 DOI: 10.19601/j.cnki.issn1943 - 9903.2025.05.001

Biodiversity Characteristics and Protection Countermeasures of Yuncheng Salt Lake

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Abstract [**Objectives**] To explore biodiversity characteristics of Yuncheng Salt Lake and provide protection countermeasures. [**Methods**] According to the field survey data of 978 plant quadrats and cluster analysis, species diversity indicators such as Margalef richness index and Shannon - Wiener index were selected to deeply explore the structure and diversity characteristics of higher plant communities in Yuncheng Salt Lake. [**Results**] There were 117 species belonging to 97 genera and 35 families of higher plants in Yuncheng Salt Lake, of which Asteraceae and Gramineae were dominant families, and the North Temperate Distribution Genus accounted for 27.35% of the total genera; according to profile coefficient method, the optimal cluster number was 7, which was divided into 7 plant community types, including *Artemisia capillaris* community and *Suaeda glauca* (Bunge) community; the *Lolium perenne* community was the highest ($d = 2.537$), the *Artemisia scoparia* community was the best ($E = 0.658$), the *Suaeda salsa* (L.) Pall community was the lowest ($H' = 1.779$), and the spatial distribution of species showed a significant aggregation pattern. [**Conclusions**] We put forward some countermeasures for biodiversity protection, including constructing dynamic monitoring system, implementing adaptive management strategy and promoting multi-party collaborative governance, so as to provide scientific theoretical basis and practical guidance for ecological restoration and sustainable development of Yuncheng Salt Lake.

Key words Yuncheng Salt Lake, Biodiversity, Community classification, Diversity index, Protection countermeasures

0 Introduction

Biodiversity is one of the most significant features of the Earth's life system. It is not only the cornerstone of ecosystem health and stability, but also the key factor to maintain ecological service function. Yuncheng Salt Lake is the largest inland saltwater lake in North China, and its biodiversity protection is very important to maintain the ecological balance of the salt lake region, and its salt mining history dates back more than 4 000 years. Yuncheng Salt Lake occupies a key position in the middle reaches of the Yellow River and becomes an important overwintering habitat for winter migratory birds in this area. In 2020, the policy of "returning salt to lake" began to be implemented, and Yuncheng Salt Lake opened the transformation from traditional industrial salt farms to ecological protection zones and comprehensively terminated various industrial production activities. The unique ecological environment of Yuncheng Salt Lake breeds unique and diverse biological species, and is increasingly becoming a high-profile focus area in biodiversity research and ecological protection.

Salt lake, as a kind of unique ecosystem, has given birth to special biological groups because of its extreme environmental conditions such as high salt and alkali. Besides, it also provides a natural experimental field for biodiversity research. International academia has focused on the study of the diversity of halophilic microorganisms and their environmental adaptability. Brans *et al.* compared *Daphnia* populations in inland salt lake groups in Europe and found regional-scale local adaptation of salt tolerance: salinity threshold response genes showed significant differentiation in different salt lake clusters[1]. Studies on salt lakes in the Qinghai - Tibet Plateau have shown that microorganisms use two complementary strategies to cope with hyperosmolality: one is the "salt strategy" for maintaining intracellular high potassium concentration through K^+/Na^+ pumps; the other is the "organic solute strategy" for synthesizing compatible solutes such as betaine and trehalose[2]. The research on plant diversity in salt lakes abroad has made remarkable progress in classification system, adaptation mechanism, ecological function and conservation strategy. A diversity survey of Lake Zeherez in Algeria recorded 112 halophytes, including nine endangered endemic species. *Salicornia europaea* and *Suaeda glauca* form monoposterior population colonies and present a zonal distribution driven by salinity gradients[3]. The diversity census of Aslan *et al.* showed 195 vascular plants in this region, with saltmarsh vegetation dominated by Juncus and *Tamarix*, supporting 71 bird migration[4]. A systematic survey by Zhao Kefu et al showed that there are a total of 423 halophytes in China, which belong to 66 families and 199 genera, accounting for 27% of halophyte species worldwide[5]. *Tamarix* spp. and species such as *Halostachys caspica* have broad salt

Received: March 2, 2025 Accepted: May 10, 2025
Supported by Central Guiding Local Science and Technology Development Fund Project Free Exploration Basic Research (YDZJSX20231A002) and Yuncheng Salt Lake Ecological Environment Background Investigation and Research Project.
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adaptability (0.2% – 27% salt content) in Xinjiang Halophyte Community, while *Reaumuria songarica* can only form dominant communities in soils with salt content less than 4%[6].

In recent years, domestic scholars have gradually investigated and analyzed various biological groups in Yuncheng Salt Lake in detail. Extensive studies have been carried out on algal plants in Yuncheng Salt Lake[7], involving many levels such as floristic classification, community structure characteristics and correlation with salinity, algal species that can be used as plant resources and optimized cultivation methods, and molecular biology of *Dunaliella salina*[8]. The distribution rules of bacterial resources in Yuncheng Salt Lake were comprehensively explored, the bacterial diversity and community composition in each water area were studied, and the changes in bacterial community structure in different water areas of Yuncheng Salt Lake were explored; the bacterial diversity in soil and sediments of Yuncheng Salt Lake was explored, and the influencing factors were analyzed[9–13]. The study investigated the community structure and niche characteristics of endemic plant populations in salt lakes, and revealed the distribution pattern, quantitative dynamics, niche characteristics of vascular plant populations and their adaptation mechanisms to the environment[14–19]. Studies on plant diversity in Yuncheng Salt Lake wetland are relatively weak, and there is only one systematic census effort[20]. The discovery of *Glycine soja*, a national key protected wild plant, shows the importance of salt lake areas in biodiversity conservation. The study of Yuncheng Salt Lake focuses on the characteristics of various biological groups, salt adaptation mechanism and landscape evaluation[21–23], and these results provide a theoretical and technical support for the study of Yuncheng Salt Lake.

In this study, the diversity index characteristics of 7 typical plant communities were quantitatively analyzed by Margalef richness index, Berger – Parker dominance index, Shannon – Wiener diversity index and McIntosh evenness index based on 978 quadrat survey data in Yuncheng Salt Lake. It is of great ecological significance to analyze the diversity index of higher plants in Yuncheng Salt Lake. This provides a solid data basis for the ecological protection practice of Yuncheng Salt Lake, helps to identify key protected areas and endangered plant species, and also builds a theoretical foundation for formulating practical and effective ecological protection and restoration strategies.

1 Study area and methods

1.1 Overview of the study area Yuncheng Salt Lake is located in the southwest of Shanxi Province, located in the warm temperate semi-arid continental, monsoon climate area. The average annual temperature is about 12 – 14 ℃, the annual precipitation is 500 – 600 mm, and concentrated in summer, the evaporation is significantly higher than the precipitation. Because of the low terrain and salinization of soil in the salt lake region, and the strong evaporation, a unique saline-alkali environment is formed. Winter climate is cold and dry, summer is hot and accompanied by more rainfall. The duration of spring and autumn is short, and the seasonal temperature difference changes significantly. This climatic condition makes the salt lake continue to evaporate and concentrate salt, and become one of the most important inland salt lakes in North China. The unique geoclimatic characteristics shape the mineral sedimentary environment of salt lakes, and also affect the distribution of salt-tolerant vegetation around and ecosystem succession.

1.2 Study methods

1.2.1 Plant sample survey. Field surveys were carried out in Yuncheng Salt Lake from July to August 2024. In this study, a fixed sample ground network was systematically arranged, including five 20 m × 100 m transect, five 30 m × 30 m quadrats, and twenty 200 m long sample lines. A total of 1 000 plant quadrats were investigated, and the following parameters were recorded in detail: species composition, number of individuals, habitat characteristics, vegetation cover, average height, growth morphology and degree of human disturbance. After data quality control, 978 valid plant quadrat datasets were finally obtained.

1.2.2 Data analysis methods. All statistical analyses in this study were performed in the R language environment (version 4.3.0) and relied primarily on packages such as vegan, cluster, ggplot2, and pheatmap. Based on the normalized plant species abundance data, Hellinger transformation was performed on the original species-quadrat matrix to reduce the weight deviation of highly abundant species, followed by hierarchical clustering analysis using the Ward. D2 algorithm based on the Bray – Curtis dissimilarity matrix, and the optimal community classification number was determined by the profile coefficient method (test range k = 2 – 16), and finally the k value corresponding to the maximum profile coefficient was used as the community division basis. On this basis, the dominant species composition, species richness and total abundance of each cluster group were calculated, and a quadrangle-community type correspondence table was generated. In terms of α diversity analysis, Margalef richness index (d), Berger – Parker dominance index (B), Shannon – Wiener diversity index (H') and McIntosh evenness index (E) were used to assess species diversity characteristics within the quadrat in this study.

2 Result analysis

2.1 Species composition and fauna analysis

2.1.1 Species composition. According to the field survey data statistics, 117 species of higher plants were recorded in Yuncheng Salt Lake, belonging to 97 genera and 35 families, including *G. soja*, a national second-level key protected wild plant. According to the number of species contained within the plant family, Salt Lake plants were divided into four classes in this study: larger families (21 – 50 species), medium families (11 – 20 species), small families (2 – 10 species), and single species families (1 species) (Table 1). Statistical analysis showed that the Salt Lake flora was dominated by a single species family (22 species in 22 families, accounting for 62.86% of the total families and 18.80% of the total species), followed by a small family (36 species in 10 families, accounting for 28.57% and 30.77%). The middle family contained 29 species (5.71% and 24.79%) in 2 families, while the larger family had only 30 species (2.86% and 25.64%) in 1 family, indicating that the plant family level taxon in this region showed a significant distribution pattern of "a few dominant families dominate, and most single families coexist".

Table 1 Statistical results of grading of higher plants in Yuncheng Salt Lake

Level	Family		Species	
	Quantity	Proportion//%	Quantity	Proportion//%
Larger families (21 – 50 species)	1	2.86	30	25.64
Medium families (11 – 20 species)	2	5.71	29	24.79
Small families (2 – 10 species)	10	28.57	36	30.77
Single species families (1 species)	22	62.86	22	18.80
Total	35	100.00	117	100.00

The larger families containing 21 – 50 species are Compositae; the medium families containing 11 – 20 species are Gramineae and Amaranthaceae; the small families containing 2 – 10 species are Labiatae, Leguminosae, Polygonaceae, Apocynaceae, Malvaceae, Crasaceae, Lythygeae, Solanaceae, *etc.*; and only one family is Urticaceae, Salicaceae, Oxidaceae, Plantaginaceae, Tamaricaceae, *etc.*

Based on the species composition characteristics of genus-level taxonomic units, the higher plants of Yuncheng Salt Lake can be divided into three classes: medium-sized genera (5 – 9 species), small-sized genera (2 – 4 species), and single-species genera (1 species) (Table 2). The survey data showed that the flora in this region was dominated by a single species (85 genera 85 species, 87.63% of the total genera and 72.65% of the total species, respectively), followed by a small genus (11 genera 23 species, 11.34% and 19.66%), while only 9 species from 1 genus (1.03% and 7.69%) were recorded for a medium-sized genus. This distribution pattern showed that the higher plants in Yuncheng Salt Lake showed significant oligotypic genera dominant characteristics at the genus-level, which was consistent with the flora composition of most saline-alkali wetland ecosystems.

Table 2 Grouping statistics of plant genus in Yuncheng Salt Lake

Level	Genus		Species	
	Quantity	Proportion//%	Quantity	Proportion//%
Medium-sized genera (5 – 9 species)	1	1.03	9	7.69
Small-sized genera (2 – 4 species)	11	11.34	23	19.66
Single-species genera (1 species)	85	87.63	85	72.65
Total	97	100.00	117	100.00

The medium-sized genera (5 – 9 species) were *Artemisia*; the small-sized genera (2 – 4 species) were *Melilotus*, *Erigeron*, *Bidens*, *Suaeda*, and *Amaranthus*; and the single-species genera (1 species) were *Echinochloa*, *Polygonum*, *Xanthium*, *Limonium*, and *Tamarix*.

2.1.2 Faunal analysis. Plant areal-types reflect repetitive patterns in spatial distribution of plant taxa, and plants with the same distribution type generally show similar ecological adaptation strategies and evolutionary histories. It is worth noting that there is often a composite distribution of multiple faunal components within a specific geographical area. Through systematic analysis and classification of geographical distribution patterns of plants, this research method provides an important theoretical basis for revealing the origin history, ecological adaptability characteristics and biogeographic significance of regional plant communities.

Based on the distribution area classification system of Chinese seed plant genera established by Wu Zhengyi in 1991, 97 plant genera in Yuncheng Salt Lake were classified into 14 distribution area types in this study (Table 3, Fig. 1). Statistical analysis showed that North temperate distribution (27.35%) and world distribution (26.50%) constituted the main components of the flora in this region, and the combined proportion of the two accounted for more than 53% of the total genera.

Table 3 Areal-types of Plant Genus in Yuncheng Salt Lake

No.	Areal-types	Genus quantity	Proportion %
1	Cosmopolitan	31	26.50
2	Pantropic	18	15.38
3	Tropical Asia & Tropical America disjuncted	3	2.56
4	Old World Tropic	1	0.85
5	Tropical Asia &Tropical Australasis	1	0.85
6	Tropical Asia to Tropical Africa	7	5.98
7	Tropical Asia (Indo – Malesia)	1	0.85
8	North Temperate	32	27.35
9	East Asia & North Amer disjuncted	5	4.27
10	Old World Temperate	11	9.40
11	Temperate Asia	1	0.85
12	Mediterranean, West Asia to Central Asia	4	3.42
13	Central Asia	1	0.85
14	East Asia	1	0.85
Total		117	100

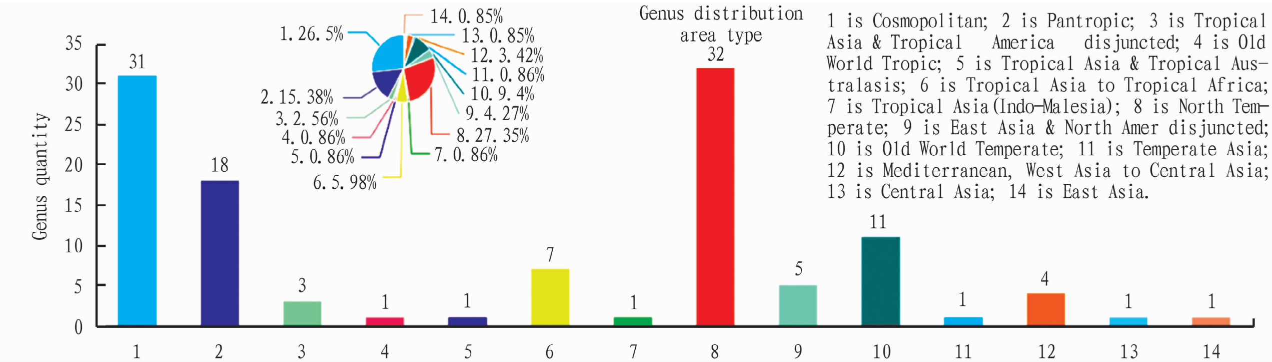


Fig. 1 Diagram of distribution area types of plant genus in Yuncheng Salt Lake

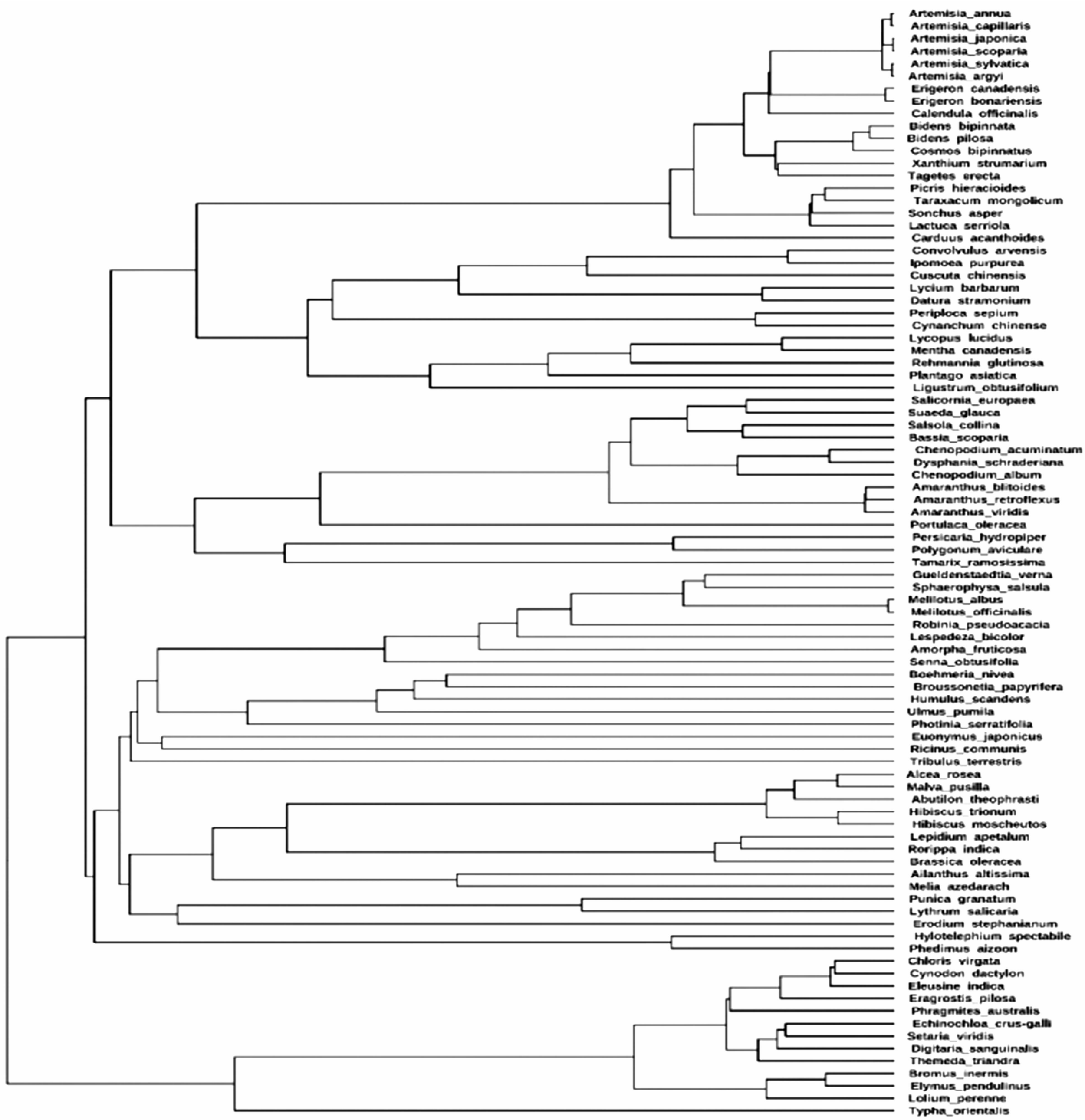


Fig. 2 Lineage diagram of higher plants in Yuncheng Salt Lake

2.2 Plant community classification Based on the quadrat-species number matrix, this study used profile analysis to determine the optimal number of clusters. By plotting the number of different clusters ($k=2-16$) against the corresponding mean profile coefficients (taking values ranging from -1 to 1), we observed that the profile coefficients peaked (0.42) when $k=7$, indicating that this clustering scheme best reflects the intrinsic structure of the data (Fig. 3). Finally, the cluster analysis divided 978 quadrats into seven plant community types with obvious characteristics, named after the dominant species: *Artemisia capillaris* community, *S. glauca* (Bunge) community, *Setaria viridis* community, *Lolium perenne* community, *Artemisia scoparia* community, *Cynodon dactylon* community and *Suaeda salsa* (L.) Pall community (Fig. 4, Table 4).

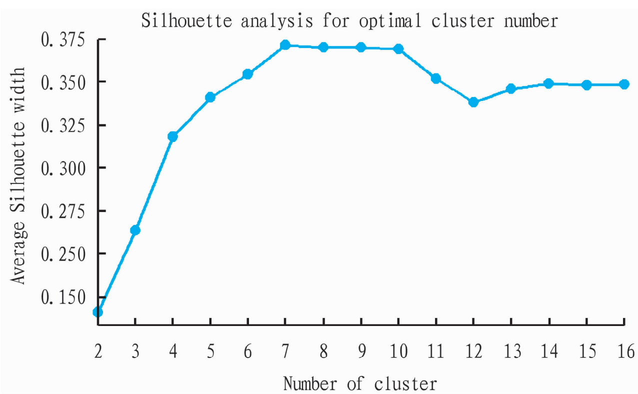


Fig. 3 Profile analysis for optimal number of clusters

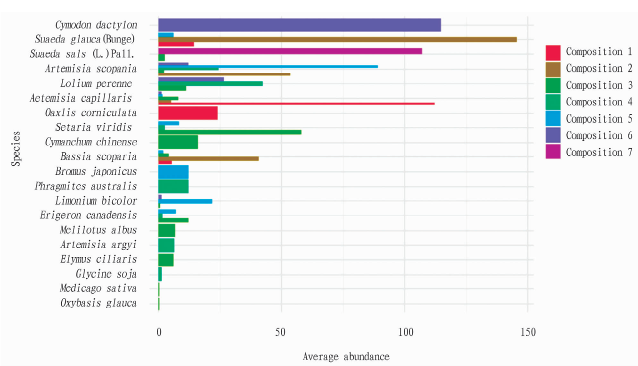


Fig. 4 Dominant species composition in different community types

Table 4 Clustering results

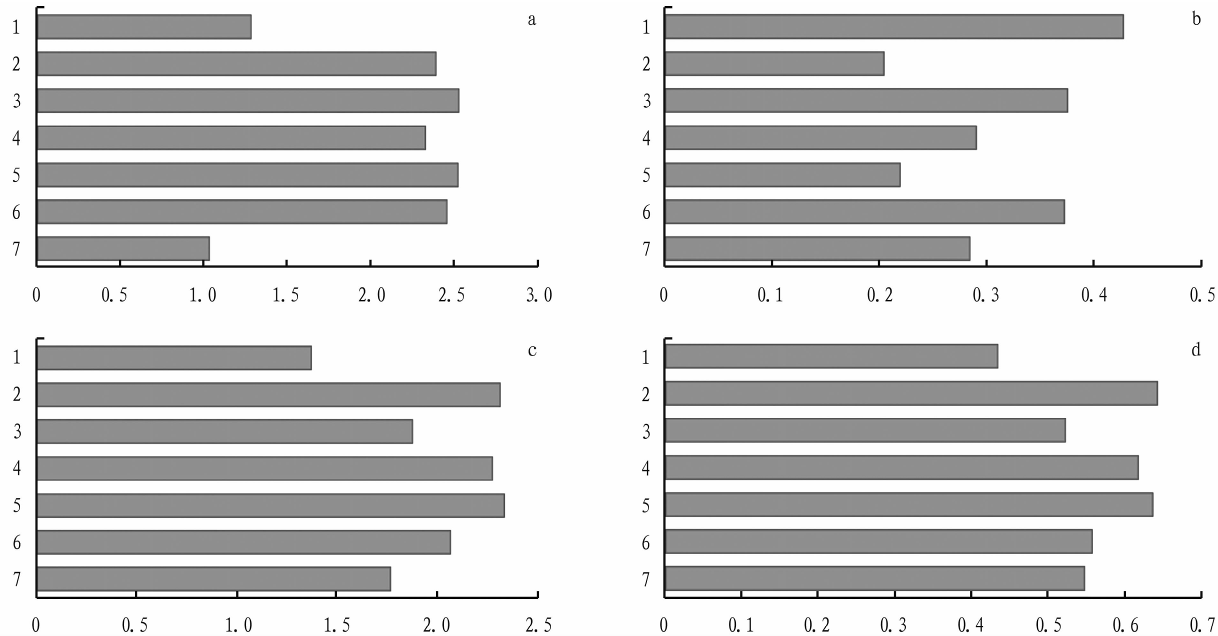
Clusters	Community Type	Number of quadrats
1	*A. capillaris* community	67
2	*S. glauca* (Bunge) community	225
3	*S. viridis* community	136
4	*L. perenne* community	62
5	*A. scoparia* community	299
6	*C. dactylon* community	142
7	*S. salsa* (L.) Pall community	47

2.3 Plant diversity profile Margalef species richness index (d), Berger – Parker dominance index (B), Shannon – Wiener diversity index (H') and Mcintosh evenness index (E) were systematically calculated for each plant community in this study. Following are detailed results. (Fig. 5a) lists the calculated results of Margalef richness index (d) for seven groups of plant communities. The results showed that there were significant differences in species richness among communities, and the index ranged from 0.5 to 2.537. The lowest richness ($d=0.5$) was found in the community of *S. salsa* (7), indicating that its species composition was the most single. The richness indicators of *A. capillaris* community (1, $d=1.043$), S. salsa community (2, $d=1.5$) and *S. barbata* community (3, $d=1.293$) were at moderate levels. *Lolium* community (4, $d=2.537$), *A. suis* community (5, $d=2.532$), and *Bermudagrass* community (6, $d=2.466$) in contrast showed high species richness, with the richness of *Lolium* community peaking ($d=2.537$). Index values were maintained at high levels ($d>2.466$) for the ryegrass, *A. suis*, and *Bermudagrass* communities, which may have more complex species composition and more stable ecological system structure.

Berger – Parker dominance index (B) calculation results showed that there were significant differences in dominance indicators among communities, ranging from 0.1 to 0.429 (Fig. 5b). The highest dominance was observed in the community of *A. capillaris* (1, $B=0.429$), indicating that its community structure was dominated by a single dominant species. *S. salsa* community (2, $B=0.206$) and *A. suchii* community (5, $B=0.221$) showed relatively uniform species distribution. The dominance of *S. communis* community (3, $B=0.377$), Bermudagrass community (6, $B=0.374$) and *Lolium communis* community (4, $B=0.292$) was at a moderate level, and the dominance of *S. salsa* community (7, $B=0.286$) was similar to that of *Lolium communis* community. All communities had dominance indicators below 0.5, indicating no absolute dominance of a single species within the study area.

The results of Shannon – Wiener diversity index (H') calculation showed that the diversity index of each community showed gradient changes, and the index ranged from 1.779 to 2.384 (Fig. 5c). The diversity levels of *A. capillaris* community (1, $H'=1.779$) and *S. capillaris* community (3, $H'=2.073$) were close to relatively low. *S. salsa* community (2, $H'=2.384$), *L. ryegrass* community (4, $H'=2.382$) and *A. suchii* community (5, $H'=2.341$) showed a high level of diversity, with the diversity of *Suaeda salsa* community peaking ($H'=2.384$). The diversity of Bermudagrass community (6) and *S. salsa* community (7) was intermediate. The H' values of *S. salsa* community and *L. ryegrass* community were very close (difference only 0.002), and these two communities had similar characteristics in species composition complexity and distribution uniformity.

McIntosh's homogeneity index (E) analysis showed significant differences in the evenness of each community, with indicators ranging from 0.436 to 0.658 (Fig. 5d). *Artemisia suis* community (5, $E=0.658$) and *S. suaeda* community (2, $E=0.644$) showed the highest evenness, indicating that their species had the most balanced individual distribution. The evenness index of the ryegrass community (4, $E=0.619$) was slightly lower. Uniformity of Bermudagrass community (6, $E=0.549$) and *Setaria* community (3, $E=0.524$) was at a moderate level. *A. capillaris* community (1, $E=0.436$) and *S. salsa* community (7) had the lowest evenness. The evenness of *S. salsa* community was significantly lower than that of other communities ($E\approx0.3$), reflecting that its species distribution showed a significant aggregation pattern.



NOTE a. Margalef richness index; b. Berger – Parker dominance index (B); c. Shannon – Wiener diversity index (H′); d. McIntosh's homogeneity index (E); 1. *A. capillaris* community; 2. *S. glauca* (Bunge) community; 3. *S. viridis* community; 4. *L. perenne* community; 5. *A. scoparia* community; 6. *C. dactylon* community; 7. *S. salsa* (L.) Pall community.

Fig. 5 Calculation of α diversity index of 7 different plant communities

3 Protection countermeasures

3.1 Establishing a long-term dynamic monitoring system

Establishing a scientific long-term dynamic monitoring system plays a key role in biodiversity conservation in Yuncheng Salt Lake. The system realizes the full coverage monitoring of various habitats by reasonably laying monitoring stations in different ecological regions of salt lakes, and uses sensor network to collect water quality and meteorological parameters in real time to provide basic data for evaluating the changes of biological habitat environment. Besides, it integrates modern technical means such as aerial photography, infrared camera and DNA barcode to systematically record the composition, spatial distribution and dynamic changes of animal and plant species. A special surveillance program was implemented for rare species, focusing on tracking their reproductive behavior, migration routes and other key ecological parameters. Through continuous data collection and analysis, we can not only establish a complete biodiversity database of salt lakes, but also identify the changing trend of biological communities in time, so as to provide a scientific basis for formulating targeted conservation strategies.

3.2 Implementing dynamic adaptive management The ecological system management of Yuncheng Salt Lake should be based on scientific analysis of long-term dynamic monitoring data and implement adaptive management strategies. When monitoring data suggests abnormal fluctuations in ecological environmental parameters — for example, deterioration of water quality indicators leads to a significant decline in the number of specific aquatic organisms — the management team needs to immediately initiate a response mechanism to control water and salt balance by adjusting water conservancy facility operating parameters. Specific measures include regulating the freshwater recharge of the Yellow River to maintain a suitable salinity gradient, so as to ensure the survival needs of key species. This dynamic management model also needs to consider the biological phenological characteristics: in the bird breeding season to focus on the implementation of habitat protection measures, strictly limit human activity interference; and in the peak algal growth period through accurate regulation of water nutrient salt concentration, to maintain a reasonable population size of primary producers. The whole management process emphasizes scientific decision-making based on real-time ecological data, and continuously optimizes the implementation effect of protective measures through periodic evaluation.

3.3 Promoting multi-party collaborative governance Yuncheng Salt Lake biodiversity protection needs to build a government-led, multi-party collaborative comprehensive management system. Government departments shall, in conjunction with environmental protection, water conservancy management and other relevant departments, make overall plans for systematic protection, and at the same time establish strategic cooperation relations with scientific research institutions — especially carrying out joint research projects by relying on the scientific research forces of local colleges and universities to provide scientific basis and technical support for protection work. At the implementation level, we must pay full attention to community participation, promote residents' ecological awareness through continuous environmental education, and establish mechanisms to encourage local communities to directly participate in ecological monitoring and protection actions. For industrial enterprises around the salt lake, it is necessary to promote green transformation through environmental protection technology upgrading and realize the balance between industrial development and ecological protection. This model of government-research-community-enterprise coordination, through policy coordination, scientific research support, public participation and corporate responsibility organic combination, ultimately form a multi-dimensional, three-dimensional biodiversity protection network.

3.4 Enhancing publicity and education and raising public awareness Implementing diversified public education strategies is a key way to enhance the social participation in biodiversity conservation in Yuncheng Salt Lake. Through producing high-quality ecological documentaries and public welfare advertisements, they are systematically placed in mainstream television media, radio platforms and digital communication channels to visually display the diversity of biological resources and special protection value of the salt lake ecosystem to the public. The education system shall integrate ecological knowledge of salt lake into the local curriculum system, and effectively cultivate students' awareness of environmental protection by organizing on-site investigation activities, carrying out popular science lectures, holding ecological knowledge competitions and other interactive forms. At the community level, it is necessary to establish a normalized environmental education mechanism, such as regularly holding thematic activities such as the "Salt Lake Ecological Protection Publicity Week", cooperating with the distribution of popular science brochures and carrying out special lectures, and guiding residents to start from the environmental protection practice of daily life. This all-round and multi-level publicity and education network can gradually build a good social atmosphere in which all sectors of society pay attention to and support the protection of biodiversity in salt lakes.

3.5 Promoting the integrated development of literature travel industry and ecological protection The ecotourism development of Yuncheng Salt Lake should take biodiversity protection as the core orientation, and integrate ecological education into the whole process of tourism experience through scientific regional planning. Based on the spatial heterogeneity of the salt lake ecosystem, differentiated sightseeing lines can be designed: typical habitats such as brine areas enriched with Artemia, shoal wetlands inhabited by birds, and lakeside zones with dense vegetation, and ecological science popularization lines can be developed separately. A specialized ecological interpretation system is set up along the line to introduce the endemic species, ecological service function and protection value of the region in detail through the pictorial display card, so as to realize the seamless connection between tourist sightseeing and natural education. In addition, innovative development of immersion ecological experience projects, including bird observation platforms equipped with professional bird observation equipment and explanation services (especially in the migratory bird migration season), interactive breeding experience areas to display the ecological function of Artemia. This trinity development model of tourism, education and protection can not only improve the level of biodiversity cognition of tourists, but also realize the synergistic effect of ecological protection and tourism development.

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