HEALTH EVALUATION OF WETLANDS DISTRIBUTED ALONG URBAN-RURAL GRADIENTS BASED ON V-IBI

YANG, G. F.[1] – QU, Z. L.[2] – WANG, Y.[1] – ZHOU, X. T.[2] – WANG, B. H.[1] – LU, Y.J.[1*]

[1]*School of Art and Archaeology, Hangzhou City University, Hangzhou 310015, China*

[2]*Huadong Engineering Corporation Limited, Hangzhou 311122, China*

[*]*Corresponding author*
e-mail: Luyijun@hzcu.edu.cn

(Received 14th Jan 2024; accepted 4th Jun 2024)

Abstract. The expansion of urban areas has led to the encroachment of built-up areas on surrounding wetlands, adversely affecting the health of these ecosystems. Assessing the health status of wetlands becomes imperative for devising targeted policies to mitigate the impact of urbanization. Plant diversity is regarded as critical indicator of their overall health. In this study, three wetlands situated along urban-rural gradients in Hangzhou City were evaluated for ecological health using the vegetation-based index of biotic integrity (V-IBI) method, employing diversity survey data. The results revealed the selection of eight core indicators from a pool of 47 candidates that were used to calculate V-IBI values. This study found a decline in ecological health along the urban-rural gradients. The sampling points in the case wetlands were categorized into four groups based on V-IBI: poor (I), general (II), good (III), and healthy (IV). Progressing from the city center outward, 52.5%, 50%, and 4.8% of samples from Xixi Wetland, Tongjian Lake, and Qingshan Lake, respectively were classified as healthy. A positive linear relationship between plant richness and wetland health, coupled with species redundancy, was observed. Augmenting the number of plant species in wetlands proves conducive to maintaining their health and enhancing resilience against external interference.

Keywords: *biodiversity, plant richness, species redundancy, water quality, ecosystem resilience*

Introduction

In the context of rapid urban expansion, numerous natural wetlands undergo gradual fragmentation, surrounded or mosaicked by urban built-up areas, thereby becoming integral components of the urban-rural complexes (Chang et al., 2021; Fluet-Chouinard et al., 2023). These wetlands offer vital ecosystem services to cities, including the mitigation of the heat island effect, flood regulation, carbon dioxide sequestration, and water conservation (Chung et al., 2021). Simultaneously, they provide aesthetically appealing spaces for leisure and recreation, facilitating the interaction of urban residents with nature (Ghosh, 2021). Urban wetlands have recently been promoted as means to enhance public health amid the COVID-19 pandemic or potential future outbreaks (Zhai and Lange, 2021). However, high-intensity human activities in cities easily disrupt the structure of wetland ecosystems, resulting in the weakening or loss of their ecological functions. As the public increasingly prioritizes urban environmental improvement, the protection of urban wetlands has gained prominence (Xi et al., 2022). Therefore, evaluating the health status of wetlands is considered a foundation for wetland protection and management (Li and Zeng, 2020; Fluet-Chouinard et al., 2023), as well as the basis for planning and implementing protection measures for urban wetlands.

The index of biotic integrity (IBI) is a widely-used method for assessing anthropogenic pressures on aquatic and wetland ecosystems (Yang et al., 2018; Zhang et al., 2019; Liu et al., 2022). This approach integrates selected attributes of biological assemblages into a single index, based on the assumption that the biological composition of habitats impacted by human activities should differ from that of natural habitats in the region. Individual indicators within the IBI reflect the biological condition by measuring the structure or composition of biological assemblages that predictably respond to anthropogenic pressures (Liu et al., 2022). The IBI index method is a crucial approach for evaluating wetland health, linking environmental pressure in water bodies to biological activities, enabling a comprehensive assessment and prediction of the integrated impact of environmental pressure on the structure of biological communities (Karr, 1981). The IBI using fish, algae, birds, large invertebrates, and vascular plants, or combinations of these indicators, have been previously used in wetland evaluation (Zhang et al., 2021; Huang et al., 2022). However, the variability in the methods for selecting IBI metrics has hindered the consistent implementation of IBI in both assessment research and practical applications.

Plant diversity is a commonly employed fundamental indicator in various wetland assessment methods (Moore et al., 2012). As a crucial component of wetland ecosystems, plants play a significant role in forming intricate food webs by providing oxygen, sustenance, and habitat to organisms such as fish and waterfowl (Yang et al., 2018). At the same time, because plants are immovable and easy to sample and identify, and can respond well to human interference, they are used as an important indicator for evaluating the health of wetland ecosystems (Beck et al., 2010; Bried et al., 2013; Gara and Stapanian, 2015). Currently, some work has been conducted on the evaluation of wetland health using the plant IBI. The evaluation results have played an important role in the protection and management of wetlands. However, these studies have mainly focused on the evaluation of natural wetland health (DeKeyser et al., 2003; Behn et al., 2018). Compared with natural wetlands, urban wetlands are more subject to artificial interference. Among them, the creation of plant communities for ornamental purposes and the introduction of foreign ornamental plants have led to certain differences between their plant species and natural wetlands, which may cause different changes in the health of urban wetlands. In addition, in the transition from the urban core built-up area to the suburb, it is unclear whether the health status of urban wetlands in different regions will be different due to different disturbance intensities and types and whether the index of vegetation integrity will have an impact on this difference. Currently, there are no specific relevant evaluation indicators used to assess the health of wetlands in different urban areas to provide effective support for urban wetland management practices and policy decisions.

Hangzhou, as one of the cities with the highest level of urbanization in China, has experienced rapid urban expansion in recent years (Guo et al., 2023). Former natural wetlands have been transformed into urban wetlands, and this transformation has affected the composition of wetland vegetation (Du and Huang, 2018). This study takes three different regional wetlands along the urban-rural gradient in Hangzhou as case studies. Through a comprehensive wetland survey, the research aims to address the following questions: (1) How to establish a V-IBI for evaluating the health of urban wetlands; (2) Whether there are differences in the metric parameters used for V-IBI assessments among different wetland health evaluations; (3) What similarities and differences exist in wetland health across different regions along the urban-rural gradient. It is anticipated that this study will provide a theoretical basis and reference for the formulation of conservation policies for urban wetlands, thereby promoting sustainable development of city.

Materials and Methods

Study area

The study focused on Hangzhou City, Zhejiang Province (29˚11' - 30˚33' N, 118˚21' - 120˚), examining the ecological health of representative lake wetlands in three distinct zones: urban core, marginal, and rural areas (*Fig. 1*) (Wang et al., 2022). Specifically, Xixi Wetland, situated in the urban built-up area and established in 2005, stands out as an urban wetland innovatively designed upon the original fishing and cultivation foundation, providing multifaceted functions such as leisure, entertainment, aesthetic appreciation, education, science, and navigation. Notably, it holds the distinction of being China's inaugural national wetland park. Tongjian Lake Wetland, located in the marginal area and completed in 2020, represents a water diversion initiative featuring manually excavated lake bodies. It serves as a newly developed urban wetland with tourist and ornamental attributes, addressing functions like water environment enhancement, water landscape improvement, and flood control, drainage, and storage. Qingshan Lake Wetland, situated in the rural city area, began partial completion in 2016, with ongoing construction in some sections. This extensive artificial lake primarily functions in flood control, irrigation, and enhancing downstream water quality, all while accommodating water tourism considerations (Wang et al., 2023).

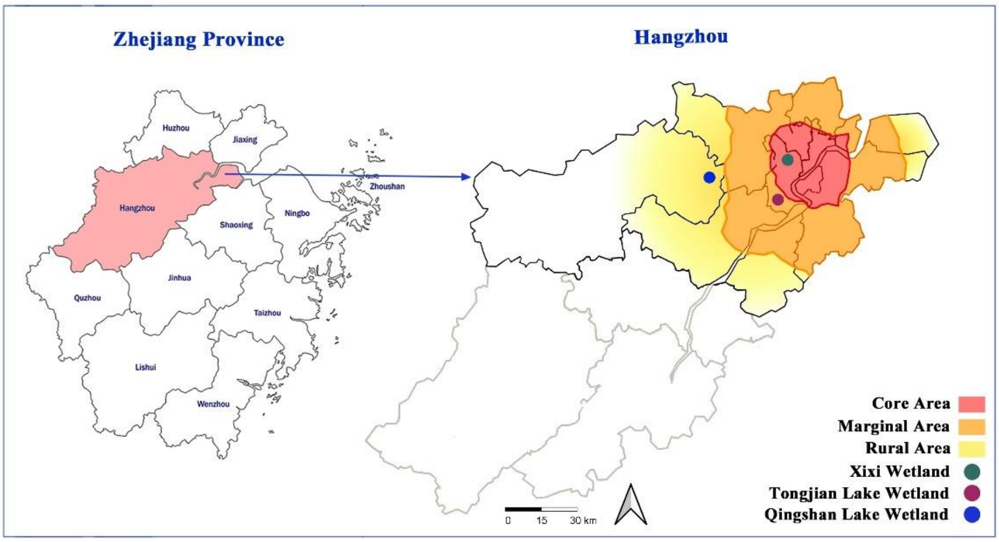

Figure 1. *The geographical location of the three urban wetlands*

Data acquisition

Sample setting

Using random selection methods and taking into account accessibility, 40, 21, and 20 survey areas were selected in the Xixi Wetland, Qingshan Lake Wetland, and Tongjian Lake Wetland, respectively, for wetland health evaluation and research (*Fig. 2*). We used non-interference samples and minimal interference samples as the evaluation criteria for reference points according to previous studies (Barbour et al., 1996; Huang et al., 2015). Combined with field visits, six survey areas were identified for each wetland as reference points, and the rest of the survey areas were damaged points.

DOI: http://dx.doi.org/10.15666/aeer/2204_31633186

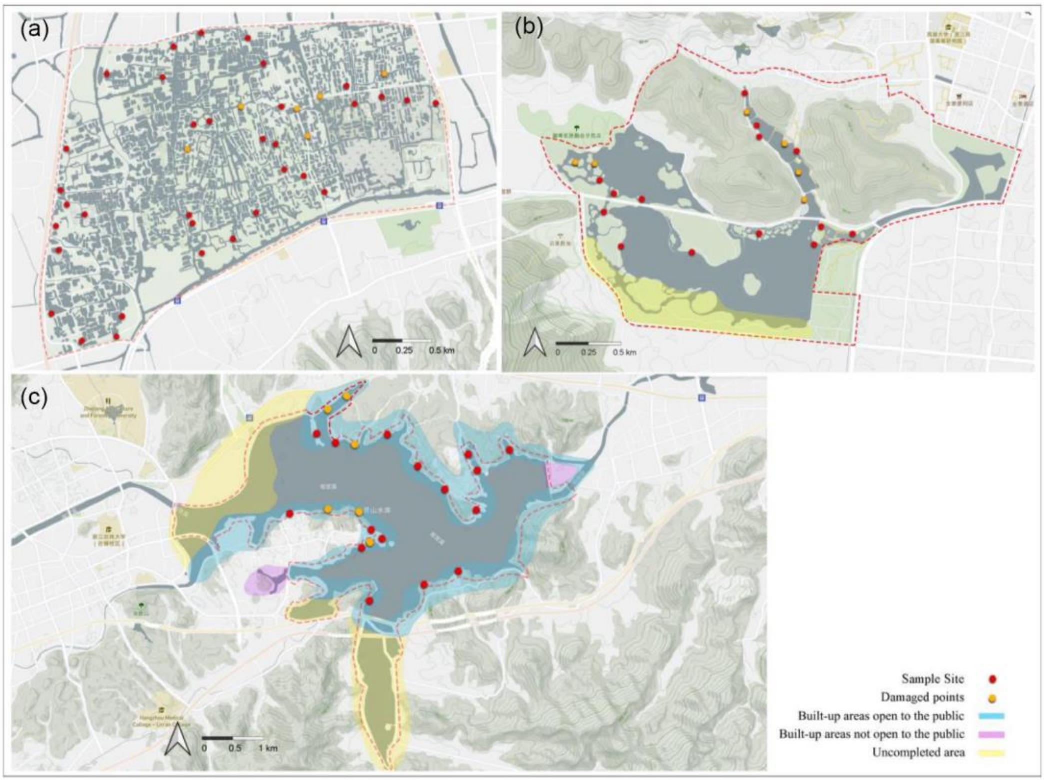

Figure 2. *Survey sampling points of Xixi Wetland (a), Tongjian Lake Wetland (b), and Qingshan Lake Wetland (c)*

Plant survey

The sample plots were based on the method reported by Fang et al. (2009) and Lu et al. (2024). Three sample lines with a length of 30 m, perpendicular to the land-water junction zone, along the transition from the aquatic area through the aquatic zone to the Mesozoic zone, were set in each survey area. A 2 × 2 m sample plot was set every 2 m along the sample line, and the interval between each sample line was 12 m (*Fig. 3*). The types, quantities, and coverage of plants in each sample were recorded. The location of the sample was located by Global Positioning System devices (GARMIN, eTrex 32x), and the geographic coordinates, altitude, and niche of the plots were recorded at the same time. The surveys were conducted in June 2022.

Water sample collection

Water samples were collected in various survey areas of the three urban wetlands, and at the same time, portable analytical instruments (Hydrolab, HL7) were used to directly determine the dissolved oxygen, temperature, pH, transparency, and other indicators on site. This study collected six water samples at each site on June 12, 2022. The determination of total nitrogen, total phosphorus, and ammonia nitrogen contents in water samples was performed following the *Water and Wastewater Monitoring and Analysis Methods* (4th Edition) (State Environmental Protection Administration *Water and Wastewater Monitoring and Analysis Methods Editorial Board*, 2002).

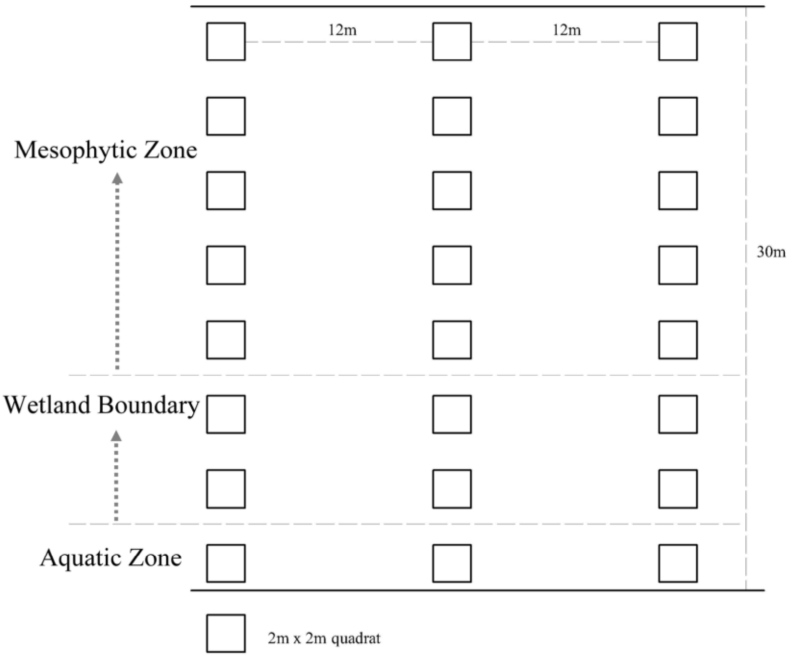

Figure 3. *Design of plant assemblage surveys for the case wetlands*

V-IBI method

Determination of candidate biological indicators

By referring to previous studies and considering the conditions of case wetlands, a range of biological indicators were used to establish the V-IBI indicator system in this study (Miller et al., 2006; Mack et al., 2008; Yang et al., 2018; Behn et al., 2018; Liu et al., 2022). In total, 47 indicators reflecting five categories, namely plant richness (M1-M21), community structure (M22-M33), plant abundance (M34-M43), plant diversity (M44-M45), and plant tolerance (M46-M47), were selected as candidate indicators (*Table* 1) to reflect the impact of environmental changes on the target biological quantity, structure, and function to effectively monitor and evaluate the quality of the wetland environment.

Biological index screening

Distribution range analysis. This study analyzed the distribution range of the biological index values of the reference points based on the mean, standard deviation, 25% quantile, median, and 75% quantile and excluded indicators whose values were too small and not sensitive to changes in external indicators (Yang et al., 2012). According to the criterion, the Xixi Wetland excluded M13, M27, M30, M31, and M46; the Qingshan Lake Wetland excluded M7, M13, M27, M31, and M46; and the Tongjian Lake Wetland excluded M13, M14, M17, M20, M31, M42, and M46.

Discrimination ability analysis. This study compared the remaining biological indicators; the reference point and the damage point were in the range of the 25–75% quantile, that is, the overlap of the IQ of the box (*Fig. 4*), according to previous study (Barbour et al., 1996).

DOI: http://dx.doi.org/10.15666/aeer/2204_31633186

Table 1. *Description of the 47 candidate indicators*

Category	SI	Candidate indicators	Response to interference	SI	Candidate indicators	Response to interference
plant richness	M1	The total number of plant species	↓	M12	Number of trees and small tree species	↓
	M2	Number of native perennial plant species	↓	M13	Number of submerged plants species	↓
	M3	Number of native annual plant species	↑	M14	Number of floating plants species	↓
	M4	Number of invasive plants species	↑	M15	Number of emergent plants	↓
	M5	Number of exotic plants species	↑	M16	The number of plant species in the Poaceae family	↑
	M6	Number of monocotyledonous plants species	↑	M17	Number of plant species in the Rosaceae family	↑
	M7	Number of ferns species	↓	M18	Number of plant species in the Asteraceae family	↑
	M8	Number of dicotyledonous plants	↓	M19	Number of facultative reproductive species	↓
	M9	Number of typical aquatic plant species	↓	M20	Number of sensitive species	↓
	M10	Number of herbaceous species	↑	M21	Number of tolerant plants species	↓
	M11	Number of shrubs species	↓			
community structure	M22	Percentage of native plant species	↓	M28	Percentage of dicotyledonous plants	↓
	M23	Percentage of exotic plant species	↑	M29	Percentage of typical aquatic plant species	↓
	M24	Percentage of native annual plant species	↑	M30	Percentage of plant species in the Poaceae family	↑
	M25	Percentage of native perennial plant species	↓	M31	Percentage of plant species in the Rosaceae family	↑
	M26	Percentage of monocotyledonous plants species	↓	M32	Percentage of plant species in the Asteraceae family	↑
	M27	Percentage of ferns species	↓	M33	Percentage of facultative reproductive species	↓
plant abundance	M34	Coverage of native plant species	↓	M39	Coverage of dicotyledonous plants	↓
	M35	Coverage of exotic plant species	↑	M40	Coverage of typical aquatic plant species	↓
	M36	Coverage of native annual plant species	↑	M41	Coverage of plant species in the Poaceae family	↑
	M37	Coverage of native perennial plant species	↓	M42	Coverage of plant species in the Rosaceae family	↑
	M38	Coverage of monocotyledonous plants species	↑	M43	Coverage of plant species in the Asteraceae family	↑
plant diversity	M44	Shannon-Wiener	↓	M45	Evenness index	↓
plant tolerance	M46	Percentage of sensitive species	↓	M47	Percentage of tolerant plants species	↑

Note: SI indicate the serial number of the candidate indicators; ↑ and ↓ respectively indicate whether the indicator increases or decreases in response to interference

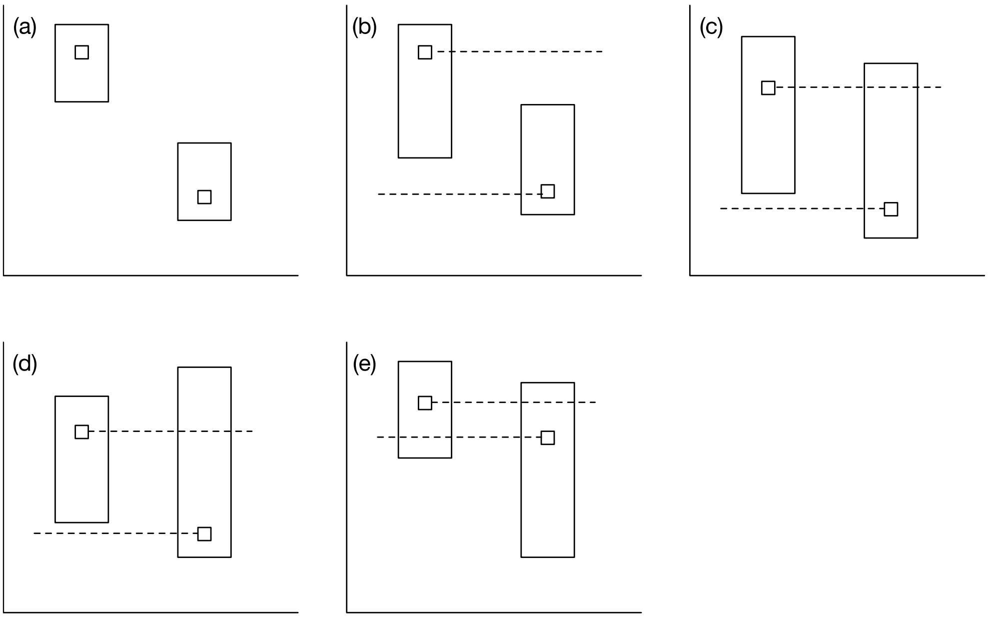

Figure 4. *Evaluation of the sensitivity of the metrics. Small squares are median values; boxes are interquartile ranges 25–75% interquartile (Barbour et al., 1996). (a) No overlap of interquartile ranges; (b) Some overlap of interquartile ranges but both medians are outside the interquartile ranges overlap; (c) Moderate overlap of interquartile ranges but at least on median is outside the interquartile ranges overlap; (d) Extensive overlap of interquartile range or (e) both medians within the overlap*

We assigned different IQ values as follows: if there was no overlap, then IQ = 3; if partial overlap but the respective median values were outside the range of the opponent's box, then IQ = 2; if only one median value was within the range of the opponent's box, then IQ = 1; and if each median value was within the range of the opponent's box, then IQ = 0. Only indicators with IQ ≥ 2 were selected for further analysis. Therefore, for the Xixi Wetland, we excluded M3, M6-7, M11-12, M14, M16-17, M19-20, M22-26, M29, M32-33, M35, and M40-43; for the Qingshan Lake Wetland, we excluded M2-6, M9, M14-15, M17-18, M20-26, M28-30, M33, M35, M38, M41-43, and M45; and for the Tongjian Lake Wetland, we excluded M3, M5, M12, M16, M18, M22-26, M28-29, M32-35, M38-39, M41, M43, and M47.

Data analysis and statistics

After analysis of the distribution range and discrimination ability of the Xixi Wetland, Qingshan Lake Wetland, and Tongjian Lake Wetland, the 19, 15, and 19 indicators retained were screened for Pearson correlation analysis and Principal Component Analysis (PCA). Among them, in Pearson correlation analysis, if the correlation coefficient r between the two indicators is > 0.75, it indicates that most of the information reflected between the two indicators overlaps, so only one of the indicators is chosen (Borja et al., 2016). Before conducting PCA, it is necessary to standardize the data of the indicators due to their monotonicity and correlation. This standardization process can be achieved using through *formula (1)*:

$$NM_{i,j} = \frac{M_{i,j} - \text{mean}(M_i)}{\text{mean}(M_i)} \quad \text{(Eq.1)}$$

where $NM_{i,j}$ is the observation value of the j-th indicator in the i-th sample square in the wetland, and mean (NM_j) is the average observation value of the j-th indicator in the wetland. The normalized data were used for PCA, and the original indicators were generated into significant axes for further clustering analysis. Clustering analysis was used to divide samples with similar health states, and the indicators in the samples in the same category showed similar characteristics. We used system clustering to analyze data in R software with the Ststs package (R Core Team, 2023). We used the median method to determine the Euclidean distance to determine the relationship among V-IBI values. The clustered genealogy chart was used to determine the appropriate number of clusters (Chang et al., 2021).

Calculation of biological index

The ratio method was used to unify the parameter scale, and the 95% quantile was used as the best expected value (the value in the state of no or very little interference) for the index whose value decreased with the increase in the interference. The calculation method of the index score is shown in equation (2). For indicators whose value increased with the increase in interference, the 5% quantile was used as the best expected value. The calculation method of the index score is shown in equation (3). We accumulated all indicators to obtain the final V-IBI score:

$$P = V_{test}/V_{0.95} \tag{Eq.2}$$

$$P = (V_{max} - V_{test})/(V_{max} - V_{0.05}) \tag{Eq.3}$$

where P is the index score, V_{test} is the actual value of the index, $V_{0.95}$ and $V_{0.05}$ are the respective 95% and 5% quantiles of the index, V_{max} is the maximum value of the index, and the P value is between 0 and 1; it is denoted as 1 when $P > 1$. The sum of the indicators of the three urban wetlands is the health value of the site.

Based on the clustering analysis results and the V-IBI values of the samples, the quality of the samples surveyed in the three urban wetlands was graded to determine the quality levels of different samples. At the same time, the correlation analysis of the V-IBI values of various places and the physical and chemical indicators of water bodies was performed to understand the factors that affect the water quality of wetlands. Data analysis was performed using the statistical software R (R Core Team, 2023).

Results

Composition characteristics of plant communities

The number of plant species in the three urban wetlands was significantly different, but the plants with the dominant number of species were similar. The *Asteraceae*, *Rosaceae*, and *Poaceae* plants appeared the most often in the three urban wetlands. A total of 104 families, 254 genera, and 336 species of plants were recorded in the Xixi Wetland, with 36, 23, and 20 species of *Asteraceae*, *Rosaceae*, and *Poaceae*, respectively; 74 families, 150 genera, and 179 species of plants were recorded in the Qingshan Lake Wetland, with 15, 16, and 12 species of *Asteraceae*, *Rosaceae*, and *Poaceae*, respectively; and 57 families, 96 genera, and 112 species of plants were recorded in the Tongjian Lake

Wetland, with 7, 9, and 6 species of *Asteraceae*, *Rosaceae*, and *Poaceae*, respectively (*Fig. 5*).

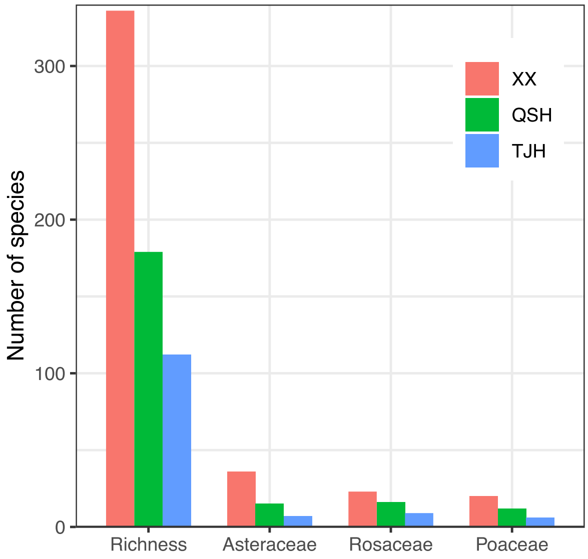

Figure 5. *Number of plant species in the three urban wetlands. Xixi Wetland (XX), Qingshan Lake Wetland (QSH) and Tongjianhu Lake Wetland (TJH)*

The plant species in the three urban wetlands were mostly mesophytes. The proportion of aquatic and wetland plant species was not high, but they often gathered as dominant communities. This may be related to their facultative reproductive characteristics, such as *Hydrocotyle vulgaris* and *Phragmites australis*. The aquatic plants were mainly *Phragmites australis*, *Arundo donax*, *Typha angustifolia*, *Thalia dealbata*, *Alisma plantago-aquatica*, and *Zizania latifolia* S. The floating plants were mainly *Nymphaea tetragona* G. and *Nuphar sinensis Hand* M. The floating plants were mainly *Lemna minor* and *Eichhornia crassipes* S., and the submerged plants were mainly *Potamogeton crispus*, *Potamogeton distinctus* B., and *Myriophyllum aquaticum* V. Some alien species have been introduced for ornamental purposes, such as *Thalia dealbata* and *Iris tectorum*, and invasive plants such as *Alternanthera philoxeroides* G., *Erigeron philadelphicus*, and *Veronica persica* P. have been found in three urban wetlands.

V-IBI indicator selection

According to the correlation coefficient of the V-IBI and considering the importance of the index, the V-IBI indicators of the three urban wetlands were finally determined. The correlation coefficients of the 19 V-IBI indicators of the Xixi Wetland (*Table 2*) showed that M1 was highly correlated with M2, M8, M10, M44, and M45, and M1 was selected to be retained because it contained more comprehensive species information. M6 was highly correlated with M9, M15, M21, and M28, and M6 was retained because the typical aquatic plants, aquatic plants, and tolerant plants in the sample were mainly monocotyledonous, and the increase in the number of monocotyledonous plants would directly reduce the percentage of dicotyledonous plants. M34 was highly correlated with M37 and M39. In addition, M34 better reflected the coverage of vegetation in the sample and was retained; therefore, the V-IBI index of the Xixi Wetland consisted of M1, M4, M6, M18, M34, M36, M38, and M47. The correlation coefficients of the 15 V-IBI indicators of the Qingshan Lake Wetland (*Table 3*) showed that M1 was highly correlated with M6, M8, M19, M44, and M47. Similar to the Xixi Wetland, M1 was selected to be retained; M11 and M12 were highly correlated. Compared with tree species, shrub species were more common in wetlands, and M11 was selected to be retained. Among the three indicators of M34, M36, and M37, M34 was also retained because it better reflected the coverage of vegetation in the sample. Therefore, the V-IBI index of the Qingshan Lake Wetland consisted of M1, M11, M16, M19, M32, M34, M39, and M40. The correlation coefficients of the 19 V-IBI indicators of the Tongjian Lake Wetland (*Table 4*) showed that M1 was highly correlated with M2, M6, M7, M8, M10, M11, M44, and M45. Therefore, M1 was retained because it contained more comprehensive species information. M9 was highly correlated with M15 and M21, and M9 was selected to be retained because the aquatic plants and tolerant plants were mainly typical aquatic plant species. Therefore, the V-IBI indicators of the Tongjian Lake Wetland were composed of M1, M4, M9, M19, M30, M36, M37, and M40.

Comparison of the health of wetlands

The V-IBI value of the Xixi Wetland was 3.34–6.65, with an average value of 5.81; the V-IBI value of the Qingshan Lake Wetland was 2.91–6.45, with an average value of 4.56; and the V-IBI value of the Tongjian Lake Wetland was 4.06–6.10, with an average value of 5.22 (*Fig. 6*). Among the three urban wetlands, the V-IBI value of the Xixi Wetland was the greatest, but the difference was not significant, while the V-IBI value of the Qingshan Lake Wetland was the lowest, and the V-IBI values differed significantly between the Xixi Wetland and Tongjian Lake Wetland.

The results of clustering analysis showed that the three urban wetlands could be divided into four quality categories: poor (I), general (II), good (III), and healthy (IV), and with the change in the wetland quality category from poor to healthy, its V-IBI value showed an increasing trend. The quality categories I, II, III, and IV of the Xixi Wetland included 1, 3, 15, and 21 samples, respectively (*Fig. 7a*). The wetland quality category of the single sample (XX18) in the cluster diagram was poor (I), and its V-IBI value was also the lowest among all samples (3.34). The three samples (XX30, XX34, and XX37) with the wetland quality category of general (II) clustered into a group, and their V-IBI value was also low (4.74–5.01). Among the 15 samples clustered in the wetland quality category rated good (III), four samples (XX1, XX6, XX7, and XX9) had V-IBI values between 6.02 and 6.22, which were higher than the V-IBI values of the remaining samples (5.40–5.91). Among the 21 samples clustered in the wetland quality category rated healthy (IV), there were also three samples (XX16, XX26, and XX39) with V-IBI values ranging from 5.42 to 5.56, which were lower than the V-IBI values (5.95–6.62) of the rest of the samples. The quality categories I, II, III, and IV of the Qingshan Lake Wetland included 4, 10, 6, and 1 samples, respectively (*Fig. 7b*). In the cluster diagram, the four samples (QSH2, QSH6, QSH7, and QSH17) with poor wetland quality category (I) grouped, and their V-IBI values were low (2.91–3.88). The 10 samples with the general wetland quality category (II) grouped, except for QSH21 (3.78), of which the V-IBI value was between 3.95 and 4.78. The V-IBI values of the six samples clustered in the wetland quality category rated good (III) were between 4.82 and 5.74, and the V-IBI values of the QSH12 samples in the wetland quality category rated healthy (IV) were significantly higher than those of categories (6.45). The quality categories I, II, III, and IV of the Tongjian Lake Wetland included 2, 1, 7, and 10 samples, respectively (*Fig. 7c*).

Table 2. *Pearson correlation coefficients between 19 candidate indicators of the Xixi Wetland*

	M1	**M2**	**M4**	**M6**	**M8**	**M9**	**M10**	**M15**	**M18**	**M21**	**M28**	**M34**	**M36**	**M37**	**M38**	**M39**	**M44**	**M45**	**M47**
M1	1	.885**	.359*	.624**	.977**	.477**	.950**	.509**	.642**	.597**	-0.155	.584**	.457**	.550**	-0.024	.586**	.948**	.889**	-.482**
M2		1	0.019	.651**	.833**	.458**	.762**	.489**	.387*	.603**	-0.257	.520**	.414**	.488**	-0.061	.546**	.825**	.774**	-.365*
M4			1	0.129	.391*	0.156	.462**	0.159	.577**	0.083	0.108	0.02	0.128	-0.011	-0.042	0.046	.377*	.366*	-0.306
M6				1	.454**	.768**	.650**	.776**	.360*	.829**	-.758**	.382*	.420**	.327*	0.241	0.225	.653**	.671**	-0.161
M8					1	.334*	.909**	.369*	.646**	.456**	0.038	.559**	.410**	.534**	-0.089	.602**	.911**	.839**	-.513**
M9						1	.560**	.984**	0.214	.932**	-.617**	.326*	0.291	0.298	.468**	0.031	.483**	.475**	0.076
M10							1	.584**	.739**	.642**	-0.215	.579**	.498**	.533**	0.052	.534**	.919**	.853**	-.438**
M15								1	0.261	.918**	-.616**	.361*	0.289	.339*	.467**	0.066	.520**	.520**	0.018
M18									1	0.238	-0.036	.484**	.416**	.446**	-0.015	.483**	.643**	.615**	-.453**
M21										1	-.572**	.370*	.415**	.315*	.417**	0.105	.553**	.533**	0.043
M28											1	-0.193	-0.157	-0.181	-.320*	0.007	-0.285	-.385*	0.19
M34												1	.649**	.978**	0.278	.807**	.573**	.556**	-.384*
M36													1	.478**	0.146	.545**	.425**	.414**	-0.17
M37														1	0.282	.784**	.547**	.529**	-.397*
M38															1	-.343*	-0.064	-0.058	0.281
M39																1	.600**	.579**	-.548**
M44																	1	.977**	-.610**
M45																		1	-.681**
M47																			1

Note: * indicates P < 0.05, ** indicates P < 0.01

Table 3. *Pearson correlation coefficients between 15 candidate indicators of the Qingshan Lake Wetland*

	M1	**M8**	**M10**	**M11**	**M12**	**M16**	**M19**	**M32**	**M34**	**M36**	**M37**	**M39**	**M40**	**M44**	**M47**
M1	1.00	.988**	.956**	.439*	.546*	.536*	.741**	.448*	.527*	.547*	0.43	0.33	-0.41	.961**	-.801**
M8		1.00	.923**	.478*	.605**	.437*	.726**	.520*	.498*	.486*	0.42	0.38	-.481*	.946**	-.801**
M10			1.00	0.19	0.30	.546*	.712**	.457*	.593**	.623**	.478*	0.26	-0.22	.949**	-.754**
M11				1.00	.783**	0.23	.434*	0.04	0.04	0.07	0.02	0.32	-.587*	0.32	-0.37
M12					1.00	0.15	0.31	0.23	0.03	-0.03	0.05	0.31	-.622*	.457*	-.473*
M16						1.00	.569**	-0.07	.502*	.599**	0.37	0.10	0.10	.572**	-.466*
M19							1.00	.514*	.448*	.573**	0.31	0.41	-0.24	.751**	-.572**
M32								1.00	0.17	0.24	0.10	0.18	-0.38	.510*	-.532*
M34									1.00	.778**	.946**	.530*	0.36	.497*	-0.19
M36										1.00	.531*	0.33	0.28	.560**	-0.35
M37											1.00	.545*	0.35	0.38	-0.08
M39												1.00	-0.11	0.23	0.03
M40													1.00	-0.38	.570**
M44														1.00	-.883**
M47															1.00

Note: * indicates P < 0.05, ** indicates P < 0.01

Table 4. *Pearson correlation coefficients between 19 candidate indicators of the Tongjian Lake Wetland*

	M1	**M2**	**M4**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M15**	**M19**	**M21**	**M27**	**M30**	**M36**	**M37**	**M40**	**M44**	**M45**
M1	1	.982**	.494*	.872**	.796**	.988**	.540*	.936**	.790**	.579**	.641**	.583**	.541*	-.600**	.550*	0.324	0.03	.924**	.915**
M2		1	.544*	.855**	.693**	.969**	.475*	.914**	.678**	.507*	.632**	.521*	.564**	-.578**	.601**	0.36	0.024	.910**	.898**
M4			1	0.382	0.155	.520*	0.352	.481*	0.416	0.365	.585**	.496*	0.052	-0.429	.527*	0.4	0.134	.482*	.467*
M6				1	.616**	.794**	.506*	.846**	.524*	.575**	.472*	.461*	0.411	-0.435	0.372	0.198	-0.041	.721**	.734**
M7					1	.633**	.567**	.682**	0.311	.579**	0.243	.536*	.925**	-0.398	0.329	0.215	0.091	.623**	.629**
M8						1	.505*	.913**	.721**	.535*	.678**	.576**	.496*	-.619**	.579**	0.345	0.042	.939**	.922**
M9							1	.616**	0.093	.980**	.444*	.951**	0.415	-0.291	0.371	0.296	.540*	.463*	.447*
M10								1	0.429	.633**	.536*	.657**	.499*	-.497*	.480*	0.256	0.114	.850**	.852**
M11									1	0.153	.628**	0.155	0.305	-.493*	.504*	0.313	-0.203	.732**	.704**
M15										1	.495*	.930**	0.4	-0.343	0.364	0.25	.461*	.476*	.463*
M19											1	.508*	0.144	-0.376	.667**	0.137	0.24	.633**	.601**
M21												1	0.378	-0.41	0.421	0.331	.527*	.514*	.491*
M27													1	-0.226	0.382	0.312	0.078	.592**	.599**
M30														1	-0.255	-0.144	0.205	-.484*	-.453*
M36															1	0.393	0.156	.671**	.647**
M37																1	0.331	0.438	0.415
M40																	1	0.001	-0.04
M44																		1	.995**
M45																			1

Note: * indicates P < 0.05, ** indicates P < 0.01

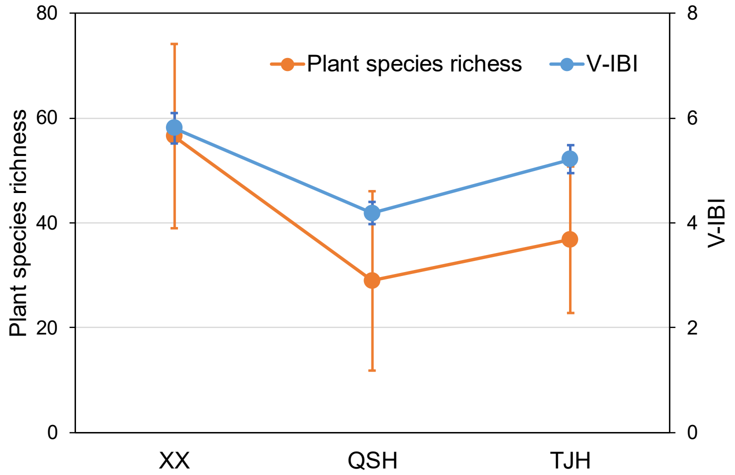

Figure 6. *Richness and V-IBI of the three urban wetlands, with a standard error bar. Xixi Wetland (XX), Qingshan Lake Wetland (QSH) and Tongjianhu Lake Wetland (TJH)*

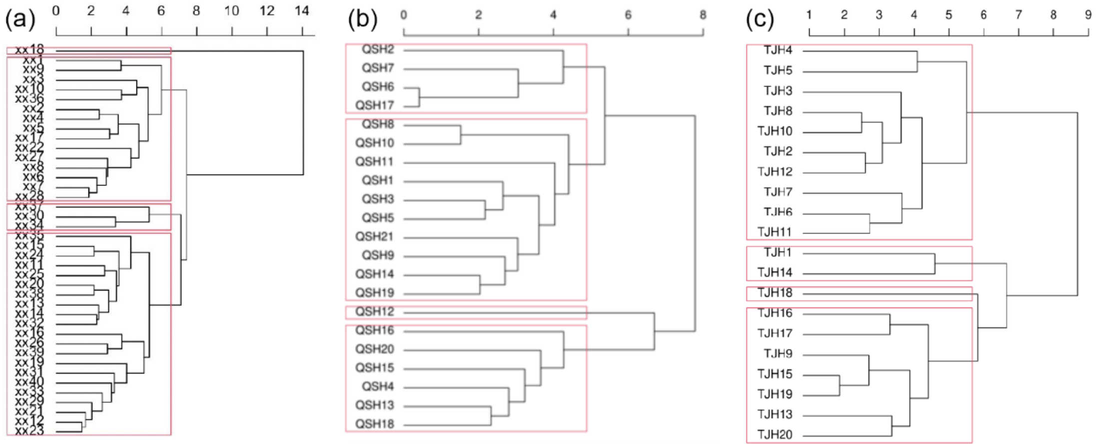

Figure 7. *Dendrogram of the cluster analysis of sample points of the Xixi Wetland (a), the Qingshan Lake Wetland (b), and the Tongjian Lake Wetland (c). XX, QSH and TJH denote Xixi Wetland, the Qingshan Lake Wetland, and the Tongjian Lake Wetland, respectively. The number following each location indcicate the sample sites*

The two samples of TJH1 and TJH14 with poor wetland quality category (I) clustered into one, and their V-IBI values were 4.06 and 4.42, respectively. The wetland quality category was general (II) only for TJH18, and its V-IBI value was 4.87; in addition to the seven samples with a good wetland quality category (III), the V-IBI values of the remaining samples were between 5.01 and 5.20, except for TJH16 (4.51), and the V-IBI values of the 10 samples with wetland quality category healthy (IV) were between 5.28 and 6.10.

The correlation analysis of the V-IBI values and wetland health indicators showed that the wetland health value of the Xixi Wetland was positively related to the total number of species ($r = 0.581$ $P < 0.01$) and the number of *Asteraceae* species ($r = 0.589$, $P < 0.01$), and was negatively related to the percentage of tolerant plants ($r = 0.791$, $P < 0.01$) and monocotyledonous plant cover ($r = 0.609$, $P < 0.01$) (*Fig. 8a–d*). The wetland health value of the Qingshan Lake Wetland was positively related to the total number of species

($r = 0.872$, $P < 0.01$), the number of grassy plant species ($r = 0.756$, $P < 0.01$), and the number of facultative reproductive species ($r = 0.783$, $P < 0.01$) (*Fig. 8e-g*). The wetland health value of the Tongjian Lake Wetland was positively related only to the total number of species ($r = 0.883$, $P < 0.01$) (*Fig. 8h*).

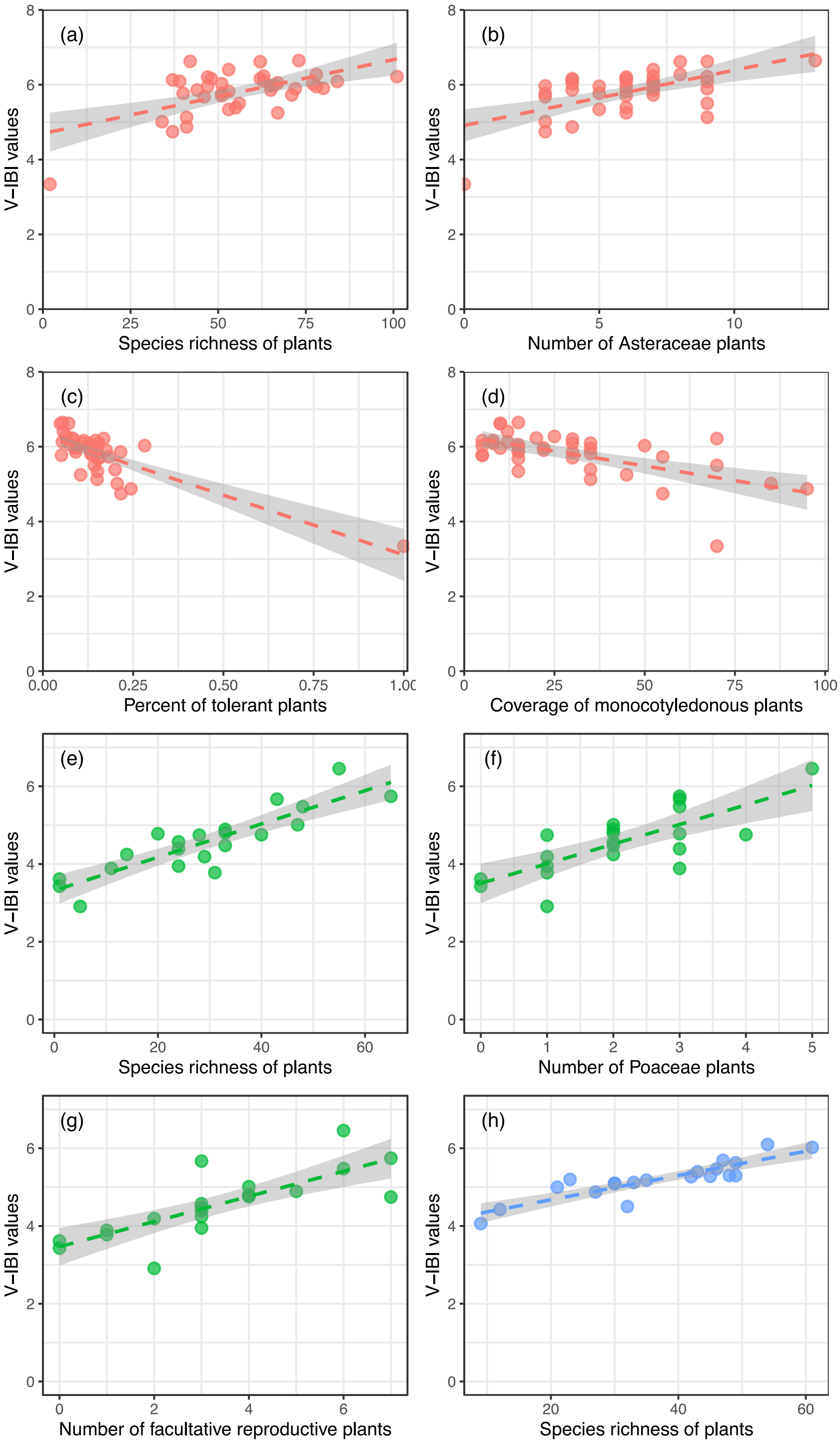

Figure 8. *The relationship between the V-IBI of the three urban wetlands and the wetland health indicators. Xixi Wetland (a–d), Qingshan Lake Wetland (e-g) and Tongjian Lake Wetland (h). All regressions are significant (P< 0.05). The shaded area indicates the 95% confidence interval band*

Wetland health and water quality

The correlation analysis of the V-IBI value and the physical and chemical properties of the water body (transparency, dissolved oxygen, pH value, ammonia nitrogen, total nitrogen, and total phosphorus) showed that the V-IBI value and transparency of the three urban wetlands showed a very significant positive correlation (Xixi Wetland: $r = 0.693$, $P < 0.01$; Qingshan Lake Wetland: $r = 0.595$, $P < 0.01$; Tongjian Lake Wetland: $r = 0.561$, $P < 0.01$) (*Fig. 9*). The V-IBI values of the Xixi Wetland and Tongjian Lake Wetland showed a very significant positive correlation with the total nitrogen content (Xixi Wetland: $r = 0.623$, $P < 0.01$; Tongjian Lake Wetland: $r = 0.575$, $P < 0.01$), and the V-IBI value of the Qingshan Lake Wetland did not show a significant correlation with the total nitrogen content ($r = 0.179$, $P > 0.05$). The correlation between the physical and chemical indicators of other water bodies and the V-IBI value was not significant.

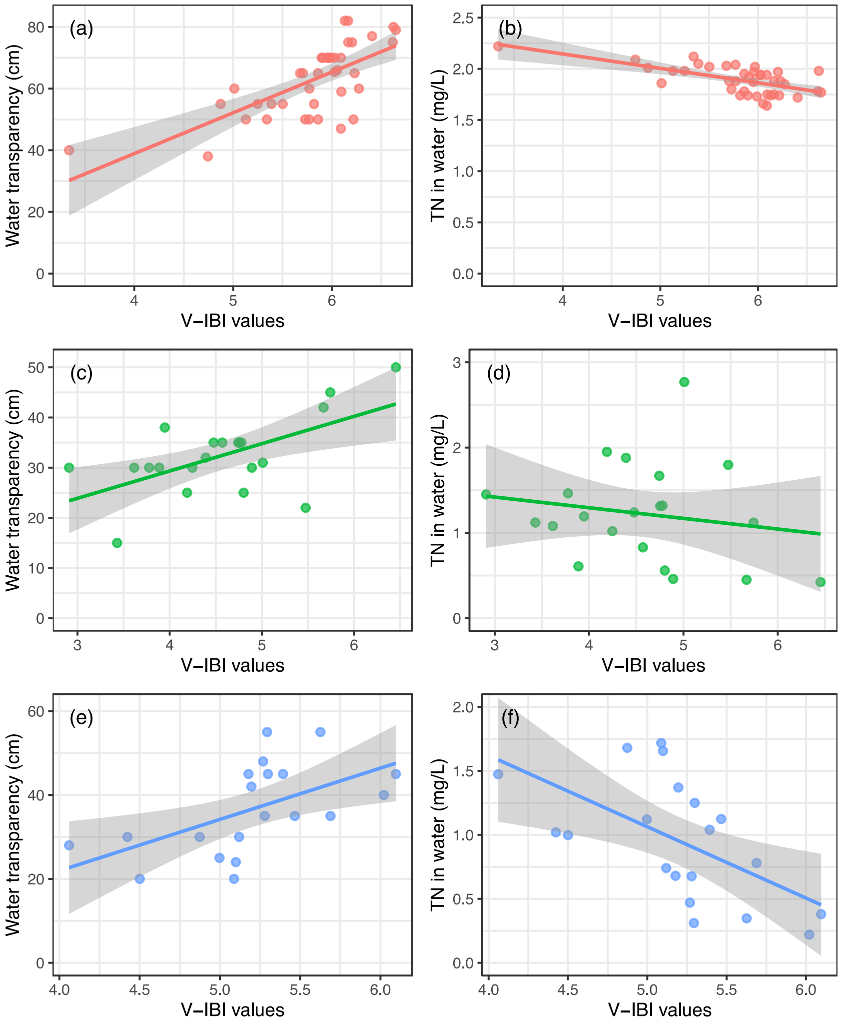

Figure 9. *Correlation between the V-IBI and water quality parameters of the three urban wetlands. Xixi Wetland (a–b), Qingshan Lake Wetland (c-d) and Tongjian Lake Wetland (e-f). All regressions are significant (P< 0.05). The shaded area indicates the 95% confidence interval band*

DOI: http://dx.doi.org/10.15666/aeer/2204_31633186

Discussion

Wetland plant community composition

The Xixi Wetland is located in the core area of the city (*Fig. 1*). The urbanization process is the evolution of the original fishing and farming wetland into an urban wetland. The high-density water network separates the wetland into patches of different sizes, and because of the height difference, it forms a transition from the edge of the wet environment to the center of the Mesozoic environment (Shen et al., 2008). This highly heterogeneous wetland habitat provides more possibilities for species diversity (Wang et al., 2023), resulting in a higher number of plant species in the Xixi Wetland than that in the other two wetlands (*Fig. 5*). Among the three wetlands, the *Asteraceae*, *Rosaceae*, and *Gramineae* are the main types of plant families, which may be related to human interference and plant habits. *Rosaceae* plants mainly include *Prunus persica*, *Prunus cerasifera*, and *Photinia serratifolia* K. These are usually artificially introduced and cultivated for ornamental purposes; *Gramineae* are mainly aquatic plants with developed root systems and good shore protection such as *Phragmites australis*, *Arundo donax*, *Phalaris arundinacea*, and *Miscanthus sinensis* A. These plants are planted in large quantities due to the protection needs of wetland slopes. Among *Asteraceae*, invasive plants such as *Erigeron canadensis*, *Erigeron philadelphicus*, and *Erigeron annuus* appear frequently, which may be related to the characteristics of invasive plants that have a high degree of environmental adaptability and can quickly occupy suitable habitats (Tomasetto et al., 2019). The similarity of plant composition shows that there is a trend of homogenization in the three urban wetland landscapes (Chen et al., 2021), which is also more common in urban green spaces that are strongly disturbed by people.

Differences in wetland health evaluation indicators

Plants are a good indicator of the response to environmental interference (Yang et al., 2018; Fennessy et al., 2002) and have a strong response to human interference, so plants can be used to assess the health of wetlands (Hargiss et al., 2008; Fluet-Chouinard et al., 2023). Vascular plant and vegetation attributes, such as the proportion of annual species, the number and coverage of invasive species, or the flora quality index (DeBerry and Perry, 2015), are often considered suitable indicators (Mack et al., 2008), because they are sensitive to human interference and easy to record and quantify (Miller et al., 2006). Our research also showed that the coverage of local annual plants was a suitable indicator for evaluating the health of wetlands. The coverage of local annual plants was used as the health evaluation indicator of the Xixi Wetland in the core area of the city and the Tongjian Lake Wetland in the marginal area of the city that are relatively subject to artificial interference. When urban wetlands are disturbed by humans, annual plants tend to be more prone to appear (Lu et al., 2024). Additionally, the proportion of annual plants, positively correlated with the height of interference, was selected as the IBI indicator for headwater wetlands in Pennsylvania (Miller et al., 2006).

The number of invasive species also appeared in the health evaluation indicators of the Xixi Wetland and Tongjian Lake Wetland but did not appear in the health evaluation indicators of the Qingshan Lake Wetland. The number of invasive species and the proportion of species accounted for are closely related to the interference state (Miller et al., 2006). In the Xixi Wetland and Tongjian Lake Wetland, which are located in the core and marginal areas of the city, respectively, the intensity of artificial management is higher than that of the Qingshan Lake Wetland, and the probability of invasive plants being removed is higher. This has led to differences in the types of invasive plants at the reference point and the damaged point. Behn et al. (2018) evaluated indicators of wetland health in East Africa and found that monocotyledon cover was a suitable indicator to evaluate but also noted that in natural marshes, dicotyledonous plants usually predominate (Behn et al., 2018), at which point using monocotyledon cover is prone to lead to erroneous results. Among the three urban wetlands, the Qingshan Lake Wetland is located in the urban countryside and suffers relatively little artificial intervention. It is more similar to natural swamps and has more types of dicotyledonous plants. Therefore, the cover of dicotyledonous plants appeared in its health evaluation indicators rather than the cover of monocotyledonous plants.

The total number of species appeared in the health evaluation parameters of the three major wetlands, and it was significantly positively correlated with the V-IBI value (*Fig. 8*), which shows that the diversity of wetland plants is also one of the main factors affecting wetland health. Richness reflects the diversity of aquatic species combinations (Zhou et al., 2023), and with the increase in diversity, habitats and food sources are sufficient to support the survival and reproduction of more species, so that the health of the aquatic species mix also increases (Barbour et al., 1996). This study also showed that when the total number of species reaches a certain number, the health value of wetlands no longer increases with the increase in the number of species, and species redundancy occurs (*Fig. 10*).

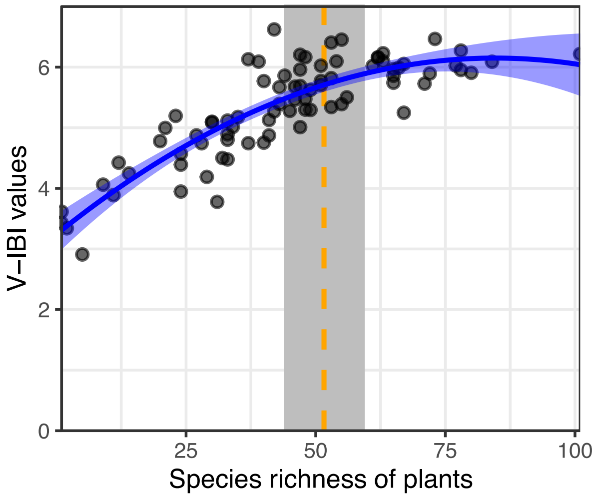

Figure 10. *The relationship between the V-IBI values and plant richness in the three urban wetlands. The solid blue line represents the V-IBI values significantly responded to the plant species richness; the blue shaded area indicates the 95% confidence interval band. The vertical dashed line indicates statistically significant breakpoints in the data as quantified by nonparametric multiple change point analysis, and shaded areas indicate 95% CIs of breakpoint estimates*

Redundancy is a vital feature of the ecosystem (Durigan et al., 2022), and one of its important functions is to provide insurance for the stability of the system or the maintenance of the functions of the integrated ecosystem (Lv et al., 2024). Therefore, although the increase in redundant species has not increased the health value of wetlands (*Fig. 8*), it has an important role in the resistance of wetlands to external interference and the maintenance of wetland health. Among the three urban wetlands, species redundancy was mainly reflected in the Xixi Wetland. This may be because the Xixi Wetland is located in the core area of the city. It was built early, and the natural plant community is stable. At the same time, more ornamental plants have been introduced and cultivated, which has increased the plant diversity in the wetland. Indicators such as the number of facultative reproductive species, the number and coverage of typical aquatic plants, the number and proportion of tolerant plants, and the number and proportion of *Gramineae* appeared in three different wetlands. These indicators were selected to evaluate the V-IBI because they reflected the geographical location, climatic conditions, plant types, artificial interference, and other factors of wetlands. Therefore, the plant species composition and community structure of wetlands will affect the selection of wetland health parameters (Behn et al., 2018). Similar evaluation indicators have also been used in other wetland health evaluation studies (Gara and Stapanian, 2015; Jones et al., 2016; Yang et al., 2018; Liu et al., 2022), which shows that the V-IBI evaluation value of the three urban wetlands in this study not only reflects the general response of plant communities to interference from human activities but also reflects the characteristics of the vegetation of the three urban wetlands themselves.

Comparison of wetland health status

Although the correlation between wetland health value and species richness showed a significant positive correlation between the two, the comparison between the three urban wetlands did not show similar patterns of change (*Figs. 6,8*). Compared with the Tongjian Lake Wetland, the total number of plant species in the Qingshan Lake Wetland was high, but the health value of the wetland was low. This may be because the average number of plant species in sample plots in the Qingshan Lake Wetland is low (Wang et al., 2023). Our investigation also found that the low intensity of artificial management of Qingshan Lake Wetland caused the dominance of single plant communities and a low number of plant species in sample plots, causing great differences in plant species among the samples (*Fig. 6*). The Tongjian Lake Wetland is located at the edge of the city. As a newly built urban wetland, tourism and ornamental functions are more prominent, and limited ornamental plant species are planted in large quantities, resulting in a small total number of species in the wetland. However, the average number of species in the sample was relatively large. The Xixi Wetland is located in the core area of the city and is more susceptible to artificial interference, which has led to a decrease in the number of species. However, the survey found that the Xixi wetland had the largest number of plant species. Moderate interference theory states that moderate interference is conducive to improving biodiversity (Kowarik, 2023). At the same time, a large number of ornamental plants introduced into the Xixi Wetland have directly increased the species diversity in the sample (*Fig. 5*); consequently, this wetland had the highest health value.

In the clustering evaluation, sample plots with higher species richness were clustered as one category, and the IBI health values of these sample plots were higher than those of sample plots in other categories (*Fig. 7*). In other words, the health values of the three urban wetlands were closely related to species richness. High richness is usually considered to be an undisturbed or unspoiled environment (Chen et al., 2021) and performed clustering evaluation of plant community data, and it was also found that wetlands with similar interference types or quality levels clustered into one group (Pinto and Ortega, 2016), similar to our results. Problems such as low vegetation coverage, low plant diversity, and low plant richness in typical wetlands may have become the main causes of wetland health problems (Li and Zeng, 2020). The V-IBI values of a few samples were not the same as the species richness, such as TJH16, QSH21, and XXSD16. This may be because the calculation of the V-IBI value is not only affected by the species richness but also by other indices, and once other indices in the sample have a greater impact on the V-IBI value, it may affect the relationship between the V-IBI value and the species richness. The study of the V-IBI exponential variable prediction model also showed that the influence of a certain variable on the value of V-IBI will be compensated by other variables (Behn et al., 2018). In the Qingshan Lake Wetland, the clustering evaluation of the sample QSH21 was good (III), but the IBI value was lower than the good (III) level. The investigation found that although there were many plant species in the sample, most of them grew sparsely, resulting in the smallest plant cover among all samples in the Qingshan Lake Wetland, thereby reducing the V-IBI value of the sample.

In the evaluation of wetland health, commonly used physical and chemical indicators can reflect the degree of pollution of water bodies to a certain extent (Chung et al., 2021; Dai et al., 2013). The relationship between the V-IBI values of the three urban wetlands and the water quality showed that the transparency of the water body was positively correlated with the V-IBI (*Fig. 9*), while the total nitrogen content was negatively correlated with the V-IBI value. The Xixi Wetland showed the strongest correlation, mainly due to the longest construction time, high intensity of artificial management, complex and stable plant communities, and the highest plant diversity. Usually, high plant diversity has a more obvious purification effect on water quality (Chang et al., 2014; Geng et al., 2017). The relevance of the Tongjian Lake Wetland was the weakest. On the one hand, it has a short completion time, and a stable wetland plant community has not yet been built. On the other hand, the water source of the wetland is a nearby source of drinking water, and the water quality is good. The effect of plants on water purification has not been fully reflected in the short term (Wang et al., 2020). The correlation between the total nitrogen content of the Qingshan Lake Wetland and the V-IBI value was not significant. This may be due to two factors. On the one hand, the water body of the Qingshan Lake Wetland has a large area, the water quality has relatively good self-purification capacity, and the total nitrogen content of the water body is low. On the other hand, a small amount of exogenous domestic sewage is discharged into the living area near some sampling points, resulting in a higher total nitrogen content of local water bodies. The difference in the total nitrogen content of all sampling points in the Qingshan Lake Wetland was also the greatest among the three urban wetlands.

Conclusions

Plants are sensitive to environmental interference and are easy to collect and classify in the filed investigation. Therefore, the V-IBI is generally used for health evaluation of wetland ecosystems. The variation in intensity and type of artificial interference of wetlands located along the urban gradient caused the changes in plant diversity in wetlands, which further affected the health of wetlands. In this study, eight core indicators were selected for the three urban wetlands, but the core indicators are not the same between different urban wetlands. According to V-IBI, the sampling points of the three urban wetlands can be divided into four health categories: poor (I), general (II), good (III), and healthy (IV). The results of the wetland health evaluation show that the comprehensive health of the Xixi Wetland is the best, followed by that of the Tongjian Lake Wetland, and that of the Qingshan Lake Wetland is the worst. Plant richness is an important indicator that affects the health evaluation of wetlands. Increasing the number of plant species in wetlands is conducive to maintaining the health of wetlands and improving their ability to resist external interference.

Acknowledgements. This research was funded by the Humanities and Social Sciences Research Project of the Ministry of Education, grant number 21YJA760040; Zhejiang Province Philosophy and Social Science Planning Project (24JCXK03YB); Zhejiang Provincial Soft Science Research Planning Project (No. 2024C35023).

REFERENCES

[1] Barbour, M. T., Gerritsen, J., Griffith, G. E., Frydenborg, R., McCarron, E., White, J. S., Bastian, M. L. (1996): A framework for biological criteria for Florida streams using benthic macroinvertebrates. – Journal of the North American Benthological Society 15(2): 185-211. https://doi.org/10.2307/1467948.

[2] Beck, M. W., Hatch, L. K., Vondracek, B., Valley, R. D. (2010): Development of a macrophyte-based index of biotic integrity for Minnesota lakes. – Ecological Indicators 10(5): 968-979. https://doi.org/10.1016/j.ecolind.2010.02.006.

[3] Behn, K., Becker, M., Burghof, S., Möseler, B. M., Willy, D. K., Alvarez, M. (2018): Using vegetation attributes to rapidly assess degradation of East African wetlands. – Ecological Indicators 89: 250-259. https://doi.org/10.1016/j.ecolind.2018.02.017.

[4] Borja, A., Elliott, M., Andersen, J. H., Berg, T., Carstensen, J., Halpern, B. S., Heiskanen, A.-S., Korpinen, S., Lowndes, J. S. S., Martin, G., Rodriguez-Ezpeleta, N. (2016): Overview of Integrative Assessment of Marine Systems: The Ecosystem Approach in Practice. – Frontiers in Marine Science 3. https://doi.org/10.3389/fmars.2016.00020.

[5] Bried, J. T., Jog, S. K., Matthews, J. W. (2013): Floristic quality assessment signals human disturbance over natural variability in a wetland system. – Ecological Indicators 34: 260-267. https://doi.org/10.1016/j.ecolind.2013.05.012.

[6] Chang, J., Fan, X., Sun, H., Zhang, C., Song, C., Chang, S. X., Gu, B., Liu, Y., Li, D., Wang, Y., Ge, Y. (2014): Plant species richness enhances nitrous oxide emissions in microcosms of constructed wetlands. – Ecological Engineering 64: 108-115. https://doi.org/10.1016/j.ecoleng.2013.12.046.

[7] Chang, J., Ge, Y., Wu, Z., Du, Y., Pan, K., Yang, G., Ren, Y., Heino, M. P., Mao, F., Cheong, K. H., Qu, Z., Fan, X., Min, Y., Peng, C., Meyerson, L. A. (2021): Modern cities modelled as “super-cells” rather than multicellular organisms: Implications for industry, goods and services. – BioEssays 43(7): 2100041. https://doi.org/10.1002/bies.202100041.

[8] Chen, Y., Ge, Y., Wu, Z., Ouyang, Y., Yang, G., Du, Y., Pan, K., Chang, J. (2021): Homogenization of tree species diversity in urban green spaces along a temperature gradient in eastern China. – Urban Forestry & Urban Greening 66: 127388. https://doi.org/10.1016/j.ufug.2021.127388.

[9] Chung, M. G., Frank, K. A., Pokhrel, Y., Dietz, T., Liu, J. (2021): Natural infrastructure in sustaining global urban freshwater ecosystem services. – Nature Sustainability 4(12): 1068-1075. https://doi.org/10.1038/s41893-021-00786-4.

[10] Dai, X., Ma, J., Zhang, H., Xu, W. (2013): Evaluation of ecosystem health for the coastal wetlands at the Yangtze Estuary, Shanghai. – Wetlands Ecology and Management 21(6): 433-445. https://doi.org/10.1007/s11273-013-9316-4.

[11] DeBerry, D. A., Perry, J. E. (2015): Using the floristic quality concept to assess created and natural wetlands: Ecological and management implications. – Ecological Indicators 53: 247-257. https://doi.org/10.1016/j.ecolind.2015.02.003.

[12] DeKeyser, E. S., Kirby, D. R., Ell, M. J. (2003): An index of plant community integrity: development of the methodology for assessing prairie wetland plant communities. – Ecological Indicators 3(2): 119-133. https://doi.org/10.1016/S1470-160X(03)00015-3.

[13] Du, X., Huang, Z. (2018): Spatial and temporal effects of urban wetlands on housing prices: Evidence from Hangzhou, China. – Land Use Policy 73: 290-298. https://doi.org/10.1016/j.landusepol.2018.02.011.

[14] Durigan, G., Munhoz, C. B., Zakia, M. J. B., Oliveira, R. S., Pilon, N. A. L., do Valle, R. S. T., Walter, B. M. T., Honda, E. A., Pott, A. (2022): Cerrado wetlands: multiple ecosystems deserving legal protection as a unique and irreplaceable treasure. – Perspectives in Ecology and Conservation 20(3): 185-196. https://doi.org/10.1016/j.pecon.2022.06.002.

[15] Fang, J., Wang, X., Shen, Z., Tang, Z., He, J., Yu, D., Jiang, Y., Wang, Z., Zheng, C., Zhu, J., Guo, Z. (2009): Methods and protocols for plant community inventory. – Biodiversity Science 17(6): 533. https://doi.org/10.3724/SP.J.1003.2009.09253.

[16] Fennessy, S., Gernes, M., Mack, J., Wardrop, D. H. (2002): Using Vegetation to Assess Environmental Conditions in Wetlands. – EPA, United States Environmental Protection Agency.

[17] Fluet-Chouinard, E., Stocker, B. D., Zhang, Z., Malhotra, A., Melton, J. R., Poulter, B., Kaplan, J. O., Goldewijk, K. K., Siebert, S., Minayeva, T., Hugelius, G., Joosten, H., Barthelmes, A., Prigent, C., Aires, F., Hoyt, A. M., Davidson, N., Finlayson, C. M., Lehner, B., . . . McIntyre, P. B. (2023): Extensive global wetland loss over the past three centuries. – Nature 614(7947): 281-286. https://doi.org/10.1038/s41586-022-05572-6.

[18] Gara, B. D., Stapanian, M. A. (2015): A candidate vegetation index of biological integrity based on species dominance and habitat fidelity. – Ecological Indicators 50: 225-232. https://doi.org/10.1016/j.ecolind.2014.10.029.

[19] Geng, Y., Han, W., Yu, C., Jiang, Q., Wu, J., Chang, J., Ge, Y. (2017): Effect of plant diversity on phosphorus removal in hydroponic microcosms simulating floating constructed wetlands. – Ecological Engineering 107: 110-119. https://doi.org/10.1016/j.ecoleng.2017.06.061.

[20] Ghosh, K. (2021): A framework to assess the benefits and challenges of ecosystem services of a reservoir-based wetland in the Himalayan foothills. – Environmental Development 40: 100669. https://doi.org/10.1016/j.envdev.2021.100669.

[21] Guo, R.-Z., Lin, L., Xu, J.-F., Dai, W.-H., Song, Y.-B., Dong, M. (2023): Spatio-temporal characteristics of cultural ecosystem services and their relations to landscape factors in Hangzhou Xixi National Wetland Park, China. – Ecological Indicators 154: 110910. https://doi.org/10.1016/j.ecolind.2023.110910.

[22] Hargiss, C. L. M., DeKeyser, E. S., Kirby, D. R., Ell, M. J. (2008): Regional assessment of wetland plant communities using the index of plant community integrity. – Ecological Indicators 8(3): 303-307. https://doi.org/10.1016/j.ecolind.2007.03.003.

[23] Huang, Q., Gao, J., Cai, Y., Yin, H., Gao, Y., Zhao, J., Liu, L., Huang, J. (2015): Development and application of benthic macroinvertebrate-based multimetric indices for the assessment of streams and rivers in the Taihu Basin, China. – Ecological Indicators 48: 649-659. https://doi.org/10.1016/j.ecolind.2014.09.014.

[24] Huang, X. Y., Xu, J., Liu, B., Guan, X., Li, J. S. (2022): Assessment of Aquatic Ecosystem Health with Indices of Biotic Integrity (IBIs) in the Ganjiang River System, China. – Water 14(3): 278. https://doi.org/10.3390/w14030278.

[25] Jones, R. C., Hawkins, C. P., Fennessy, M. S., Vander Laan, J. J. (2016): Modeling wetland plant metrics to improve the performance of vegetation-based indices of biological integrity. – Ecological Indicators 71: 533-543. https://doi.org/10.1016/j.ecolind.2016.07.030.

[26] Karr, J. R. (1981): Assessment of Biotic Integrity Using Fish Communities. – Fisheries 6(6): 21-27. https://doi.org/10.1577/1548-8446(1981)006<0021:AOBIUF>2.0.CO;2.

[27] Kowarik, I. (2023): Urban biodiversity, ecosystems and the city. Insights from 50 years of the Berlin School of urban ecology. – Landscape and Urban Planning 240: 104877. https://doi.org/10.1016/j.landurbplan.2023.104877.

[28] Li, Z., Zeng, B. (2020): Health assessment of important tributaries of Three Georges Reservoir based on the benthic index of biotic integrity. – Scientific Reports 10(1): 18743. https://doi.org/10.1038/s41598-020-75746-7.

[29] Liu, D., Liu, L., You, Q., Hu, Q., Jian, M., Liu, G., Cong, M., Yao, B., Xia, Y., Zhong, J., Yang, W. (2022): Development of a Landscape-Based Multi-Metric Index to Assess Wetland Health of the Poyang Lake. – Remote Sensing 14(5): 1082. https://doi.org/10.3390/rs14051082.

[30] Lu, Y., Yang, G., Zhang, Y., Wei, B., He, Q., Yu, H., Wang, Y. (2024): The influence of management practices on plant diversity: a comparative study of three urban wetlands in an expanding city in eastern China. – PeerJ 12: e16701. https://doi.org/10.7717/peerj.16701.

[31] Lv, P., Sun, S., Li, Y., Zhao, S., Zhang, J., Hu, Y., Yue, P., Zuo, X. (2024): Growing-season drought and nitrogen addition interactively impair grassland ecosystem stability by reducing species diversity, asynchrony, and stability. – Science of The Total Environment 912: 169122. https://doi.org/10.1016/j.scitotenv.2023.169122.

[32] Mack, J. J., Avdis, N. H., Braig IV, E. C., Johnson, D. L. (2008): Application of a Vegetation-Based Index of Biotic Integrity for Lake Erie coastal marshes in Ohio. – Aquatic Ecosystem Health & Management 11(1): 91-104. https://doi.org/10.1080/14634980701880823.

[33] Miller, S. J., Wardrop, D. H., Mahaney, W. M., Brooks, R. P. (2006): A plant-based index of biological integrity (IBI) for headwater wetlands in central Pennsylvania. – Ecological Indicators 6(2): 290-312. https://doi.org/10.1016/j.ecolind.2005.03.011.

[34] Moore, M. J. C., Langrehr, H. A., Angradi, T. R. (2012): A submersed macrophyte index of condition for the Upper Mississippi River. – Ecological Indicators 13(1): 196-205. https://doi.org/10.1016/j.ecolind.2011.06.003.

[35] Pinto, S. M., Ortega, Y. K. (2016): Native species richness buffers invader impact in undisturbed but not disturbed grassland assemblages. – Biological Invasions 18(11): 3193-3204. https://doi.org/10.1007/s10530-016-1208-0.

[36] R Core Team (2023): R: A Language and Environment for Statistical Computing. – R Foundation for Statistical Computing, Vienna, Austria, https://www.R-project.org.

[37] Shen, Q., Liu, K., Li, S.-Y., Zhang, J., Jiang, Y.-P., Ge, Y., Chang, J. (2008): Relationships of plant composition, water level and solar radiation in Xixi wetland, Hangzhou, China. – Zhiwu Shengtai Xuebao 32(1): 114-122. <Go to ISI>://BCI:BCI200800335622.

[38] Tomasetto, F., Duncan, R. P., Hulme, P. E. (2019): Resolving the invasion paradox: pervasive scale and study dependence in the native-alien species richness relationship. – Ecology Letters 22(6): 1038-1046. https://doi.org/10.1111/ele.13261.

[39] Wang, X., Luo, B., Wang, L., Zhao, Y., Wang, Q., Li, D., Gu, B., Min, Y., Chang, S. X., Ge, Y., Chang, J. (2020): Plant diversity improves the effluent quality and stability of floating constructed wetlands under increased ammonium/nitrate ratio in influent. – Journal of Environmental Management 266: 110607. https://doi.org/10.1016/j.jenvman.2020.110607.

[40] Wang, Y., Fukuda, H., Zhang, P., Wang, T., Yang, G., Gao, W., Lu, Y. (2022): Urban wetlands as a potential habitat for an endangered aquatic plant, Isoetes sinensis. – Global Ecology and Conservation 34: e02012. https://doi.org/10.1016/j.gecco.2022.e02012.

[41] Wang, Y., Yang, G., Lu, Y. (2023): Evaluation of urban wetland landscapes based on a comprehensive model - a comparative study of three urban wetlands in Hangzhou, China. – Environmental Research Communications 5(3): 035004. https://doi.org/10.1088/2515-7620/acbf12.

[42] Xi, Y., Peng, S., Liu, G., Ducharne, A., Ciais, P., Prigent, C., Li, X., Tang, X. (2022): Trade-off between tree planting and wetland conservation in China. – Nature Communications 13(1): 1967. https://doi.org/10.1038/s41467-022-29616-7.

[43] Yang, L., Li, Y., Wang, J., Yang, Y., Ding, Z. (2012): The assessment of river health using Benthic-Index of biotic integrity for Wenyu River [基于 b-ibi 指数的温榆河生态健康评价]. – Acta Ecologica Sinica 32(11): 3313-3322, Article 1000-0933(2012)32:11<3313:Jybizs>2.0.Tx;2-5. <Go to ISI>://CSCD:4555220.

[44] Yang, W., You, Q., Fang, N., Xu, L., Zhou, Y., Wu, N., Ni, C., Liu, Y., Liu, G., Yang, T., Wang, Y. (2018): Assessment of wetland health status of Poyang Lake using vegetation-based indices of biotic integrity. – Ecological Indicators 90: 79-89. https://doi.org/10.1016/j.ecolind.2017.12.056.

[45] Zhai, X., Lange, E. (2021): The Influence of Covid-19 on Perceived Health Effects of Wetland Parks in China. – Wetlands 41(8): 101. https://doi.org/10.1007/s13157-021-01505-7.

[46] Zhang, H., Duan, Z., Wang, Z., Zhong, M., Tian, W., Wang, H., Huang, H. (2019): Freshwater lake ecosystem health assessment and its response to pollution stresses based on planktonic index of biotic integrity. – Environmental Science and Pollution Research 26(34): 35240-35252. https://doi.org/10.1007/s11356-019-06655-0.

[47] Zhang, K., Wang, J., Ge, Y., Xie, P., Ma, X., Zhou, Q. (2021): Health assessment of the Ili River based on benthic index of biotic integrity (B-IBI) and the effects of different months and years. – Acta Ecologica Sinica 41(14): 5868-5878. https://doi.org/10.5846/stxb202002280365

[48] Zhou, J., Li, Y., Lyu, T., Yu, H., Meng, J., Song, W., Kang, Y., Yu, D., Wang, Z. (2023): Environmental determinants of aquatic plant diversity differ between growth forms and range sizes. – Ecological Indicators 157: 111280. https://doi.org/10.1016/j.ecolind.2023.111280.