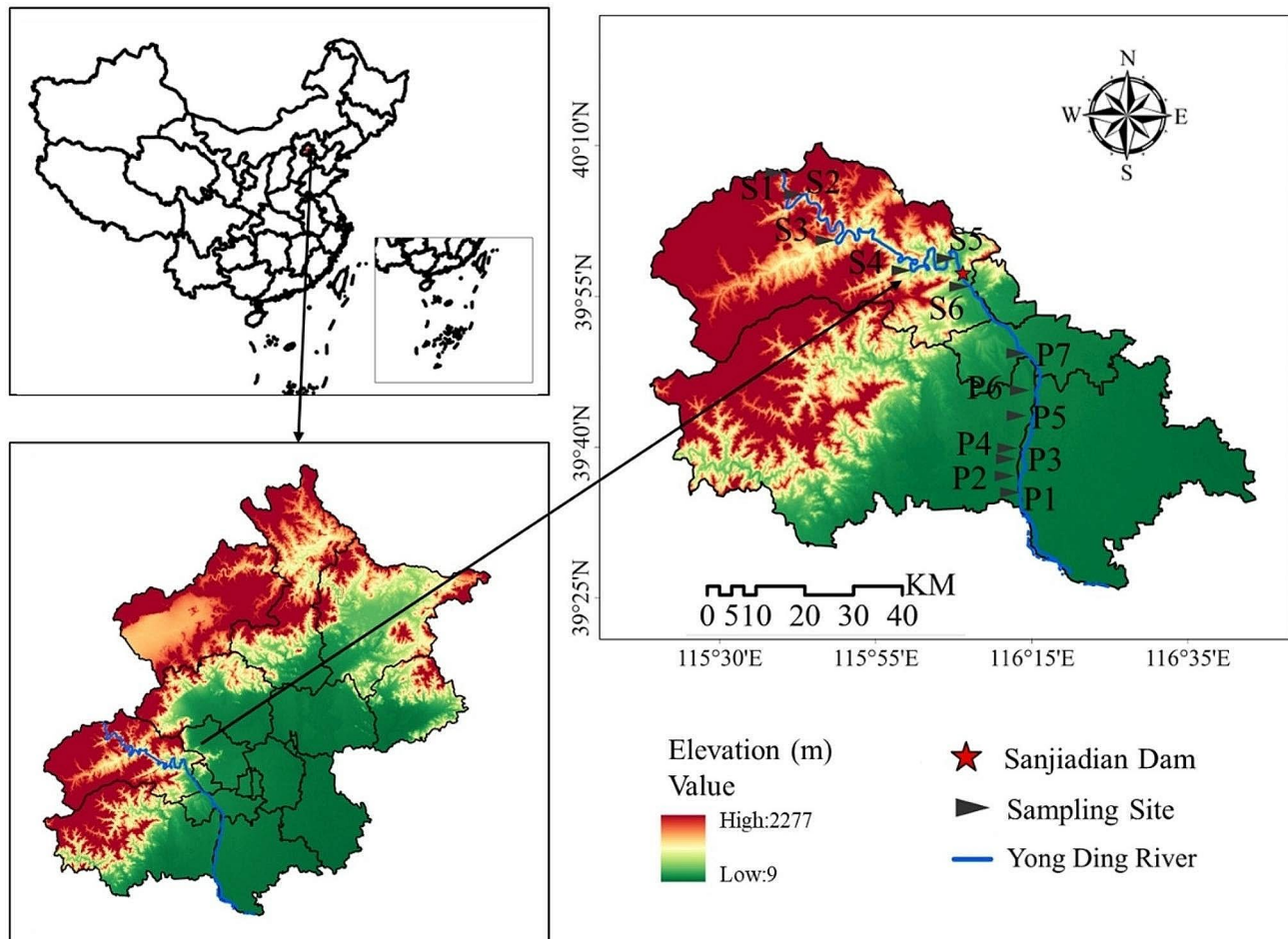
**Fig. 1** The distribution of 13 riparian vegetation community survey sites in Yongding River (Beijing section). S1-S6 are mountain sites and P1-P7 are plain sites

spring and autumn in 2022. This study conducted riparian vegetation surveys at six sites in the mountain section (S1-S6) and seven sites in the plain section (P1-P7) before (from April 28th to May 2nd) and after (From June 28th to July 1st) spring replenishment of river channels (From May 1st to June 15th) in 2022 (Fig. 1; Table 1).

## Field Survey

Small-scale environmental flow application testing in the Yongding River proved that the approach effectively alleviated the water stress and improved the local hydrological conditions (Luo et al. 2019; Qin et al. 2019). The goal for the mountain section is to maintain a persistent river flow. In the plain section, the goal is to maintain the presentence of surface water for more than 200 days in a year with a combination of reservoir and local recycled water. As the targets and durations of environmental flow in the mountain and plain sections of the Yongding River varied, this study stratified sampling between these river segments. Our

field surveys were used to estimate riparian vegetation community characteristics including species composition, abundance, and dominant species variation before and after an environmental flow release.

Because the environment is highly modified in Yongding River, we chose the display of transects and quadrats to make sure it covers the widest riparian area. As the width of riparian zone varies so we chose 2–3 transects at each site, and each transect has 3–6 quadrats. The transects with various lengths were set perpendicular to the riverbank (Table 1). The transects were at least 10 m apart. From the riverine area to the edge of the river, along these transects, 3–6 1 m × 1 m sample quadrats were set along the transect line. A GPS was used to record the latitude, longitude, and altitude of the center point of each quadrat. In total, across the 13 sites, 98 vegetation quadrats were surveyed before the environmental flow application and 110 quadrats were surveyed after environmental flow application due to differences in vegetation distribution along the Yongding River.

**Table 1** Riparian vegetation community survey sample point information

| Site name | Site Codes | River width (m) | Altitude (m) | Number of transect lines. (before environmental flow application) | Number of transect lines. (after environmental flow application) | Number of sample quadrats (before environmental flow application) | Number of sample quadrats (after environmental flow application) |
|---|---|---|---|---|---|---|---|
| Yanhe City | S1 | 35 | 383 | 2 | 3 | 6 | 9 |
| Zhuwo Reservoir | S2 | 36 | 335 | 3 | 3 | 6 | 6 |
| Qingbaikou | S3 | 64 | 225 | 3 | 3 | 6 | 6 |
| Wangping Wetland | S4 | 65 | 178 | 3 | 3 | 6 | 6 |
| Sanjiadian | S5 | 72 | 105 | 3 | 3 | 6 | 6 |
| Yongding Building | S6 | 156 | 96 | 3 | 3 | 3 | 9 |
| Jinmen Gate | P1 | 165 | 31 | 3 | 3 | 9 | 9 |
| Pit 10 | P2 | 400 | 25 | 3 | 3 | 12 | 12 |
| Jingqin Road | P3 | 220 | 21 | 3 | 3 | 10 | 10 |
| Pit 9 | P4 | 350 | 24 | 2 | 3 | 6 | 9 |
| Machang | P5 | 100 | 30 | 3 | 3 | 9 | 9 |
| Jingliang Road | P6 | 150 | 38 | 3 | 3 | 9 | 9 |
| Fangshan | P7 | 190 | 35 | 3 | 3 | 10 | 10 |

The species identity and abundance, total vegetation coverage, and mean height for each species in each quadrat were recorded. The above-ground parts of the harvested plants were brought back to the laboratory, oven-dried at 70℃, and weighed to calculate standing biomass. Each plant species in every quadrat was individually weighed for measurement. Soil moisture and redox potential were measured using a Delta-T Theta Probe sensor (UK) by inserting a probe into the surface to a depth of 10 cm. The surface layer soil (0–20 cm) was collected from each quadrat, air-dried in the laboratory, and then crushed and sieved. Total nitrogen (TN) and soil organic matter (SOM) of the soil were measured using an automatic soil carbon and nitrogen analyzer (Flash Smart, Germany). Total phosphorus (TP) of the soil was measured using the alkali-melting method and molybdenum-antimony spectrophotometry.

## Data Analysis

The importance value of each species in the quadrat was calculated as follows:

Importance value = (relative height + relative frequency + relative coverage) / 3.

The plant community matrix was composed of species with importance values greater than 5% in the quadrat. Species with less than 5% importance value deemed to be of small ecological contribution (Dai et al. 2006; Rolecek et al. 2009).

Two-way indicator species analysis (TWINSPAN) was used to classify the samples and plant species. According to the principles of vegetation classification and field investigation, the vegetation types of indicative and dominant species were analyzed.

Species richness ($S$) is the sum of the number of species in the community.

Pielou's index ($J$) indicates the evenness of the distribution of different species in the community, measured using biomass, coverage, or other indicators. It is an important indicator for measuring the evenness of the distribution of different species.

$$J = \frac{H}{\ln(S)}$$

$H$ is the Shannon-Wiener diversity index.

The hazard level of invasive plants was divided into 7 levels (Level 1: malignant invasion; Level 2: severe invasion; Level 3: partial invasion; Level 4: general invasion; Level 5: to be observed; Level 6: recommended exclusion; Level 7: China domestic species) based on the Chinese Invasive Species Information System (http://www.iplant.cn/ias/protlist) (Hao and Ma 2023).

Based on the Bray-Curtis dissimilarity measure, the SIMPER (Similarity Percentage) analysis was used to identify riparian vegetation contributions to community dissimilarity before and after environmental flow application in Yongding River.

Canonical correspondence analysis (CCA) was used to analyze the relationship between plant abundance and environmental factors (soil moisture content, soil redox potential, soil total nitrogen, soil total phosphorus, soil organic matter). The main environmental factors affecting the spatial distribution of the community were determined by the Monte Carlo test (significance level 0.05), correlation coefficient and explanatory rate. Non-metric multidimensional scaling (NMDS) was used to analyze the differences in plant community composition before and after environmental flow application in mountain and plain sections of

the Yongding River. Analyses were performed using R4.2.2 (https://www.r-project.org/) and Origin (https://www.originlab.com/).

Two-way indicator species analysis (TWINSPAN) was used to help identify and group riparian vegetation communities before and after environmental flow application in Yongding River.

## Results

### Riparian Vegetation Community Composition Variation Before And After Yongding River Environmental Flow Application

A total of 123 species of herbaceous plants were found in the riparian zone of the Yongding River before and after the environmental flow application, belonging to 43 families and 92 genera. Before the environmental flow application, 43 species of herbaceous plants were sampled in the mountain section of Yongding River, mainly composed of *Asteraceae* (10 species, 23.26%), *Poaceae* (3 species, 6.98%), and *Potamogetonaceae* (3 species, 6.98%). In the plain section before environmental flow application, plants such as *Asteraceae* (13 species, 28.26%).

SIMPER analysis showed the top 10 species contributing to the dissimilarity between mountain and plain section riparian vegetation communities were mainly hygrophytic plants and introduced Xanthium italicum, while after environmental flow application four submerged plants appeared to determine community dissimilarity (Table 2).

*Poaceae* (6 species, 13.04%), and *Fabaceae* (5 species, 10.87%) were predominant. After the environmental flow application, *Poaceae*, *Asteraceae*, *Cyperaceae*, and *Potamogetonaceae* were the main families found in both the plain and mountain sections.

In addition, 17 species of introduced invasive plants were found, belonging to 8 families and 14 genera (Appendix S1). Among them, 8 introduced invasive species were found before the environmental flow application, and 14 introduced invasive species were found after environmental flow application. Among all the invasive plants, 53% belonged to *Asteraceae*, 11% belonged to *Poaceae*. 29% were classified as level 1 malignant invasive, and 24% were classified as level 2 serious invasive. The level 1 malignant invasive species *Ambrosia trifida* and *Conyza canadensis* were found before and after the environmental flow application.

### Riparian Vegetation Community Diversity Variation Before And After Yongding River Environmental Flow Application

Plant species richness in Yongding River slightly increased after environmental flow application, but the difference was not significant. The homogeneity of the mountain section was significantly increased after environmental flow application (Fig. 2a and b). In the plain section, the richness was significantly higher after environmental flow application, but the inter-site homogeneity did not show significant changes (Fig. 2c and d).

### Factors Determined Riparian Vegetation Communities Before And After Yongding River Environmental Flow Application

CCA results showed that the first axis described 30.25% of mountain section plant community structure variations before and after environmental flow application, which was mainly related to soil TP, soil TN, and SOM. The second axis explained 24.62% of the changes, which was mainly related to soil redox potential and soil moisture content (Fig. 3a). For the plain section, the first axis described 30.95% of the plant community structure changes, which was mainly related to soil redox potential and soil moisture content. The second axis explained 22.30% of the changes, which was mainly related to SOM and TP (Fig. 3b).

Before environmental watering soil moisture was associated with higher plant richness, but after watering this was a less important predictor of plant species richness, which was more strongly associated with nutrient level (TN and TP). The Monte Carlo test found that the dominant factors affecting the distribution of plant communities before and after environmental flow application in the mountain section were soil TN and SOM. For the plain section, environmental factors affecting plant communities before and after
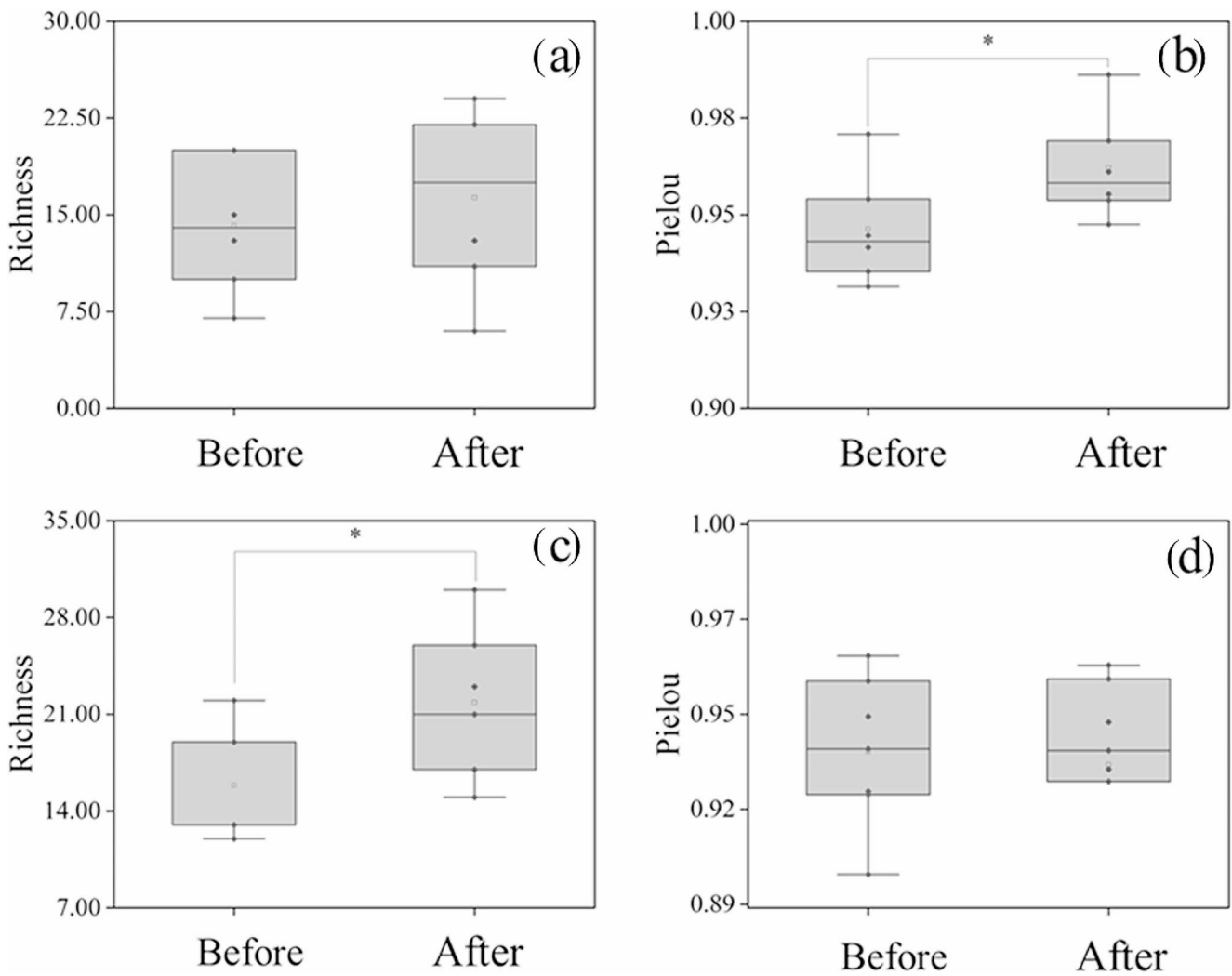
**Table 2** Top ten contributors of individual species to Yongding River riparian vegetation communities' dissimilarity before and after environmental flow application

| Before environmental flow application | | After environmental flow application | |
|---|---|---|---|
| Specie | Contribution (%) | Species | Contribution (%) |
| *Xanthium italicum* | 5.77 | *Echinochloa crusgalli* | 0.80 |
| *Humulus scandens* | 5.67 | *Myriophyllum spicatum* | 0.65 |
| *Phragmites australis* | 5.04 | *Potamogeton crispus* | 0.51 |
| *Artemisia capillaris* | 3.70 | *Xanthium italicum* | 0.44 |
| *Chenopodium album* | 3.26 | *Digitaria chrysoblephara* | 0.10 |
| *Potentilla supina* | 3.22 | *Cyperus glomeratus* | 0.09 |
| *Potamogeton crispus* | 3.08 | *Phragmites australis* | 0.09 |
| *Polygonum lapathifolium* | 2.74 | *Typha angustifolia* | 0.06 |
| *Myriophyllum spicatum* | 2.59 | *Artemisia capillaris* | 0.02 |
| *Imperata cylindrica* | 2.35 | *Potamogeton pusillus* | 0.01 |

Fig. 2 Richness variations (**a**) and Pielou variations (**b**) of riparian vegetation communities in the Yongding River mountain sections before and after environmental flow application. Richness variations (**c**) and Pielou variations (**d**) of riparian vegetation communities in the Yong-ding River plain sections before and after environmental flow application. Asterisk indicates significant differences among riparian vegetation communities

Fig. 3 Canonical Correspondence Analysis of environmental factor and their relationship with richness variations of riparian vegetation communities in the Yongding River mountain section (a) and plain section (b) SMC - Soil moisture content, Eh - Soil redox potential, TN - Soil total nitrogen, TP - Soil total phosphorus, SOM- Soil organic matter
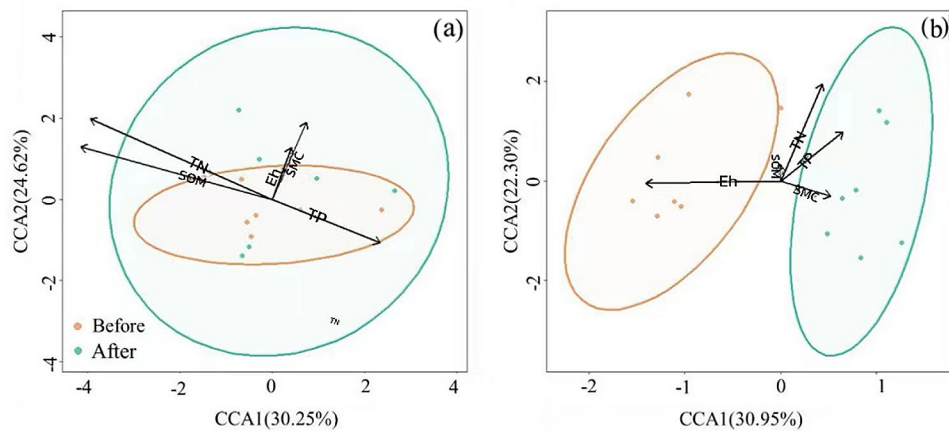
**Table 3** Monte Carlo test of environmental factors differentiating plant communities in the Yongding River mountain section and plain section before and after environmental flow application

| | Mountain sections | | Plain sections | |
| --- | --- | --- | --- | --- |
| | R² | P | R² | P |
| Soil moisture content (%) | 0.108 | 0.601 | 0.010 | 0.951 |
| Soil redox potential (mV) | 0.047 | 0.800 | 0.053 | 0.736 |
| Soil total nitrogen (g/kg) | 0.526 | **0.044** | 0.105 | 0.553 |
| Soil total phosphorus (g/kg) | 0.179 | 0.410 | 0.037 | 0.786 |
| Soil organic matter (%) | 0.514 | **0.045** | 0.003 | 0.977 |

Bold indicates significant differences ($P<0.05$)

watering included soil redox potential, TN, and TP, but the effect was not significant (Table 3).

## NMDS Analysis Of The Riparian Vegetation Communities Before And After Yongding River Environmental Flow Application

Based on the Bray-Curtis similarity coefficient, riparian vegetation communities NMDS analysis found there was little overlap in species prior to the environmental flow application and overlap increased after the environmental flow application indicating that the plant communities in the mountain and the plain sections tended toward homogeneity after environmental flow (Fig. 4a and b).

## TWINSPAN Classification of the Riparian Vegetation Communities Before And After Environmental Flow Application

In order to understand the assemblage structure of riparian vegetation communities before and after Yongding River environmental flow application 13 sample sites were analyzed using TWINSPAN classification (Fig. 5).

The riparian vegetation communities before environmental flow application were divided into 5 groups by the hierarchical classification, with each group being named using the association method. The specific details are as follows (Table 4).

**Fig. 4** NMDS ordination plot showing the riparian vegetation community structure of the Beijing section of the Yongding River before and after environmental flow application. (**a**) Differences in riparian vegetation communities between the mountain section and the plain section before environmental flow application, and (**b**) differences in riparian vegetation communities between the mountain section and the plain section after environmental flow application. Points represent sample quadrats with the color indicating the type of each section
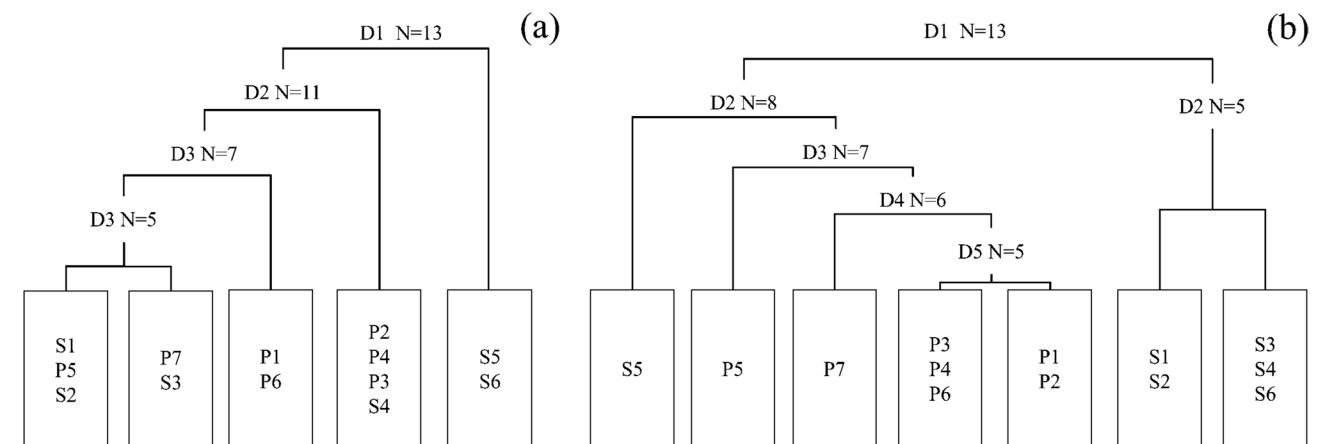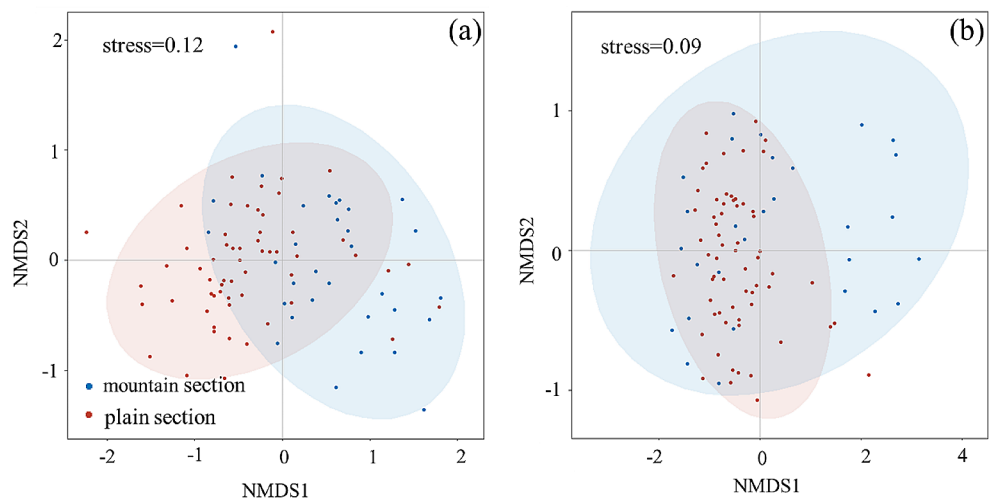




**Fig. 5** Results of TWINSPAN classification of recorded riparian vegetation communities on the Yongding River before (**a**) and after (**b**) environmental flow application

**Table 4** Results of TWINSPAN analysis before environmental flow application

| The community numbering | Association | Description |
|---|---|---|
| I | *Phragmites australis* + *Xanthium italicum* + *Artemisia capillaris* | This community was found at two sample sites; P1 and P6, with the dominant species: *Xanthium italicum*, *Artemisia capillaris*, *Humulus scandens*. The main companion species were *Heteropappus altaicus*, *Imperata cylindrica*, *Chenopodium acuminatum*, *Metaplexis japonica*, *Humulus scandens*, *Lespedeza daurica*, *Buchloe dactyloides* and *Salsola collina*. |
| II | *Phragmites australis* + *Typha angustifolia* + *Humulus scandens* | This community was found at three sample sites; S1, S2, and P5. The dominant species were *Phragmites australis*, *Humulus scandens*, *Typha angustifolia*. The main companion species were *Oenanthe javanica*, *Chenopodium album*, *Xanthium italicum*, *Imperata cylindrica*, *Artemisia annua*, *Galium aparine var. echinospermum*. |
| III | *Phragmites australis* + *Typha angustifolia* + *Potamogeton pusillus* | This community was found at two sample sites; S3 and S7. The dominant species were *Phragmites australis*, *Typha angustifolia*, *Potamogeton pusillus*, *Artemisia mongolica*. The main companion species were *Potamogeton perfoliatus*, *Myriophyllum spicatum*, *Xanthium italicum*, *Artemisia capillaris*. |
| IV | *Potamogeton crispus* + *Nymphoides peltata* + *Phragmites australis* | This community was found at two sample sites; S5 and S6. The dominant species were *Potamogeton crispus*, *Phragmites australis*, *Nymphoides peltata*. The main companion species were *Iris pseudacorus*, *Myriophyllum spicatum*, *Nymphaea sp.*, *Inula japonica*, *Potamogeton pusillus*. |
| V | *Phragmites australis* + *Potamogeton crispus* + *Myriophyllum spicatu* | This community was found at four sample sites; P2, P4, P3, and S4. The dominant species were *Phragmites australis*, *Potamogeton crispus*, *Myriophyllum spicatum*. The main companion species were *Imperata cylindrica*, *Chenopodium album*, *Potentilla supina*, *Xanthium italicum*, *Kochia scoparia*, *Typha angustifolia*, *Bolboschoenus planiculmis*, *Capsella bursa-pastoris*, *Polygonum lapathifolium*, *Artemisia capillaris*, *Humulus scandens*, *Eleusine indica*. |

After environmental flow application, the riparian vegetation communities could be classified into 7 groups, which are detailed below (Table 5).

## Discussion

There is growing recognition of the urgent need to restore aquatic ecosystems in the face of urbanization and environmental degradation (Geist and Hawkins 2016; Piczak et al. 2023; Stoffers et al. 2024). By assessing the effects of environmental flow application in a heavily affected river system, valuable insights can be gained not only for the restoration of Yongding River but also for informing future efforts to rehabilitate other rivers associated with large cities worldwide.

### Impact of Environmental Flow Application On The Riparian Vegetation Community Compositions In The Yongding River

We found the dominant riparian vegetation in the Yongding River to belong to the families *Asteraceae* and *Poaceae*. *Asteraceae*, the largest family of angiosperms (Wang et al. 2022a), has adapted to riparian habitats through reproductive advantages and stress resistance (Liu et al. 2021; Zheng et al. 2021b). In Beijing wetlands, *Asteraceae* is widely represented and among the most common species (Li et al. 2022). The *Poaceae* family has a pervasive global distribution and holds a dominant position in several herbaceous vegetation communities worldwide (Moges et al. 2017;

Zhong et al. 2021; Folega et al. 2023), including in hygrophytes communities (Li et al. 2006, 2019).

Before the environmental flow application, the dominant families in the mountain section were *Asteraceae*, *Poaceae* and *Potamogeton*. After the environmental flow application, *Cyperaceae* emerged as a co-dominant. The dominant families in the plain section before application were *Asteraceae*, *Poaceae* and *Fabaceae*, and after environmental flow application, *Cyperaceae* replaced *Fabaceae* as a co-dominant. *Cyperaceae* are the primary builders of wetland ecosystems, aquatic plants in lakes and rivers are predominantly classified under *Cyperaceae* (Ekoko et al. 2021). The family exhibits a high degree of diversity in reproduction and seed dispersal mechanisms. For instance, *Cyperaceae* species utilize various methods such as dispersal by birds, insects, and wind (Larridon et al. 2021). This diversity in reproductive strategies contributes to the widespread distribution of *Cyperaceae* following environmental flow application. Seasonal fluctuations in water levels facilitate the spread of *Cyperaceae* species (Wang et al. 2023). In our study, environmental flow provided suitable conditions for the growth and development of the *Cyperaceae* vegetation, for example allowing *Cyperus glomeratus* and *Cyperus microiria* to become dominant species in P5 and P6. The moisture in soil after environmental flow makes other species lose the competitive strength with *Fabaceae* (Gris et al. 2024). After environmental flow application, representation of submerged plants increased in the plain section of the river, including *Potamogeton pusillus*, *Hydrilla verticillate* and *Myriophyllum spicatum*. In addition to providing sufficient water resources for the plain section of the river, the

**Table 5** Results of TWINSPAN analysis after environmental flow application

| The community numbering | Association | Description |
|---|---|---|
| I | *Phragmites australis + Scirpus triqueter + Inula japonica* | This community was found at one sample sites; S5. The dominant species were *Phragmites australis, Scirpus triqueter, Inula japonica*. The main companion species were *Cyperus difformis, Echinochloa crusgalli, Xanthium sibiricum*. |
| II | *Echinochloa crusgalli + Cyperus glomeratus + Polygonum lapathifolium* | This community was found at three sample sites; P3, P4, and P6. The dominant species were *Echinochloa crusgalli, Cyperus glomeratus, Polygonum lapathifolium*. The main companion species were *Xanthium italicum, Phragmites australis, Myriophyllum spicatum, Najas marina, Artemisia capillaris, Digitaria chrysoblephara, Setaria viridis, Potentilla supina, Xanthium sibiricum, Lespedeza daurica, Eclipta prostrata*. |
| III | *Xanthium italicum + Digitaria chrysoblephara + Imperata cylindrica* | This community was found at two sample sites; P2 and P1. The dominant species were *Xanthium italicum, Digitaria chrysoblephara, Imperata cylindrica*. The main companion species were *Artemisia capillaris, Phragmites australis, Myriophyllum spicatum, Setaria viridis, Bolboschoenus planiculmis, Echinochloa crusgalli*. |
| IV | *Phragmites australis + Potamogeton pusillus + Bidens frondosa* | This community was found at two sample sites; S1 and S2. The dominant species were *Phragmites australis, Potamogeton pusillus* and *Bidens frondosa*. The main companion species were *Typha angustifolia, Xanthium italicum, Echinochloa caudata, Ambrosia trifida, Oenanthe javanica, Artemisia mongolica, Humulus scandens, Commelina communis*. |
| V | *Phragmites australis + Potamogeton crispus + Myriophyllum spicatu* | This community was found at three sample sites; S4, S6, and S3. The dominant species were *Phragmites australis, Nymphoides peltata, Hydrilla verticillata*. The main companion species were *Potamogeton pusillus, Najas marina, Myriophyllum spicatum, Typha angustifolia, Ceratophyllum demersum, Lythrum salicaria, Myriophyllum verticillatum, Leersia japonica, Bidens biternata, Setaria viridis*. |
| VI | *Xanthium italicum + Phragmites australis + Echinochloa crusgalli* | This community was found at sample site; P5. The dominant species were *Xanthium italicum, Phragmites australis, Echinochloa crusgalli*. The main companion species were *Cyperus microiria, Artemisia annua, Metaplexis japonica*. |
| VII | *Imperata cylindrica + Echinochloa crusgalli + Bolboschoenus planiculmis* | This community was found at one sample site; P7. The dominant species were *Imperata cylindrica, Echinochloa crusgalli, Bolboschoenus planiculmis*. The main companion species were *Scirpus triqueter, Xanthium sibiricum, Potentilla supina, Najas marina*. |

environmental flow application also promoted the growth of aquatic plants by increasing the width and depth of the river (Ecke et al. 2016). Before the environmental flow application, there were 21 hygrophytes, and the number increased to 36 after environmental flow application. The number of aquatic plants increased from 9 species to 11 species.

The surveys identified a total of 17 invasive species, primarily belonging to the *Asteraceae* family, known for their high reproductive rates and extensive distribution, thus posing a significant threat to the ecosystem. Among these species, five are classified as malignant invaders. *Bidens frondosa*, a member of the *Asteraceae* family, exhibited the highest frequency in the surveys. With its large, lightweight seeds adorned with spiny tips, *Bidens frondosa* can rapidly disperse through water flow, wind, or attachment to animals and humans, maintaining germination viability for up to two years (Zhou et al. 2015). Similarly, *Conyza canadensis*, characterized by its small and abundant seeds, relies on wind dispersal for rapid expansion (Shah et al. 2014). *Ambrosia trifida* seeds primarily spread through road construction and vehicular traffic (Son et al. 2024), posing a significant threat to the density and diversity of the local seed bank (Wang et al. 2022b). Meanwhile, *Cenchrus longispinus*, highly tolerant to soil conditions, establishes dominant monospecific populations through seed reproduction (Wu 2023), whereas *Ambrosia artemisiifolia*, producing copious amounts of harmful pollen, quickly adapts to invaded habitats (Zhao et al. 2022).

The most widely distributed invasive species was the second-level invasive species *Xanthium italicum*, which also belongs to *Asteraceae*. It grows quickly, uses spiny seeds to spread by attaching them to human luggage, clothing, and animal fur, rapidly spreading to farther places as these carriers move and have strong adaptability, often forming a single plant community and out-competing local plants (Tai et al. 2016; Zhang et al. 2021). In

the Yongding River, the lasting hydrological disconnection caused by urbanization and associated water abstraction may provide favorable conditions for invasive species (Wang et al. 2011; Xiu et al. 2016), though local environmental factors may also play a role. In the plain section of Yongding River, the riparian zone is close to a road with a large number of residents. Moreover, the river section is also associated with intensive construction projects and garbage dumping. These factors were conducive to the spread of introduced invasive plant seeds aided by human and vehicle traffic. These invasive plants can quickly occupy the habitat through rapid growth and reproduction, which has a negative impact on the stability of the habitat and the balance of the ecosystem (Rood et al. 2020; Zheng et al. 2021a). Therefore, it is necessary to consider the timing of environmental flow to prevent the reproduction and spread of invasive plants. In addition, water level fluctuations associated with the environmental flow may have introduced seeds of invasive species. This may be the reason why *Xanthium italicum* was widely distributed in the plain section after environmental flow application, and *Bidens frondosa* also appears in the mountain sections S1 and S2, where there were multiple interferences such as rubble piles, buildings, drainage pipes, and crops. Opportunities for the invasion of alien species are presented during the initial years of environmental flow application due to available niche space in the Yongding river riparian ecosystem, and therefore continuous monitoring is required.

## Impact of Environmental Flow Application On The Vegetation Diversity Of Riparian Ecosystems In Yongding River

Biodiversity is an important factor that affects the functioning and dynamic balance of communities and ecosystems (Tilman et al. 2014). The richness directly reflects the number of species, and plant species richness was highly correlated with density (Wang et al. 2012). Homogeneity can also reflect the stability of the community succession process (Ding et al. 2018). After the environmental flow application, the inter-site homogeneity of plant communities in the mountain sections significantly increased. Environmental flow promotes hydrological connectivity, therefore riparian plant seeds can spread and diffuse through surface water flow (Jansson et al. 2005; Garssen et al. 2017, Zhang et al. 2023), more species spread out the riparian zone and increase plant diversity resulting the homogeneity of the whole riparian zone. At the same time, the increase in water flow in the plain sections after environmental flow application could promote the replenishment of the plant seed bank in plain

area riparian soil, which may be beneficial to the growth and reproduction of local riparian vegetation (Pereira et al. 2021; Gaudichet et al. 2022). As a result, the species number after environmental flow application will be higher than before (Aronson et al. 2017). Periodic flooding is essential to maintain the stability and persistence of riparian vegetation communities (Richards et al. 2020; Fischer et al. 2021). However, due to the short duration of flooding in this study, the impact to plant community was limited, suggesting that moderate inundation is needed for successful restoration (Song et al. 2024).

## Environmental Factors Influence On Riparian Vegetation In The Yongding River

Soil moisture content in the mountain section was higher than in the plain section at both surveys. After the environmental flow application, plant richness was significantly increased in the plain section. Compared to continuous environmental flow in mountain sections of Yongding River, intermittent water replenishment and lack of water may still be the main determinants of riparian plant diversity in the Plain section. Altitude is also an important factor in plant growth and distribution, the growth of wetland plants at low altitudes is limited by flood hazards, while the growth of plants at high altitudes may be limited by soil nutrients (Lan et al. 2021). The averaged soil TN, SOM were slightly higher in the mountain section than the plain section, while TP content in soil was on the contrary. Soil nutrients in the mountain section showed no significant difference, while P5 and P7 had the highest TN content, triple that of the P1, P2, P3 TN content. P3 had the highest TP content, which may influence hierarchical classification of plant community in Yongding River. The CCA results indicated that the main factors affecting the plant diversity in the mountain sections before and after environmental flow application are total nitrogen (TN) and soil organic matter (SOM). SOM is regarded as an important indicator for judging soil fertility, as it reflects the availability of plant nutrients that are essential for promoting plant growth and development. Highly fertile soils stimulate plant development but also increase plant biomass (Welch et al. 2006; Charles et al. 2023). The vegetation in mountainous areas is mainly dominated by TN and SOM. However, the standard deviation of environmental factors in plain section is smaller compared to mountainous section, thus the environmental factors we measured cannot explain the differences in communities. Different species respond differently to changes in soil environment, for example, *Nymphaea. spp.* is most influenced by soil moisture content and soil redox potential, while *Potamogeton pusillus*

increases with the increase in soil total nitrogen and soil organic matter content. In the mountain area, topographic variation is higher, and the variation of TN and SOM is also higher than in the plain area. These may cause the increase of the coverage of *Potamogeton pusillus*.

NMDS results showed that the similarity of riparian vegetation communities between the mountain and plain sections increased after environmental flow application. Similarity increase is caused by environmental flow application dispersal of increased plant diversity and promote germinations from seed bank (Pereira et al. 2021), Providing environmental flow could enhance diversity. Hydrological connectivity made plant communities in the mountain and plain sections become more similar which may be caused by river flow bringing plant seeds and propagules from upstream to downstream, enriching the plant species in the plain, promoting vegetation restoration, and benefiting river restoration (O'Donnell et al. 2016; Richards et al. 2020; Zheng et al. 2021a). Similar species before and after environmental flow application include *Xanthium italicum Moretti, Potamogeton pusillus, Imperata cylindrica, Phragmites australis, Humulus scandens*.

## Conclusions

Future management strategies should prioritize efforts to control invasive species, acknowledging the role of environmental flow in facilitating their spread. The timing of environmental flow should consider the growth and reproduction time of invasive species to prevent their widespread dissemination, while also paying attention to the rate of environmental flow to provide suitable environmental conditions for the seed bank of riparian vegetation. Long-term monitoring later would be more conducive to a comprehensive understanding of the impact of environmental flow on vegetation in the Yongding River.

## Appendix S1 Invasive Plant Found In The Beijing Section Of Yongding River

| Species | Before environmental flow application (98 plots) | | After environmental flow application (110 plots) | | Hazard level |
|---|---|---|---|---|---|
| | Mountain sections | Plain sections | Mountain sections | Plain sections | |
| *Ambrosia trifida* | 4 | 0 | 1 | 0 | 1 |
| *Ambrosia artemisiifolia* | 0 | 0 | 1 | 0 | 1 |
| *Conyza canadensis* | 0 | 9 | 0 | 2 | 1 |
| *Bidens frondosa* | 0 | 0 | 7 | 0 | 1 |
| *Cenchrus longispinus* | 0 | 0 | 0 | 5 | 1 |
| *Xanthium italicum* | 2 | 29 | 4 | 38 | 2 |
| *Xanthium occidentale* | 0 | 2 | 0 | 0 | 2 |
| *Pharbitis nil* | 0 | 0 | 0 | 3 | 2 |
| *Amaranthus palmeri* | 0 | 0 | 0 | 5 | 2 |
| *Bidens bipinnata* | 0 | 0 | 0 | 4 | 3 |
| *Euphorbia hypericifolia* | 0 | 0 | 1 | 0 | 3 |
| *Abutilon theophrasti* | 0 | 1 | 0 | 0 | 3 |
| *Helianthus tuberosus* | 0 | 0 | 1 | 0 | 4 |
| *Eclipta prostrata* | 0 | 0 | 2 | 11 | 4 |
| *Buchloe dactyloides* | 0 | 2 | 0 | 0 | 4 |
| *Cannabis sativa* | 0 | 2 | 0 | 1 | 4 |
| *Melilotus officinalis* | 0 | 1 | 0 | 0 | 4 |

## Declarations

# References

Ahmadi A, Zolfagharipoor MA, Afzali AA (2019) Stability Analysis of Stakeholders' Cooperation in Inter-basin Water Transfer Projects: a case study. Water Resour Manage 33:1–18. https://doi.org/10.1007/s11269-018-2065-7

Aronson MFJ, Patel MV, O'Neill KM, Ehrenfeld JG (2017) Urban riparian systems function as corridors for both native and invasive plant species. Biol Invasions 19:3645–3657. https://doi.org/10.1007/s10530-017-1583-1

Arthington AH, Bhaduri A, Bunn SE, Jackson SE, Tharme RE, Tickner D, Young B, Acreman M, Baker N, Capon S, Horne AC, Kendy E, McClain ME, Poff NL, Richter BD, Ward S (2018) The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018). Frontiers in Environmental Science 6: 15. https://doi.org/10.3389/fenvs.2018.00045

Bai L, Bai Y, Hou Y, Zhang S, Wang S, Ding A (2023) Ecological water replenishment to the Yongding River, China: effects of different water sources on inorganic ions and organic matter characteristics. Environ Sci Pollut Res 30:39107–39120. https://doi.org/10.1007/s11356-022-25017-x

Bennett AF, Nimmo DG, Radford JQ (2014) Riparian vegetation has disproportionate benefits for landscape-scale conservation of woodland birds in highly modified environments. J Appl Ecol 51:514–523. https://doi.org/10.1111/1365-2664.12200

Cao LH, Lang Q, Lei K, Wang DW, Yang K, Yang WH (2023) Dynamic changes and driving forces of landscape pattern in the Yongding River basin from 1980 to 2020. J Environ Eng Technol 13:143–153. https://doi.org/10.12153/j.issn.1674-991X.20210881

Charles B, Chase M, Pociask G, Bhattarai R, Matthews JW (2023) Restored wetlands are greatly influenced by hydrology and non-native plant invasion. Wetlands Ecol Manage 31:129–142. https://doi.org/10.1007/s11273-022-09905-0

Chen Z, Yuan X, Roß-Nickoll M, Hollert H, Schäffer A (2020) Moderate inundation stimulates plant community assembly in the draw-down zone of China's three gorges Reservoir. Environ Sci Europe 32:79. https://doi.org/10.1186/s12302-020-00355-0

Chen JJ, Wu Y, Tao L, Guo J, Xu SS, Xi Y, Jing HW (2023) Influence of EWR on groundwater level and water quality along the Yongding River. Earth Environ 51:266–273. https://doi.org/10.14050/j.cnki.1672-9250.2022.50.113

Cornejo-Denman L, Romo-Leon JR, Castellanos AE, Diaz-Caravantes RE, Moreno-Vazquez JL, Mendez-Estrella R (2018) Assessing Riparian Vegetation Condition and function in disturbed sites of the Arid Northwestern Mexico. Land 7:24. https://doi.org/10.3390/land7010013

Dai X, Page B, Duffy KJ (2006) Indicator value analysis as a group prediction technique in community classification. South Afr J Bot 72:589–596. https://doi.org/10.1016/j.sajb.2006.04.008

Datry T, Larned ST, Tockner K (2014) Intermittent Rivers: a challenge for Freshwater Ecology. Bioscience 64:229–235. https://doi.org/10.1093/biosci/bit027

del Tanago MG, Martinez-Fernandez V, Aguiar FC, Bertoldi W, Dufour S, de Jalon DG, Garofano-Gomez V, Mandzukovski D, Rodriguez-Gonzalez PM (2021) Improving river hydromorphological assessment through better integration of riparian vegetation: scientific evidence and guidelines. J Environ Manage 292:19. https://doi.org/10.1016/j.jenvman.2021.112730

Ding Y, Jiang BH, Ding X, Yang F, Sun T (2018) Species composition, structure characteristics of plant communities in the water-level-fluctuation zone of tropical reservoirs: a case study on the Songtao Reservoir, Hainan. J Lake Sci 30(6):1745–1754. https://doi.org/10.18307/2018.0625

Du Y, Bao A, Zhang T, Ding W (2023) Quantifying the impacts of climate change and human activities on seasonal runoff in the Yongding River basin. Ecol Ind 154:110839. https://doi.org/10.1016/j.ecolind.2023.110839

Dwire KA, Kauffman JB, Baham JE (2006) Plant species distribution in relation to water-table depth and soil redox potential in montane riparian meadows. Wetlands 26:131–146. https://doi.org/10.1672/0277-5212(2006)26[131:PSDIRT]2.0.CO;2

Ecke F, Hellsten S, Kohler J, Lorenz AW, Raapysjarvi J, Scheunig S, Segersten J, Baattrup-Pedersen A (2016) The response of hydrophyte growth forms and plant strategies to river restoration. Hydrobiologia 769:41–54. https://doi.org/10.1007/s10750-015-2605-6

Ekoko WA, Yao YL, Shan YQ, Liu B, Shabani IE (2021) Aquatic vascular plants from the sanjiang plain, northeast China. Appl Ecol Environ Res 19:2689–2699. https://doi.org/10.15666/aeer/1904_26892699

Ellery Mayence C, Marshall DJ, Godfree RC (2010) Hydrologic and mechanical control for an invasive wetland plant, *Juncus ingens*, and implications for rehabilitating and managing Murray River floodplain wetlands, Australia. Wetlands Ecol Manage 18:717–730. https://doi.org/10.1007/s11273-010-9191-1

Epaphras AM, Gereta E, Lejora IA, Mtahiko MGG (2007) The importance of shading by riparian vegetation and wetlands in fish survival in stagnant water holes, Great Ruaha River, Tanzania. Wetlands Ecol Manage 15:329–333. https://doi.org/10.1007/s11273-007-9033-y

Fischer S, Greet J, Walsh CJ, Catford JA (2021) Flood disturbance affects morphology and reproduction of woody riparian plants. Sci Rep 11:16477. https://doi.org/10.1038/s41598-021-95543-0

Folega F, Kanda M, Fandjinou K, Bohnett E, Wala K, Batawila K, Akpagana K (2023) Flora and Typology of wetlands of Haho River Watershed, Togo. Sustainability 15. https://doi.org/10.3390/su15032814

Gaudichet C, Greulich S, Grellier S, Rodrigues S (2022) Effect of flooding gradient on soil seedbank and standing vegetation in a disconnecting side channel of the Loire River (France). Hydrobiologia 849:1383–1396. https://doi.org/10.1007/s10750-021-04785-6

Geist J, Hawkins SJ (2016) Habitat recovery and restoration in aquatic ecosystems: current progress and future challenges. Aquat Conservation-Marine Freshw Ecosyst 26:942–962. https://doi.org/10.1002/aqc.2702

Gomez-Sapiens MM, Jarchow CJ, Flessa KW, Shafroth PB, Glenn EP, Nagler PL (2020) Effect of an environmental flow on vegetation growth and health using ground and remote sensing metrics. Hydrol Process 34:1682–1713. https://doi.org/10.1002/hyp.13689

Gris D, Casagrande JC, Marques MR, Oldeland J, Damasceno GA Jr. (2024) Periodic flooding and edaphic factors shape Erythrina fusca dominance in riparian forests in the Pantanal wetland. Trop Ecol 15. https://doi.org/10.1007/s42965-024-00335-y

Guo EH, Fan ZH, Zhang RX, Sun JH, Yang XT (2021) Research progress on the response of riparian ecosystem vegetation and soil to hydrological changes. Acta Ecol Sin 41:9164–9173. https://doi.org/10.5846/stxb202011162948

Hao Q, Ma JS (2023) Invasive alien plants in China: an update. Plant Divers 45:117–121. https://doi.org/10.1016/j.pld.2022.11.004

Jansson R, Zinko U, Merritt DM, Nilsson C (2005) Hydrochory increases riparian plant species richness: a comparison between a free-flowing and a regulated river. J Ecol 93:1094–1103. https://doi.org/10.1111/j.1365-2745.2005.01057.x

Koehn JD, Todd CR, Zampatti BP, Stuart IG, Conallin A, Thwaites L, Ye QF (2018) Using a Population Model to inform the management of River flows and invasive carp (*Cyprinus carpio*). Environ Manage 61:432–442. https://doi.org/10.1007/s00267-017-0855-y

Kong ZJ, Deng MJ, Ling HB, Wang GY, Xu SW, Wang ZR (2021) Ecological security assessment and ecological restoration

countermeasures in the dryup area of the ower Tarim River. Arid Zone Res 38:1128–1139. https://doi.org/10.13866/j.azr.2021.04.25

Lan Z, Chen Y, Shen R, Cai Y, Luo H, Jin B, Chen J (2021) Effects of flooding duration on wetland plant biomass: the importance of soil nutrients and season. Freshw Biol 66:211–222. https://doi.org/10.1111/fwb.13630

Larridon I, Zuntini AR, Léveillé-Bourret E, Barrett RL, Starr JR, Muasya AM, Villaverde T, Bauters K, Brewer GE, Bruhl JJ, Costa SM, Elliott TL, Epitawalage N, Escudero M, Fairlie I, Goetghebeur P, Hipp AL, Jiménez-Mejías P, Kikuchi I, Luceño M, Márquez-Corro JI, Martín-Bravo S, Maurin O, Pokorny L, Roalson EH, Semmouri I, Simpson DA, Spalink D, Thomas WW, Wilson KL, Xanthos M, Forest F, Baker WJ (2021) A new classification of Cyperaceae (Poales) supported by phylogenomic data. J Syst Evol 59:852–895. https://doi.org/10.1111/jse.12757

Li WF, Ouyang ZY, Meng XS, Wang XK (2006) Plant species composition in relation to green cover configuration and function of urban parks in Beijing, China. Ecol Res 21:221–237. https://doi.org/10.1007/s11284-005-0110-5

Li XP, Fan SX, Hao PY, Dong L (2019) Temporal variations of spontaneous plants colonizing in different type of planted vegetation-a case of Beijing Olympic Forest Park. Urban Forestry Urban Green 46:12. https://doi.org/10.1016/j.ufug.2019.126459

Li G, Sun G, Zhao ZY, Liu DM, Xiao NW, Zhao ZP, Luo ZL (2022) Ecological quality assessment of wetlands in Beijing based on plant diversity. Environ Sci 43:1988–1996. https://doi.org/10.13227/j.hjkx.202108050

Liu X, Tan N, Zhou G, Zhang D, Zhang Q, Liu S, Chu G, Liu J (2021) Plant diversity and species turnover co-regulate soil nitrogen and phosphorus availability in Dinghushan forests, southern China. Plant Soil 464:257–272. https://doi.org/10.1007/s11104-021-04940-x

Luo Z, Zhao S, Wu J, Zhang Y, Liu P, Jia R (2019) The influence of ecological restoration projects on groundwater in Yongding River Basin in Beijing, China. Water Supply 19:2391–2399. https://doi.org/10.2166/ws.2019.119

Ma FL, Ma YH (2022) Effects of drought stress on plants and their response mechanisms. J Ningxia Univ (Natural Sci Edition) 43:391–399

Mathers KL, White JC, Fornaroli R, Chadd R (2020) Flow regimes control the establishment of invasive crayfish and alter their effects on lotic macroinvertebrate communities. J Appl Ecol 57:886–902. https://doi.org/10.1111/1365-2664.13584

Moges A, Beyene A, Ambelu A, Mereta ST, Trieste L, Kelbessa E (2017) Plant species composition and diversity in wetlands under forest, agriculture, and urban land uses. Aquat Bot 138:9–15. https://doi.org/10.1016/j.aquabot.2016.12.001

Mohan C, Gleeson T, Famiglietti JS, Virkki V, Kummu M, Porkka M, Wang-Erlandsson L, Huggins X, Gerten D, Jähnig SC (2022) Poor correlation between large-scale environmental flow violations and freshwater biodiversity: implications for water resource management and the freshwater planetary boundary. Hydrol Earth Syst Sci 26:6247–6262. https://doi.org/10.5194/hess-26-6247-2022

O'Donnell J, Fryirs KA, Leishman MR (2016) Seed banks as a source of vegetation regeneration to support the recovery of degraded rivers: a comparison of river reaches of varying condition. Sci Total Environ 542:591–602. https://doi.org/10.1016/j.scitotenv.2015.10.118

Pereira M, Greet J, Jones CS (2021) Native riparian plant species dominate the Soil Seedbank of In-channel Geomorphic features of a Regulated River. Environ Manage 67:589–599. https://doi.org/10.1007/s00267-021-01435-4

Perkins DW, Scott ML, Naumann T (2016) Abundance of Invasive, non-native riparian herbs in relation to River Regulation. River Res Appl 32:1279–1288. https://doi.org/10.1002/rra.2981

Piczak ML, Perry D, Cooke SJ, Harrison I, Benitez S, Koning A, Peng L, Limbu P, Smokorowski KE, Salinas-Rodriguez S, Koehn JD, Creed IF (2023) Protecting and restoring habitats to benefit freshwater biodiversity. Environ Reviews 19. https://doi.org/10.1139/er-2023-0034

Qin DJ, Sun J, Guo Y, Li L, Haji M, Wang DD, Liu WC (2019) Impact of the Yongding River on karst water in Xishan and spring water in Yuguquan, Beijing. J Eng Geol 27:162–169. https://doi.org/10.13544/j.cnki.jeg.2019-006

Ren LS, Zhang SR, Guo XL, Cheng LR, Guo YJ, Ding AZ (2021) Interannual variation in riparian vegetation cover and its relationship with river flow under a high level of human intervention: an example from the Yongding River Basin. Environ Monit Assess 193:13. https://doi.org/10.1007/s10661-021-09187-8

Richards DR, Moggridge HL, Warren PH, Maltby L (2020) Impacts of hydrological restoration on lowland river floodplain plant communities. Wetlands Ecol Manage 28:403–417. https://doi.org/10.1007/s11273-020-09717-0

Riis T, Kelly-Quinn M, Aguiar FC, Manolaki P, Bruno D, Bejarano MD, Clerici N, Fernandes MR, Franco JC, Pettit N, Portela AP, Tammeorg O, Tammeorg P, Rodriguez-Gonzalez PM, Dufour S (2020) Global Overview of Ecosystem Services provided by riparian vegetation. Bioscience 70:501–514. https://doi.org/10.1093/biosci/biaa041

Rolecek J, Tichy L, Zeleny D, Chytry M (2009) Modified TWINSPAN classification in which the hierarchy respects cluster heterogeneity. J Veg Sci 20:596–602. https://doi.org/10.1111/j.1654-1103.2009.01062.x

Rood SB, Scott ML, Dixon M, González E, Marks CO, Shafroth PB, Volke MA (2020) Ecological interfaces between Land and Flowing Water: themes and trends in Riparian Research and Management. Wetlands 40:1801–1811. https://doi.org/10.1007/s13157-020-01392-4

Sargac J, Johnson RK, Burdon FJ, Truchy A, Risnoveanu G, Goethals P, McKie BG (2021) Forested riparian buffers change the taxonomic and functional composition of Stream Invertebrate communities in Agricultural catchments. Water 13:17. https://doi.org/10.3390/w13081028

Shaeri Karimi S, Saintilan N, Wen L, Valavi R, Cox J (2021) The ecohydrological impact of water resource developments through inundation regime analysis of a large semi-arid floodplain. J Hydrol 596:126127. https://doi.org/10.1016/j.jhydrol.2021.126127

Shah MA, Callaway RM, Shah T, Houseman GR, Pal RW, Xiao S, Luo W, Rosche C, Reshi ZA, Khasa DP, Chen S (2014) Conyza canadensis suppresses plant diversity in its nonnative ranges but not at home: a transcontinental comparison. New Phytol 202:1286–1296. https://doi.org/10.1111/nph.12733

Sirolli H, Bazylenko A, Ramello ME (2022) Impact of Flood Duration on Germination Success of Paraná River Delta (Argentina) plants. Wetlands 42:77. https://doi.org/10.1007/s13157-022-01599-7

Son D, Chu Y, Lee H (2024) Roads as conduits for alien plant introduction and dispersal: the amplifying role of road construction in Ambrosia trifida dispersal. Sci Total Environ 912:14. https://doi.org/10.1016/j.scitotenv.2023.169109

Song J, Betz F, Aishan T, Halik U, Abliz A (2024) Impact of water supply on the restoration of the severely damaged riparian plants along the Tarim River in Xinjiang, Northwest China. Ecol Ind 158:14. https://doi.org/10.1016/j.ecolind.2024.111570

Stoffers T, Altermatt F, Baldan D, Bilous O, Borgwardt F, Buijse AD, Bondar-Kunze E, Cid N, Eros T, Ferreira MT, Funk A, Haidvogl G, Hohensinner S, Kowal J, Nagelkerke LAJ, Neuburg J, Peller T, Schmutz S, Singer GA, Unfer G, Vitecek S, Jähnig SC, Hein T (2024) Reviving Europe's rivers: seven challenges in

the implementation of the Nature Restoration Law to restore free-flowing rivers. Wiley Interdisciplinary Reviews-Water: 23. https://doi.org/10.1002/wat2.1717

Tai FJ, Zhu XZ, Han CX, Zhang C, Shao H (2016) Effects of the invasive plant *Xanthium italicum* on soil microbial community, soil enzyme activity and soil nutrients. Scientia Ecol Sinica 35:71–78. https://doi.org/10.14108/j.cnki.1008-8873.2016.04.009

Tilman D, Isbell F, Cowles JM (2014) Biodiversity and Ecosystem Functioning. Annu Rev Ecol Evol Syst 45:471–493. https://doi.org/10.1146/annurev-ecolsys-120213-091917

Vivian LM, Marshall DJ, Godfree RC (2014) Response of an invasive native wetland plant to environmental flows: implications for managing regulated floodplain ecosystems. J Environ Manage 132:268–277. https://doi.org/10.1016/j.jenvman.2013.11.015

Wang HF, Lopez-Pujol J, Meyerson LA, Qiu JX, Wang XK, Ouyang ZY (2011) Biological invasions in rapidly urbanizing areas: a case study of Beijing, China. Biodivers Conserv 20:2483–2509. https://doi.org/10.1007/s10531-011-9999-x

Wang H-F, MacGregor-Fors I, López-Pujol J (2012) Warm-temperate, immense, and sprawling: plant diversity drivers in urban Beijing, China. Plant Ecol 213:967–992. https://doi.org/10.1007/s11258-012-0058-9

Wang LZ, Dong B, Song HL (2018) Effects of flow rate changes on growth indexes and differences of *Hydrilla verticillata* under simulated water flow. Wetland Sci 16:138–143. https://doi.org/10.13248/j.cnki.wetlandsci.2018.02.006

Wang R, Du ZZ, Ma ZC, Zhang H, Chen W, Yang P (2022a) Characteristics of *Asteraceae* weeds species and diversity in urban and rural areas in the southern Junggar Basin. J Arid Land Resour Environ 36:130–135. https://doi.org/10.13448/j.cnki.jalre.2022.046

Wang HY, Liu T, Dong HG, Zhao WX, Liu XL, Wang RL, Xu WB (2022b) Changes in the composition of the soil seed bank of grassland after giant ragweed (*Ambrosia trifida*L.) Invasion. J Environ Manage 317:7. https://doi.org/10.1016/j.jenvman.2022.115468

Wang B, Jia X, Huangfu C (2023) Soil water content mediates the spatiotemporal nitrogen uptake by a dominant plant species in a subtropical wetland ecosystem. Plant Soil 483:395–410. https://doi.org/10.1007/s11104-022-05748-z

Wassens S, Ning N, Hardwick L, Bino G, Maguire J (2017) Long-term changes in freshwater aquatic plant communities following extreme drought. Hydrobiologia 799:233–247. https://doi.org/10.1007/s10750-017-3219-y

Welch BA, Davis CB, Gates RJ (2006) Dominant environmental factors in wetland plant communities invaded by Phragmites australis in East Harbor. Ohio USA Wetlands Ecol Manage 14:511–525. https://doi.org/10.1007/s11273-006-9004-8

Wu DB (2023) Study on biological mechanism of heteromorphic seed germination of *Cenchrus longispinus*. Dissertation, Anhui Agricultural University

Xie HY, Li YM (2022) An ecological water replenishment model of urban lake riparian plant restoration based on the groundwater-vegetation interactions. Ecol Eng 176:9. https://doi.org/10.1016/j.ecoleng.2021.106510

Xiu C, Zheng H, Ouyang ZY (2016) Effects of different types of human activities on invasive plant communities in riparian zones: a case study of the Yongding River in Beijing. Acta Ecol Sin 36:4689–4698

Yang J, Li EH, Xia Y, Zhang YY, Wang XL (2020) Research progress on the effects of hydrological situations, soil and hydropower

development on plants in river wetlands. Wetland Sci 18:115–121. https://doi.org/10.13248/j.cnki.wetlandsci.2020.01.016

Yang YH, Wang X, Bai X (2022) Influence of ecological water diversion on the spatial and temporal distribution of water quality in Guanting Reservoir and analysis of pollution sources. Water Resour Dev Manage 8:61–69. https://doi.org/10.16616/j.cnki.10-1326/TV.2022.03.12

Zhang N, Yang XY, Li MY (2017) Study on wetland ecological restoration effect based on ecological water supplement. Environ Dev 29:186–188. https://doi.org/10.16647/j.cnki.cn15-1369/X.2017.08.108

Zhang Y, Tang J, Ren G, Zhao K, Wang X (2021) Global potential distribution prediction of *Xanthium italicum* based on Maxent model. Sci Rep 11:16545. https://doi.org/10.1038/s41598-021-96041-z

Zhang X, Yu YL, Li SN, Xu WG, Wei W, Hao JH (2022) Study on distribution characteristics and diversity of riparian vegetation in typical rivers in Beijing using reclaimed water for water supplementation. J Hydroecology 43:45–55. https://doi.org/10.15928/j.1674-3075.202012160349

Zhang MY, Fan SX, Li XL, Li K, Xing XY, Hao PY, Dong L (2023) How urban riparian corridors affect the diversity of spontaneous herbaceous plants as pollination and dispersal routes - a case of the Wenyu River- North Canal in Beijing, China. Ecol Ind 146. https://doi.org/10.1016/j.ecolind.2023.109869

Zhao WX, Liu T, Sun MM, Wang HY, Liu XL, Su P (2022) Rapid monitoring of Ambrosia artemisiifoliain semi-arid regions based on ecological convergence and phylogenetic relationships. Front Ecol Evol 10:15. https://doi.org/10.3389/fevo.2022.926990

Zheng J, Arif M, Zhang S, Yuan Z, Zhang L, Li J, Ding D, Li C (2021a) Dam inundation simplifies the plant community composition. Sci Total Environ 801:149827. https://doi.org/10.1016/j.scitotenv.2021.149827

Zheng J, Arif M, Zhang S, Yuan Z, Zhang L, Dong Z, Tan X, Charles W, Li C (2021b) The convergence of species composition along the drawdown zone of the Three Gorges Dam Reservoir, China: implications for restoration. Environ Sci Pollut Res 28:42609–42621. https://doi.org/10.1007/s11356-021-13774-0

Zhong YH, Xue ZS, Jiang M, Liu B, Wang GD (2021) The application of species distribution modeling in wetland restoration: a case study in the Songnen Plain, Northeast China. Ecol Ind 121:13. https://doi.org/10.1016/j.ecolind.2020.107137

Zhou CQ, Tang SC, Pan YM, Wei CQ (2015) Effects of light and temperature on germination of heteromorphic achenes of Bidens frondosa L. J Trop Subtrop Bot 23:662–668. https://doi.org/10.11926/j.issn.1005-3395.2015.06.010

Zhu XC, Yuan GF, Yi XB, Du T (2017) Quantifying the impacts of river hydrology on riparian vegetation spatial structure: a case study in the lower basin of the Tarim River, China. Ecohydrology 10:9. https://doi.org/10.1002/eco.1887