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QUANTITATIVE CLASSIFICATION AND ENVIRONMENTAL FACTOR ANALYSIS OF PLANT COMMUNITIES IN ALPINE WETLANDS: A CASE STUDY OF THE BAYINBULUK SWAN LAKE AREA CHINA

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Abstract

Elucidating the influence of environmental factors on the spatial distribution of plant communities is crucial for understanding the intricate relationships between plant communities and their environment. Currently, the relationship between the spatial distribution of plant communities and environmental factors in the alpine wetland of Bayinbuluk Swan Lake remains incompletely understood. This study aims to elucidate the classification and diversity characteristics of plant communities and compare the effects of environmental factors on their spatial distribution. The results revealed four distinct clusters: cluster I (Ass. *Papaver nudicaule* + *Oxytropis ochrocephala* + *Leontopodium leontopodioides*), cluster II (Ass. *Juncus nigra* + Ass. *Juncus atratus* + *Primula malacoides* + *Cirsium esculentum*), cluster III (Ass. *Primula malacoides* + *Carex myosuroides* + *Carex melanantha*), and cluster IV (Ass. *Eleocharis palustris* + *Carex rhynchophysa* + *Potamogeton distinctus*). All clusters comprised herbaceous plants, with Cyperaceae species being the most prevalent. Cluster III exhibited the highest diversity, richness, and stability, while cluster IV demonstrated the lowest. The interspecific competition in clusters II and III was relatively moderate, indicating high stability. Conversely, cluster IV showed strong interspecific competition and no similarity with the other clusters due to significant differences in topography and soil conditions. The primary environmental factors influencing the spatial distribution of plant clusters in the alpine wetland of Bayinbuluk Swan Lake included soil electrical conductivity, soil organic carbon (SOC) content, soil total phosphorus, soil pH, slope, aspect, readily available nitrogen, and soil total nitrogen. Soil electrical conductivity emerged as the most significant factor, followed by SOC content. Understanding the types of alpine wetland communities, their distribution, and the relationship with environmental factors is essential for the scientific management of alpine wetlands and biodiversity conservation. The study findings can inform ecological construction and sustainable utilization strategies for the alpine wetland of Bayinbuluk Swan Lake.

Key words: Alpine wetland; Plant communities; Quantitative classification; Environmental factors

Introduction

Alpine wetlands, situated in high-altitude regions with cold climates, constitute a unique category of wetlands in China (Wang *et al*., 2022). These ecosystems are characterized by relatively monotonous vegetation types and increased vulnerability due to their elevated altitude and harsh climate (Hu *et al*., 2022). Vegetation serves as a crucial primary producer in alpine wetland ecosystems. In ecological research, the relationship between the spatial distribution of plant communities and environmental factors has drawn considerable attention (Peterson & Lieberman, 2012). Environmental changes act as the primary driving force for plant species composition and regulation, with the most competitive species becoming dominant as plants adapt to changing conditions. On a macro scale, climate emerges as the principal environmental factor influencing plant community distribution, while at the local level, topography and soil habitat conditions play determinant roles (Castillon *et al*., 2015; El-Ghanim *et al*., 2010; Liang *et al*., 2023).

Numerous studies have investigated the relationship between alpine wetland plant communities and various environmental factors, including altitude, longitude, pH, soil moisture, and soil nutrients (Lu *et al*., 2015; La *et al*., 2014; Wang *et al*., 2020; Liu *et al*., 2018). However, the diversity in research areas and regional scales results in significant differences in environmental conditions and community structures, leading to potential biases in community characteristics and understanding (Liu *et al*., 2021). Existing research on the Bayinbuluk alpine wetland has focused on wetland birds (Dong *et al*., 2013), wetland soil carbon (C) pool and C cycle (Bao *et al*., 2018), wetland nitrogen (N) deposition (Shen *et al*., 2022), and wetland vegetation distribution and patterns (Xu, 2018; Xu *et al*., 2020). Despite these efforts, limited studies have addressed the spatial distribution of plant communities and their relationship with environmental factors (Xu *et al*., 2017; Wang *et al*., 2021; Gao *et al*., 2018). Furthermore, current research lacks a systematic quantitative classification of plant communities and a comprehensive analysis of the relationships between plant communities, soil environment, climate, and topographical factors in the alpine wetland of Bayinbuluk Swan Lake. Understanding these complex relationships between plant communities and environmental factors is crucial to reveal the ecological adaptation strategies of plant communities and maintain the stability of the alpine wetland ecosystem in Bayinbuluk.

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The rapid advancement of multivariate analysis techniques has led to the widespread adoption of quantitative classification and ordination methods for plant communities in studies examining plant-environment relationships (Pinder *et al*., 1997; Yao *et al*., 2018). This approach has been extensively utilized in vegetation research across ecosystems, including forests, grasslands, deserts, dry valleys, and wetlands (Zhang *et al*., 2018; Xu *et al*., 2010; Tian *et al*., 2022; Wang *et al*., 2016). By using plant community classification and ordination techniques, researchers can comprehensively elucidate the ecological interactions between vegetation and environmental factors, contributing to the preservation of biodiversity and ecosystem functions (Guo *et al*., 2018). In this study, two-way indicator species analysis (TWINSPAN) was used to assess differences, similarities, and stability of plant communities through community division of the investigated sample plots. Furthermore, the research explored the influence of environmental factors on the spatial distribution of each community type, aiming to unravel the relationship between species diversity changes, spatial distribution of plant communities, and environmental factors in the alpine wetland of Bayinbuluk Swan Lake. The primary objective of this study was to provide a theoretical foundation for the conservation of species diversity and sustainable utilization of wetland resources in the Bayinbuluk Swan Lake alpine wetland ecosystem.

Material and Methods

Study area: The alpine wetland of Bayinbuluk Swan Lake (42°40′–43°00′ N, 83°40′–84°35′ E) is situated in Hejing County, Xinjiang Uygur Autonomous Region, China (Fig. 1). It is the largest swan reserve in Asia and the sole swan reserve in China. The area is characterized by a typical alpine climate, with an average annual temperature of 4.6°C and an annual minimum temperature of −49.6°C. The average annual precipitation is 273 mm, while the annual evaporation amounts to 1250 mm. The average annual relative humidity is 60%. The primary water sources of the wetland include ice, snow, and phreatic water, with the buried depth of groundwater ranging from 0.5 to 1.0 m (Chen *et al*., 2020). Based on the type of surface water and vegetation, the wetland can be categorized into three distinct areas: swamp (S), swamp meadow (SM), and meadow (M).

Sampling design: Field surveys of vegetation were conducted in 15 sample plots across S, SM, and M during August 2022. A 10 m × 10 m sample plot was established by random sampling in the plant communities of three typical wetland succession sequences. Within each sample plot, five 1 m × 1 m subplots were established by quincunx sampling. Plant investigations were performed at each sample point, recording species composition and measuring plant height, coverage, frequency, and other indicators. The latitude and longitude of each sample point were recorded using GPS. Concurrent with vegetation measurements, multiple soil samples were collected using the "S" five-point method in each sample plot. During collection, litter was removed, and soil samples were taken from a 0–20 cm soil layer using a soil drill, with three repetitions. The collected soil samples were placed in ziplock bags and transported to the laboratory for subsequent analysis.

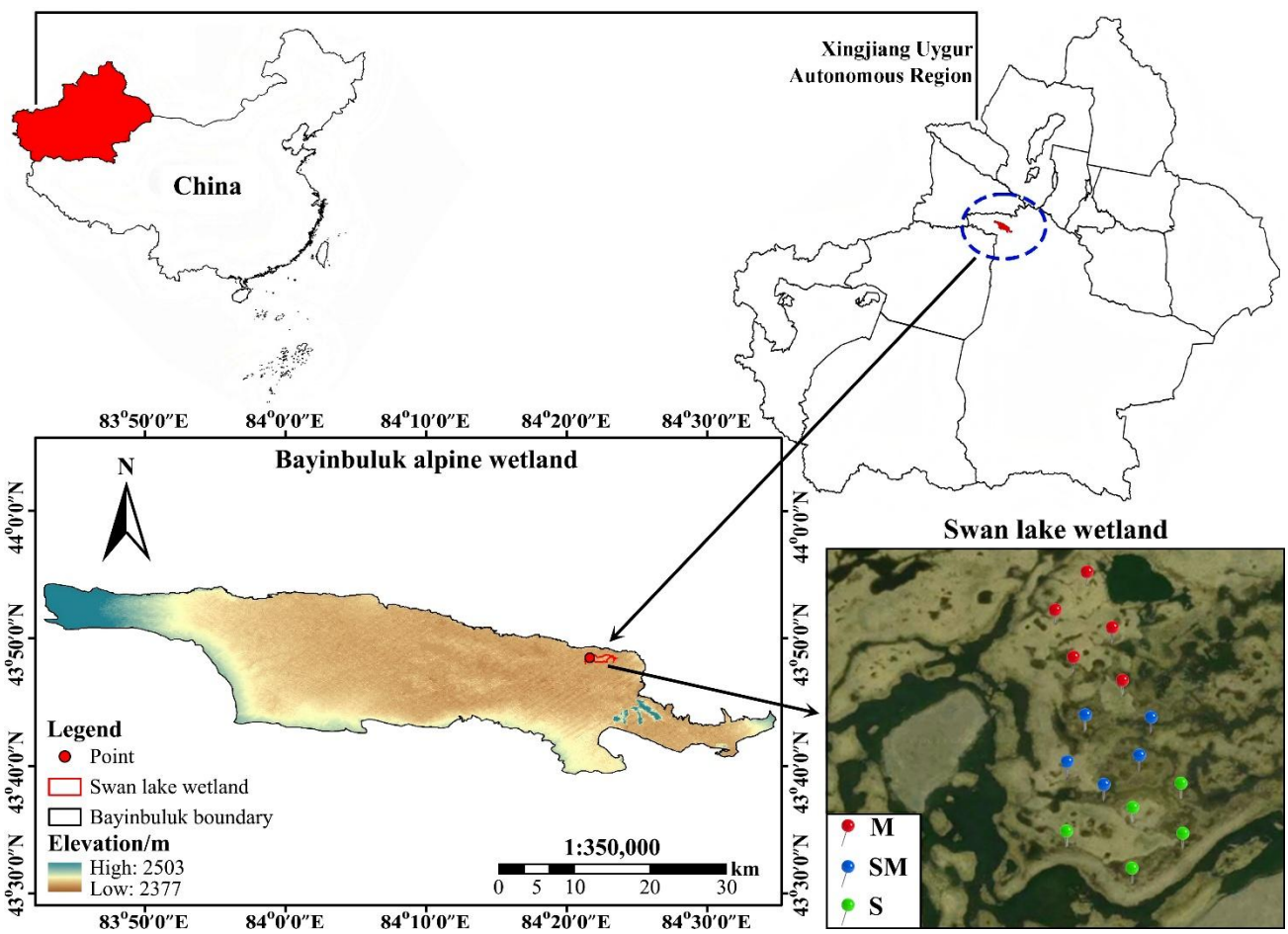

Fig. 1. Map of the study area.

Environmental factor data acquisition: Soil pH was measured with an acidimeter using a 1:5 ratio of soil-to-water suspension. Soil electrical conductivity (EC) was also measured using a 1:5 ratio of soil to water. The soil organic carbon (SOC) content was determined by the potassium dichromate volumetric method. Soil total nitrogen (STN) was assessed using the semi-micro Kjeldahl method, while soil total phosphorus (STP) was determined by the molybdenum antimony colorimetric method. Soil available N was quantified by colorimetry, and soil available phosphorus was measured using the sodium bicarbonate leaching–molybdenum antimony colorimetric method. Both soil total potassium and soil available potassium were determined using flame photometry.

The meteorological data for each station in Xinjiang was obtained from the National Meteorological Data Center (http://data.cma.cn/). Based on the coordinates of the sample plots, the average annual precipitation, temperature, and evaporation data from 54 stations over the past decade were selected. Microsoft Excel 2021 was used to perform weighted averages, yielding the average annual precipitation, temperature, and evaporation. Subsequently, the kriging method in the spatial interpolation analysis of ArcGIS v.10.7.0 was used to interpolate the meteorological data and extract meteorological factor data for each sample plot. Terrain factors were processed using ArcGIS for the Xinjiang digital elevation model image, while the slope and data of each sample plot were extracted using the Aspect (3D Analyst) slope tool.

Species importance value and diversity measurement: We used species importance value to indicate the functional status of species within the community (Li *et al*., 2019). The characteristics of diversity change in each community were compared using several indices in α-diversity measurement: the Margalef richness index (*DMa*), Simpson diversity index (*D*), Shannon–Wiener diversity index (*H′*), and Pielou evenness index (*J*). To measure the β-diversity of communities or habitats and compare the similarity characteristics among communities, Sorensen similarity index (*So*) and Jaccard similarity index (*Ja*) were used. The species importance value was expressed as follows:

$$\mathrm{IV} = (P + H + C) / 3 \quad (1)$$

where IV represents the importance value, *P* indicates the relative frequency, *H* denotes the relative height, and *C* refers to the relative coverage.

The frequency of occurrence of a species was obtained as follows:

$$\mathrm{F} = \frac{Q}{\mathrm{M}} \times 100\% \quad (2)$$

where F represents the frequency of occurrence of a species (%), Q denotes the number of occurrences of a species in the sample plot, and M signifies the total number of sample plots.

The proportion of species in the sample plot was determined as follows:

$$\mathrm{G} = \frac{\mathrm{W}}{\mathrm{V}} \times 100\% \quad (3)$$

where G represents the proportion of species in the sample plot (%), W denotes the number of species in a sample plot, and V indicates the total number of species across all sample plots.

Margalef richness index (*DMa*):

$$D_{Ma} = \frac{S\text{-}1}{\ln N} \quad (4)$$

Simpson dominance index (*D*):

$$D = 1 - \sum P_i^2 \quad (5)$$

Shannon–Wiener diversity index (*H′*):

$$H' = -\sum P_i \ln P_i \quad (6)$$

Pielou evenness index (*J*):

$$J = \left(-\sum P_i \ln P_i\right) / \ln S \quad (7)$$

$$p_i = N_i / N \quad (8)$$

In formulae (4) to (8), *S* represents the total number of species in the sample plot; *N* indicates the total number of individuals in the sample plot; *Ni* denotes the number of individuals of plant species *i*; and *Pi* refers to the proportion of individuals of plant species *i*, relative to the total number of individuals.

Sorensen similarity index (*So*):

$$S_o = \frac{2S_{12}}{2S_{12} + S_1 + S_2} \quad (9)$$

Jaccard similarity index (*Ja*):

$$J_a = \frac{S_{12}}{S_1 + S_2 - S_{12}} \quad (10)$$

In formulae (9) and (10), *S12* denotes the number of species present in both communities, while *S1* and *S2* represent the number of species in communities 1 and 2, respectively.

Data analysis: For the quantitative classification and ordination of plant communities in the alpine wetland of Bayinbuluk Swan Lake, calculations utilized species importance values and sample plot compositions as foundational data. Data from field surveys were processed using Microsoft Excel 2021, resulting in a 15 × 36 species matrix and a 15 × 15 environmental factor data matrix. TWINSPAN of the sample plot–species matrix was performed using Win TWINS v.2.3 (Kleef *et al*., 2006). The division categorized all sample plots and species into two initial groups, labeled 0 and 1. These groups were subsequently divided into subcategories, with the process continuing until the desired division level was achieved. Five levels of pseudo species were selected: 0–2, 2–5, 5–10, 10–20, and >20. The maximum division level was set at 6, with a maximum of 2 classifications per division,

facilitating the categorization of plant association types in the alpine wetland. Canonical correspondence analysis (CCA) was performed using CANOCO v.5.0 (El-Bana *et al*., 2002) for ranking analysis. To elucidate the characteristics of community diversity changes, one-way analysis of variance was performed using SPSS v.20.0.

Results

Species composition: Although the alpine wetland of Bayinbuluk Swan Lake hosts numerous species, its structural diversity is limited because of the predominance of herbaceous plants. As shown in (Table 1) this investigation identified 36 plant species, including 17 families and 28 genera. The Cyperaceae family exhibited the highest species richness across all sample plots, comprising 7 species and representing 19.44% of the total species. Poaceae followed with 6 species, constituting 16.67% of the total. Several families, including Potamogetonaceae, Plantaginaceae, Utriculariaceae, Orchidaceae, Liriophoraceae, Equisetaceae, Rosaceae, Scrophulariaceae, Boraginaceae, and Leguminosae, were represented by a single species each, accounting for 2.78% of the total species. The flora comprises 5 species of annual herbs, 1 species of biennial herbs, and 30 species of perennial herbs.

Figure 2 illustrates the distribution of species across sample plots, both in terms of species occurrence and proportion of species in each plot. Sample plot 9 contained the highest number of plant species, representing 27.78% of all species identified. Sample plots 7 and 8 followed, each containing 9 plant species, which accounted for 22.23% of the total species. In contrast, sample plots 2, 3, and 4 exhibited the lowest diversity, each containing only 2 plant species, or 5.56% of the total species. *Primula malacoides* and *Papaver nudicaule* exhibited the highest frequency, occurring in 46.67% of the sample plots. *Cirsium esculentum* followed, present in 33.33% of the plots. Several species, including *Festuca ovina*, *Elymus nutans*, *Elymus dahuricus*, *Koeleria macrantha*, *Ixeris polycephala*, *Juncus bufonius*, *Juncus effusus*, *Hippuris vulgaris*, *Equisetum hyemale*, *Potentilla chinensis*, and *Euphrasia pectinata*, exhibited the lowest frequency, each occurring in 6.67% of the sample plots.

Although we identified 36 plant species, the structural diversity was limited as all identified species were herbaceous plants.

Quantitative classification of plant communities: Figure 3 illustrates the TWINSPAN classification results of 15 sample plots in the alpine wetland of Bayinbuluk Swan Lake. All investigated sample points can be categorized into 5 groups. Considering the field investigation practicalities and the indicator species of community habitat characteristics and their groups, the division standard of the fourth association level was used to consolidate them into 4 associations. These associations were named according to the China vegetation classification system (Wu *et al*., 1980). The primary characteristics of each association type were as follows:

I. Ass. *Papaver nudicaule* + *Oxytropis ochrocephala* + *Leontopodium leontopodioides*. This association encompassed 11–13 sample points situated in the M area, at an elevation ranging from 2396 to 2404 m. The terrain has a gentle slope of 1.28–3.03°, with a southerly aspect. Soil characteristics included an EC of 16.25–18.38 μs/cm and alkaline pH (7.5–8.5). The predominant species *P. nudicaule* exhibited an average height of 12.87 cm. Secondary dominant species comprised *O. ochrocephala* and *L. leontopodioides*, with average heights of 3.67 cm and 17.33 cm, respectively. Endemic species included *Swertia chinensis* and *Juncus effusus*, displaying average heights of 4.00 cm and 6.80 cm, respectively. The overall coverage of the associations ranged from 24% to 27% (mean 25%).

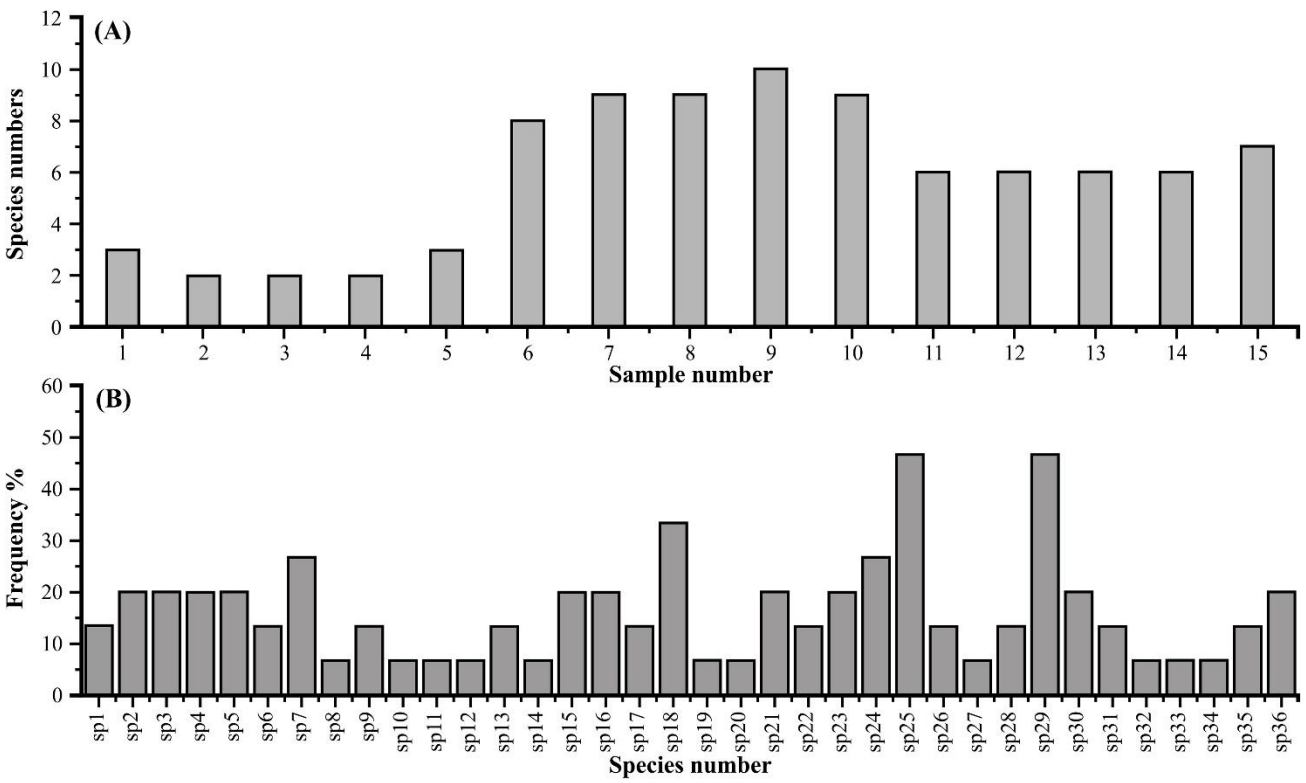

Fig. 2. Species occurrence in sample plots and proportion of species in each sample plot.

Table 1. Plants Questionnaire in the alpine wetland of Bayinbuluk Swan Lake

Number	Family	Genera	Species	Life form	Collection site
1.	Cyperaceae	*Carex*	*C. melanantha*	Perennial herbs	7,10
2.			*C. rhynchophysa*	Perennial herbs	2,4,5
3.			*C. microglochin*	Perennial herbs	9,14,15
4.			*C. atrofusca*	Perennial herbs	6,7,8
5.		*Kobresia Willd*	*K. myosuroides*	Perennial herbs	6,7,8
6.			*K. capillifolia*	Perennial herbs	9,10
7.		*Eleocharis*	*E. palustris*	Perennial herbs	1,3,4,5
8.	Gramineae	*Festuca*	*F. ovina*	Perennial herbs	13
9.			*F. rubra*	Perennial herbs	6,7
10.		*Elymus*	*E. nutans*	Perennial herbs	14
11.			*E. dahuricus*	Perennial herbs	6
12.		*Koeleria*	*K. macrantha*	Perennial herbs	15
13.		*Poa*	*P. annua*	Annual herbaceous	13,15
14.	Compositae	*Ixeris*	*I. polycephala*	Annual herbaceous	14
15.		*Taraxacum*	*T. mongolicum*	Perennial herbs	8,9,10
16.		*Achillea*	*A. millefolium*	Perennial herbs	7,8,9
17.		*Leontopodium*	*L. leontopodioides*	Perennial herbs	11,12
18.		*Cirsium*	*C. esculentum*	Perennial herbs	9,10,13,14,15
19.	Juncaceae	*Juncus*	*J. bufonius*	Annual herbaceous	11
20.			*J. effusus*	Perennial herbs	12
21.			*J. atratus*	Perennial herbs	9,14,15
22.	Gentianaceae	*Swertia*	*S. bimaculata*	Annual herbaceous	8,13
23.		*Gentiana*	*G. algida*	Perennial herbs	10,11,12
24.	Primulaceae	*Lysimachia*	*L. maritima*	Perennial herbs	6,7,8,9
25.		*Primula*	*P. malacoides*	Biennial herbs	6,7,8,9,10,14,15
26.	Potamogetonaceae	*Potamogeton*	*P. distinctus*	Perennial herbs	1,2
27.	Plantaginaceae	*Hippuris*	*H. vulgaris*	Perennial herbs	1
28.	Lentibulariaceae	*Utricularia*	*U. vulgaris*	Perennial herbs	3,5
29.	Papaveraceae	*Papaver*	*P. nudicaule*	Perennial herbs	6,7,9,11,12,13,15
30.	Orchidaceae	*Orchis*	*O. latifolia*	Perennial herbs	6,7,8
31.	Juncaginaceae	*Triglochin*	*T. palustris*	Perennial herbs	8,10
32.	Equisetaceae	*Equisetum*	*E. hyemale*	Perennial herbs	9
33.	Rosaceae	*Potentilla*	*P. chinensis*	Perennial herbs	10
34.	Scrophulariaceae	*Euphrasia*	*E. pectinata*	Annual herbaceous	10
35.	Boraginaceae	*Lithospermum*	*L. erythrorhizon*	Perennial herbs	11,12
36.	Leguminosae	*Oxytropis*	*O. ochrocephala*	Perennial herbs	11,12,13

II. Ass. *Juncus nigra* + Ass. *Juncus atratus* + *Primula malacoides* + *Cirsium esculentum.* This association encompassed sample points 9, 14, and 15, located in SM and M areas at altitudes ranging from 2396 to 2406 m. The terrain has a slope of 0.88–3.19°, with south- and southwest-facing aspects. Soil conditions indicated EC between 13.79 and 21.46 μs/cm and alkaline pH (7.5–8.5). *J. nigra* dominated the association, with an average height of 13.56 cm. Secondary dominant species included *Primula* and *C. esculentum*, averaging 16.23 cm and 4.50 cm in height, respectively. Endemic species comprised *Taraxacum mongolicum*, *Achillea millefolium*, *Artemisia capillaris*, and *Equisetum hyemale*, with average heights of 20.70, 25.00, 12.90, 3.00, and 12.20 cm, respectively. The total coverage of the association exhibited significant variation, ranging from 34% to 73% (mean 57.67%).

III. Ass. *Primula malacoides* + *Carex myosuroides* + *Carex melanantha*. This association encompassed sample plots 6–8 and 10, situated in the SM area. The plots were characterized by an altitude of 2391–2399 m, slopes of 0.88–2.79° facing south and southwest, soil EC measurements of 8.41–13.86 μs/cm, and alkaline soil conditions (pH 7.5–8.5). *Primula* emerged as the dominant species, with an average height of 16.20 cm. Secondary dominant species included *Artemisia* and *Carex nigra*, averaging 8.41 cm and 13.47 cm in height, respectively. Endemic species were *Cirsium rosulatum*, *Elymus dahuricus*, *Potentilla chinensis*, *Gentiana alpina*, *Swertia chinensis*, *Euphrasia japonica*, and *Artemisia capillaris*, with average heights of 5.50, 21.50, 3.20, 3.00, 2.75, 3.00, and 11.40 cm, respectively. The total coverage of the associations exhibited considerable variation, ranging from 21% to 79% (mean 56.25%).

IV. Ass. *Eleocharis palustris* + *Carex rhynchophysa* + *Potamogeton distinctus*. This association encompassed 1–5 sample plots, situated in the S area, with an elevation of 2392–2396 m. The terrain has a slope of 0.64–1.40°, primarily facing southeast and south. Soil characteristics included an EC of 3.88–6.03 μs/cm and neutral pH (6.5–7.5). The dominant species *Heleocharis hoya* reached an average height of 30.53 cm. Secondary dominant species included *Carex macrostachya* and *Potamogeton distinctus*, with average heights of 38.80 cm and 2.50 cm, respectively. The total coverage of the association remained relatively consistent, ranging from 38% to 47% (mean 41.00%).

In accordance with the China vegetation classification system, clusters I–IV corresponded to the following plant associations: Ass. *Papaver nudicaule* + *Oxytropis ochrocephala* + *Leontopodium leontopodioides*; Ass. *Juncus nigra* + Ass. *Juncus atratus* + *Primula malacoides* + *Cirsium esculentum*; Ass. *Primula malacoides* + *Carex myosuroides* + *Carex melanantha*; and Ass. *Eleocharis palustris* + *Carex rhynchophysa* + *Potamogeton distinctus*. All of these associations were classified as herbaceous.

Plant community species diversity analysis: Figure 4 illustrates the variations in α-species diversity of plant associations in each wetland, categorized by TWINSPAN clustering. The Simpson diversity index followed the order: cluster III > I > II > IV (Fig. 4A). Cluster III exhibited the highest index at 0.838, followed by cluster I at 0.792, while cluster IV showed the lowest at 0.437. The Simpson diversity ratio of cluster III was notably higher than that of cluster IV (p<0.05). The Shannon–Wiener diversity index variation for each cluster was in the order: cluster III > II > I > IV (Fig. 4B). Cluster III displayed the highest index at 1.969, cluster II followed at 1.678, and cluster IV had the lowest at 0.664. The Shannon–Wiener diversity of cluster IV was significantly lower than that of other clusters (p<0.05). Fig. 4C illustrates the evenness of distribution for each cluster type. The Pielou Evenness index variation followed the order: cluster I > III > II > IV. Species distribution in cluster I was the most uniform with an index of 0.932, followed by cluster III at 0.908, while cluster IV had the lowest Pielou evenness index at 0.787. The Pielou Evenness index of cluster I was 18.46% higher than that of cluster IV. Fig. 4D presents the variation in richness for each cluster type. The Margalef richness index variation followed the order: cluster III > II > I > IV. Cluster III contained the most species with an index of 1.971, cluster II followed at 1.597, and cluster IV had the fewest species with an index of 0.267. The richness of cluster III was significantly higher than that of cluster IV (p<0.05).

The Simpson diversity index, Shannon–Wiener diversity index, and Margalef richness index were the highest in cluster III, indicating a greater species diversity in this cluster. Cluster I exhibited the highest Pielou evenness index, suggesting a more uniform distribution of species within this group.

In the β-diversity analysis of various cluster types (Tables 2 and 3), clusters II and III exhibited the highest level of similarity, with Sorensen and Jaccard index scores of 0.304 and 0.389, respectively. They were followed by clusters I and III, with index scores of 0.216 and 0.190, respectively. Thus, the interspecific competition in clusters II and III was relatively limited, resulting in higher stability compared with other clusters. Notably, cluster IV demonstrated the lowest level of similarity with all other clusters, with both Sorensen and Jaccard index scores at 0. This lack of similarity can be attributed to the absence of common species between cluster IV and the other clusters. In addition, significant differences in terrain and soil factors contributed to intense competition between species in cluster IV and those in other clusters. Thus, cluster IV exhibited low stability and no discernible similarity with other clusters.

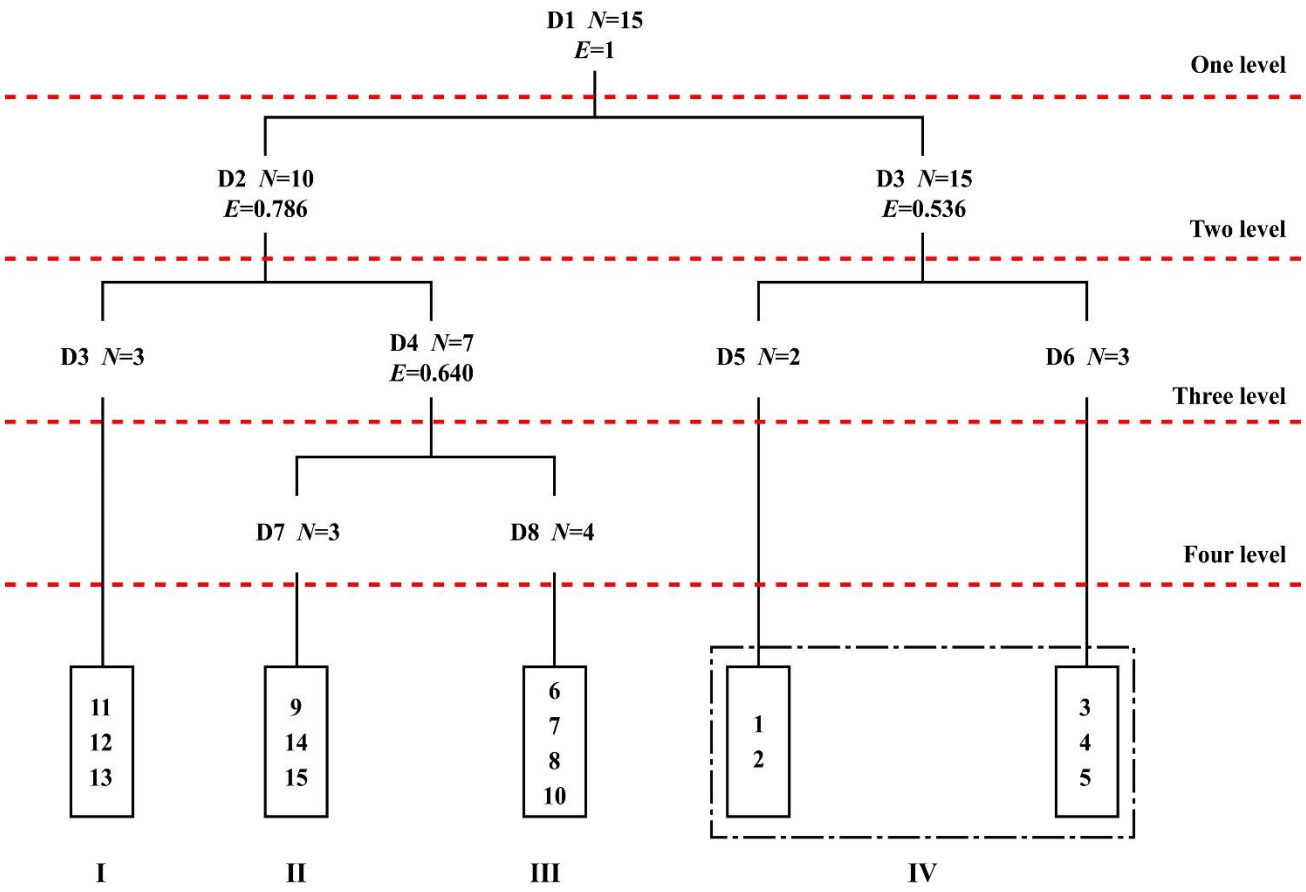

Fig. 3. TWINSPAN plot tree classification map in the alpine wetland of Bayinbuluk Swan Lake.
Note: E represents the characteristic value, N indicates sample number, D refers to the classification frequency, "grade" denotes classification level number, and Roman numerals represent association type.

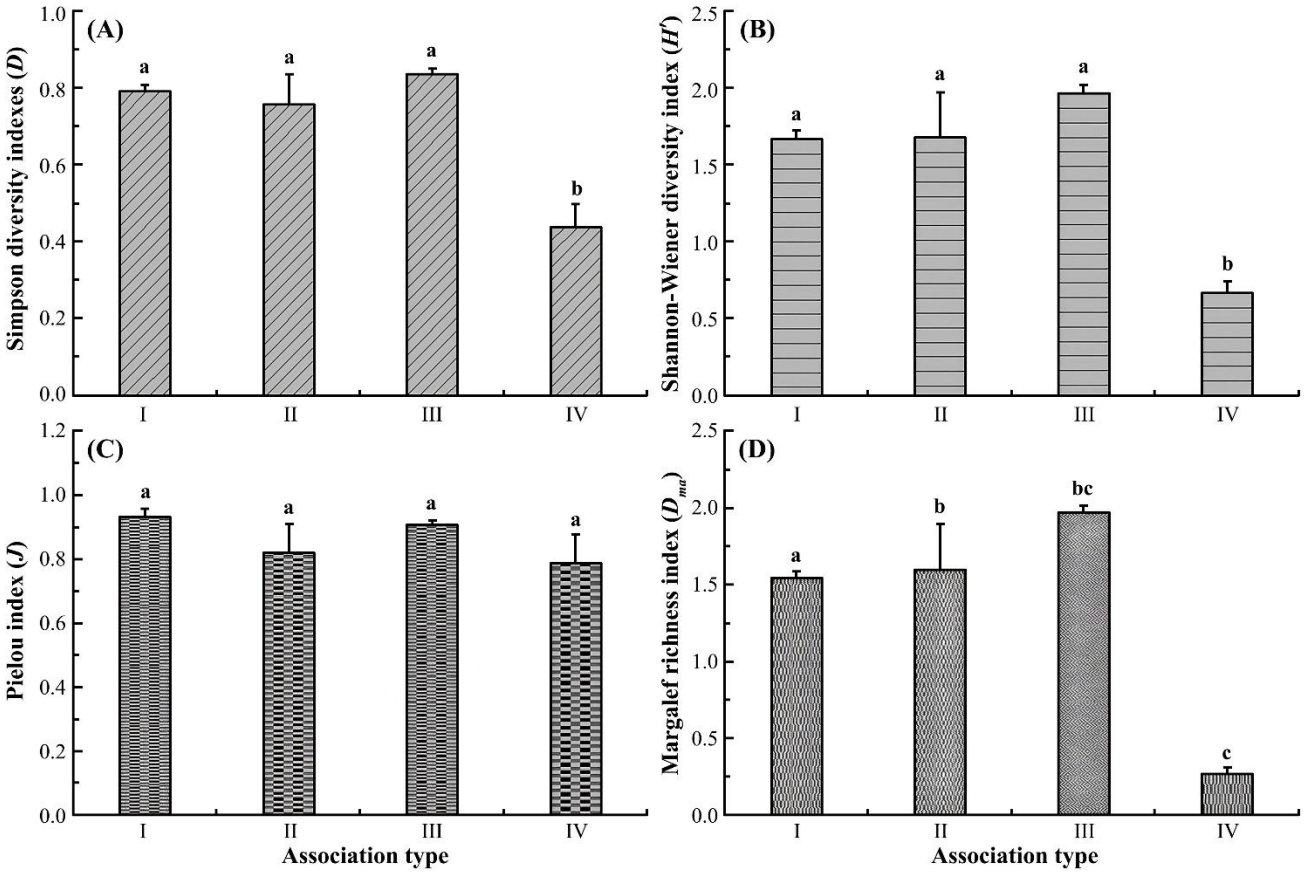

Fig. 4. Variation characteristics of plant community species diversity in the alpine wetland of Bayinbuluk Swan Lake.
Note: Different letters indicate significant difference between groups at the 0.05 level.

Table 2. Sorensen similarity comparison of wetland plant associations in the alpine wetland of Bayinbuluk Swan Lake.

Sorensen similarity	Assoc. I	Assoc. II	Assoc. III
Assoc. II	0.194		
Assoc. III	0.216	0.304	
Assoc. IV	0.000	0.000	0.000

Table 3. Jaccard similarity comparison of wetland flora in the alpine wetland of Bayinbuluk Swan Lake.

Jaccard similarity	Assoc. I	Assoc. II	Assoc. III
Assoc. II	0.158		
Assoc. III	0.190	0.389	
Assoc. IV	0.000	0.000	0.000

Correlation between spatial distribution of plant communities and environmental factors: Before the ordination analysis, 12 environmental factors (including soil pH, soil EC, STN, slope, and altitude) were evaluated in the initial selection process. During the analysis, environmental factors without significant influence were eliminated, resulting in 8 factors for further analysis, such as soil EC, SOC content, and STP. An appropriate model for ranking analysis was constructed based on the gradient value of the total length of response data. The gradient value of the total length of response data in this study was 4.79 > 4.0, satisfying the requirement for a unimodal model. Thus, the CCA model was used. Fig. 5 illustrates relatively long arrows for three environmental factors: soil EC, SOC content, and STP. The first two axes of the four CCA ordination axes cumulatively explain 51.86% of the data.

All ranking axes in the CCA model passed the Monte Carlo test (Table 4), with all canonical axes reaching a significant level (p<0.002). Soil pH, soil EC, and STP exhibited significant negative correlations with the first ordination axis (p<0.001). The second ordination axis showed significant negative correlations with SOC, STN, and available N (p<0.001). In addition, STN demonstrated a significant negative correlation with the third axis (p<0.05). Soil EC, SOC content, and STP were the primary factors influencing the spatial distribution of plant communities, while other environmental factors had a less significant impact on this distribution.

Analysis of significant factors affecting the spatial distribution of plant communities: To identify the key factors influencing the spatial distribution changes in plant communities, a comprehensive analysis of environmental factors was conducted (Fig. 6). The importance of each environmental factor, based on its explanatory power, was ranked as follows: soil EC > SOC content > STP > soil pH > STN > available N > slope gradient > slope aspect. The cumulative explanation rate of these environmental factors accounted for 69.80% of the variation, while the remaining 30.20% was attributed to interactions among these factors. Soil EC (18.4%) was the most influential factor in determining the spatial distribution of plant communities, followed closely by SOC content (15.6%).

Table 4. Comparison of correlation factors, eigenvalues, and interpretation variance of environmental factors and species ranking axes.

Environmental factors	AX1	AX2	AX3	AX4
Slope	-0.5563*	0.1872	0.2637	-0.2047
Aspect	-0.3085	-0.3050	-0.0930	-0.3067
pH	-0.8318***	0.4195	0.2555	0.0828
EC	-0.8550***	0.3286	0.3257	0.0611
SOC	0.0492	-0.8435***	-0.4361	0.0755
TN	0.0036	-0.7560***	-0.5454*	-0.1560
AN	0.1782	-0.8044***	-0.4628	-0.0327
TP	-0.7953***	0.3822	-0.1286	-0.3623
Eigenvalues	0.9810	0.7368	0.4801	0.4380
Species-environment correlations	0.9936	0.9825	0.9386	0.9917
Cumulative proportion of variance interpretation of species-environment relationship (%)	29.62	51.86	66.36	79.58
Test of significance of all canonical axes	0.0009			

Note: * and * * * indicate significant differences at p<0.05 and p<0.001, respectively

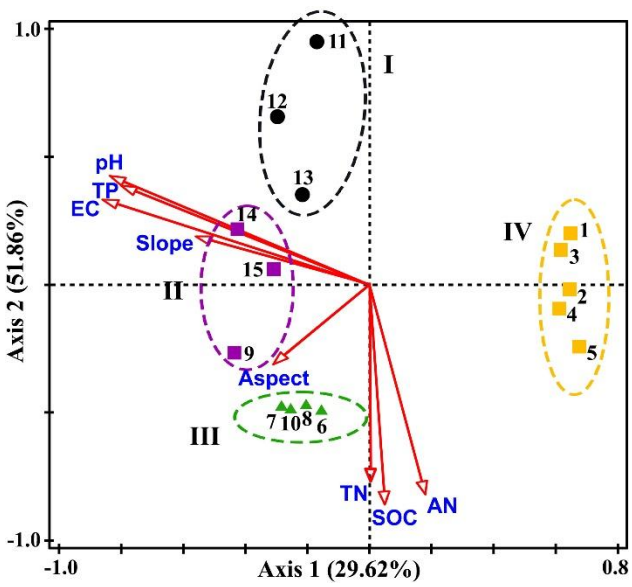

Fig. 5. CCA two-dimensional spatial ordination diagram of species and environmental data.
Note: pH: soil acidity and alkalinity; STP: soil total phosphorus; EC: soil electrical conductivity; STN: soil total nitrogen; SOC: soil organic carbon content; AN: readily available N.

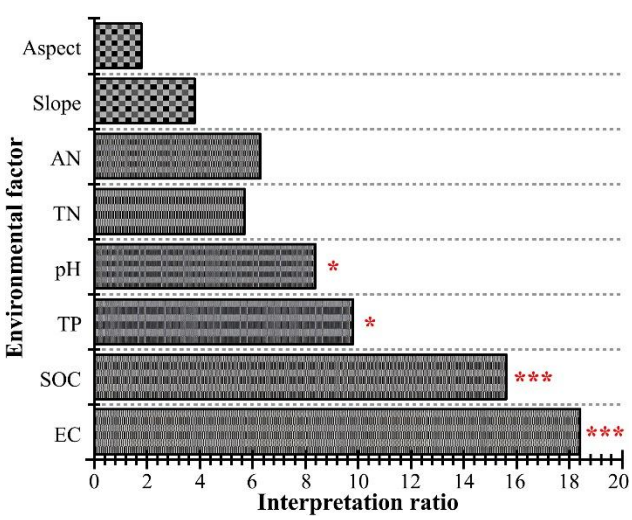

Fig. 6. Results of significant factor analysis.
Note: * and * * * indicate significant differences at $p<0.05$ and $p<0.001$, respectively.

Discussion

Classification and diversity analysis of alpine wetland plant communities: This study demonstrates that Cyperaceae plants predominate in the alpine wetland of Bayinbuluk Swan Lake. Despite the sensitivity of Cyperaceae to low temperatures, the alpine wetland of Bayinbuluk Swan Lake experiences seasonal soil freezing. Warm, humid summers and snow-covered winters create favorable conditions for Cyperaceae growth in the area (Chen *et al*., 2021). The importance value of graminoids in the plant community increased progressively from S to SM to M areas, aligning with the findings from the Luanhaizi alpine wetland survey (Lü *et al*., 2017). However, a study of the Haibei alpine wetland in the Qilian Mountains (Li *et al*., 2006) revealed differences in dominant plant species between shady and sunny slope wetlands. While soil moisture content significantly influences dominant plant species, additional factors such as light, temperature, and evaporation also play crucial roles in wetland plant succession.

The α-species diversity analysis of each plant association, categorized by TWINSPAN clustering, revealed that cluster III consistently exhibited the highest diversity and species abundance across all plant associations, while cluster IV demonstrated the lowest diversity, fewer species, and uneven distribution. This pattern can be attributed to the distribution of cluster III in the SM area and cluster IV in the S area. As one moves from S to SM, soil moisture levels gradually decrease. Correspondingly, species richness and diversity indices show an increasing trend with the reduction in soil moisture content. A similar conclusion regarding the response of plant community structure to water changes was drawn in a study of the Luanhaizi alpine wetland in Qinghai Province (Lü *et al*., 2017). However, this pattern did not persist in the transition from SM to M as soil moisture continues to decrease. This deviation may be because of the high species evenness in M, their stable structure, absence of surface ponding, and low levels of soil moisture saturation. The emergence of more drought-resistant plant species adapted to alpine climates was likely a result of long-term evolution, influenced by both environmental stress and historical/evolutionary factors (Whittaker *et al*., 2001; Jetz *et al*., 2004). β-diversity

analysis indicated that cluster IV lacked similarity with other clusters and exhibited lower community stability. This was because cluster IV, located in S areas, experiences long-term ponding, which deteriorates soil aeration conditions beyond the tolerance of some plants. Consequently, these plants perish, leading to the development of a monodominant species community. The distribution pattern of communities was influenced by complex environmental factors in the study area. The distinct habitat conditions of cluster IV created strong interspecific competition, resulting in a dissimilarity with other clusters and its low stability.

Correlation analysis of plant community spatial distribution and environmental factors in alpine wetlands: The CCA ordination diagram effectively illustrates the correlation between plant community spatial distribution and environmental factors in alpine wetlands. This approach is particularly suitable for studying the spatial distribution of plant community species. In this study, the correlation coefficients between species and environmental factors for the first two CCA ordination axes were 0.9810 and 0.7368, respectively, indicating their strong explanatory power. Generally, a cumulative contribution rate of variance exceeding 40% for the first three ordination axes suggests a satisfactory ordination effect (Fernández *et al*., 2005). CCA of the plant community in the Bayinbuluk Swan Lake alpine wetland yielded a cumulative contribution rate of 51.86% for the first three axes, confirming both suitability of CCA ordination and reliability of the results. The analysis revealed that soil EC, SOC content, and STP were the key environmental factors influencing plant community distribution in this alpine wetland, with other factors playing less significant roles. Liu *et al*. (2018) found that soil temperature, bulk mass, effective N, and STN were more closely related to vegetation in the alpine meadows of Guoluo Tibetan Autonomous Prefecture, Qinghai Province. Faisal *et al*. (2021) observed that species distribution and community structure in Chour Valley, Hazara Division, Pakistan, were directly correlated with altitude, slope aspect, and soil properties. These findings differ from the present study, possibly because of the scale-dependent nature of environmental factors affecting plant community distribution (Siefert *et al*., 2012). Climatic factors predominantly influenced community distribution at large regional scales, while topographic and soil-related factors were more influential at small regional scales. A study by Lei *et al*. (2023) in the core region of the Tibetan Plateau found that precipitation was the main factor affecting plant diversity and community stability in alpine grasslands, with SOC content, pH value, and ammonium N content also playing roles. This aligns more closely with the findings of the present study. At smaller regional scales, soil properties largely determine local plant community composition and structure, with vegetation closely related to soil factors (Burnside *et al*., 2007). Differences in the findings may be attributed to variations in regional environments, ecosystem limiting factors, and soil factors influencing plant community distribution. Plant community formation reflects the combined effects of terrain, climate, and soil factors (Fernández *et al*., 2005). In this study, soil EC emerged as a primary factor affecting plant community spatial distribution, possibly because of the alkaline soil and high groundwater and soil salt concentration in the area. In addition, the high altitude and cold climate contribute to slow soil organic matter decomposition (Lin *et al*., 2022), leading to long-term accumulation and large-scale underground C storage (Wang *et al*., 2015), thus making SOC content another major influencing factor. In conclusion, the plant community is impacted by the interaction of various environmental factors. Alpine wetland ecosystems exhibit greater complexity and vulnerability compared with terrestrial ecosystems, with more intricate relationships between plant communities and soil environmental factors. The alpine wetland of Bayinbuluk Swan Lake, China's first reserve established for whooper swan protection, serves as a crucial breeding ground for rare bird species such as *Cygnus cygnus* (whooper swan), *Grus grus*, and *Anser indicus* (Tong *et al*., 2017). Annually, over 3000 wild whooper swans visit this area for breeding. Given the reserve's vital importance for rare and endangered birds, elucidating the complex relationship between plant communities and the environment is crucial for maintaining the stability of the alpine wetland ecosystem. Future research should incorporate additional samples, including soil microorganisms, soil animals, and soil basic respiration, to provide a more comprehensive understanding of the relationships between alpine wetland plants and environmental factors, thereby offering scientific reference for the study and management of alpine wetland ecosystems.

Conclusions

(1) The alpine wetland of Bayinbuluk Swan Lake hosted 36 vegetation species, comprising 17 families and 28 genera. However, the diverse array of plant species had a relatively homogeneous structure consisting exclusively of herbaceous plants. Within this ecosystem, Cyperaceae plants exhibited the highest species diversity.

(2) Cluster III exhibited a higher species richness, while cluster I demonstrated greater uniformity. The interspecific competition in clusters II and III was relatively limited, resulting in a higher level of cluster stability compared with other clusters. In contrast, cluster IV showed no discernible similarity with other clusters. This cluster was characterized by significant variations in terrain and soil factors, coupled with intense competition among species. Consequently, the stability of this cluster was low.

(3) Soil EC emerged as the most significant influencing factor, followed by SOC content. In contrast, slope, aspect, available N, and STN exerted minimal influence on the spatial distribution of plant associations in this alpine wetland.

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