Spatial Distribution and Species Diversity of Saline-Alkaline-Land Plants in the Desert-Oasis Transition Zone of the Hexi Corridor and Their Relationships with Environmental Factors

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2026-06-18

ChinaRxiv

Abstract

To explore the distribution patterns of plant communities in saline-alkali land in the desert-oasis transition zone of the Hexi Corridor and to further investigate the environmental factors affecting plant distribution in saline-alkali land in the Hexi Corridor, this study used the importance value of each species as an indicator and applied two-way indicator species analysis (TWINSPAN), detrended correspondence analysis (DCA), and canonical correspondence analysis (CCA) to classify and ordinate plant communities in this region, thereby examining the relationship between plant diversity and environmental factors. The results showed that TWINSPAN divided the plants in 113 sample plots into 11 different types of plant communities. Among them, association had the lowest diversity index, association had the lowest richness index, and associations and had the highest similarity index. RDA analysis showed that altitude, soil water content, and soil electrical conductivity were positively correlated with the Shannon-Wiener diversity index, Margalef richness index, Simpson index, and Pielou evenness index, whereas pH was negatively correlated with these indices. CCA ordination of the sample plots showed that altitude, precipitation, and total salt content explained 4.6%, 2.8%, and 1.5% of community distribution, respectively, with contribution rates of 33.3%, 20.2%, and 11.2%, respectively. In summary, the most important environmental factor affecting the distribution of plant communities in saline-alkali land in the desert-oasis transition zone of the Hexi Corridor is altitude, followed by precipitation and total salt content. Different plant communities exhibit certain distribution patterns along the altitudinal gradient. These findings provide a scientific basis for understanding the distribution and diversity variation characteristics of plant communities in saline-alkali land in the Hexi Corridor and are of great significance for the future protection and restoration of plant ecosystems in saline-alkali land in the Hexi Corridor.

Full Text

DOI: 10.13866/j.azr.2026.04.08
CSTR: 32277.14.AZR.20260408

Spatial Distribution and Species Diversity of Saline-Alkaline-Land Plants in the Desert-Oasis Transition Zone of the Hexi Corridor and Their Relationships with Environmental Factors

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Abstract: To explore the distribution pattern of plant communities on saline-alkaline land in the desert-oasis transition zone of the Hexi Corridor, and to investigate in depth the environmental factors affecting the distribution of saline-alkaline-land plants in the Hexi Corridor, this study used the importance value of each species as an indicator. Two-way indicator species analysis (TWINSPAN), detrended correspondence analysis (DCA), and canonical correspondence analysis (CCA) were used to classify and ordinate the plant communities in the study area, and to examine the relationships between plant diversity and environmental factors. The results showed that TWINSPAN divided the plants at 113 sampling sites into 11 different types of plant communities. Among them, community VII had the lowest diversity index, community XI had the lowest richness index, and communities II and III had the highest similarity index. RDA analysis showed that elevation, soil water content, and soil electrical conductivity were positively correlated with the Shannon–Wiener diversity index, Margalef richness index, Simpson index, and Pielou evenness index, whereas pH was negatively correlated with them. The CCA ordination of sample plots showed that elevation, precipitation, and total salt content explained 4.6%, 2.8%, and 1.5% of the variation in community distribution, respectively, with contribution rates of 33.3%, 20.2%, and 11.2%. In summary, the most important environmental factor influencing the distribution of saline-alkaline-land plant communities in the desert-oasis transition zone of the Hexi Corridor is elevation, followed by precipitation and total salt content. Different plant communities exhibit certain distribution patterns along changes in elevation. These findings provide a scientific basis for understanding the distribution and diversity variation characteristics of saline-alkaline-land plant communities in the Hexi Corridor, and are also of great significance for the future protection and restoration of saline-alkaline-land plant ecosystems in the Hexi Corridor.

Keywords: Hexi Corridor; saline-alkaline land; quantitative classification and ordination; species diversity

Plants are the source of energy input for ecosystems, as well as regulators of the environment and constructors of habitats. They play a vital role in the functioning of ecosystems. Plant growth is affected by many environmental factors; under different living environments, plants develop suitable strategies to adapt to environmental change[1], especially in arid and semiarid saline-alkaline lands, where the living environment for plants is even harsher. Saline-alkaline land is characterized by excessive salt ions in the soil. Salt stress makes it difficult for non-halophytic plants to survive, causing a decline in biodiversity in saline-alkaline areas, which in turn leads to low biological productivity of saline-

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alkaline land and seriously threatens agricultural production and food security[2]. Therefore, analyzing the distribution and characteristics of saline–alkaline-land plant communities, and scientifically understanding, reasonably classifying, and ordinating plant communities, are of great significance for the protection and management of vegetation resources in saline–alkaline regions.

At present, commonly used quantitative classification methods include cluster analysis[3], two-way indicator species analysis (TWINSPAN)[4], and multivariate regression tree (MRT)[5]. Commonly used ordination methods include canonical correspondence analysis (CCA) and detrended correspondence analysis (DCA)[6]. These methods can not only scientifically classify the positions of sample plots and species, but also express the relationships between environmental factors and sample plots or species. Combining TWINSPAN classification with DCA and CCA can more clearly express the relationships among species, sample plots, and environmental factors[7].

In recent years, many scholars have conducted extensive studies on the distribution patterns of saline–alkaline-land plant communities and the relationships between diversity and environmental factors, finding that the environmental factors affecting the distribution of saline–alkaline-land plant communities differ among regions. Wang Yuzhen[8], in a study of the distribution of saline–alkaline-land plant communities in Dongying City, found that soil salt content affected the plants in this region

Received: 2025-08-13; **Revised:** 2025-10-10
Funding: National Natural Science Foundation of China (U23A2061, 32160253); Key Research and Development Program of Gansu Province (24YFFH002, 22YF7FA117); Major Science and Technology Special Project of Gansu Province (22ZD6FA052)
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distribution; Koull et al.

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found, in their study of saline wetlands and plant distribution in northeastern Algeria, that soil salinity and moisture were the most important factors affecting the distribution of saline–alkaline vegetation in that region. Liu Xinghong et al.

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studied the distribution pattern of vegetation communities in saline–alkaline lands of northern Xinjiang and found that elevation was the most important factor affecting that region, followed by multi-year mean precipitation, temperature, evaporation, and soil electrical conductivity. Although many studies of this kind have examined the relationships between the distribution of saline-alkaline plant communities and environmental factors, research on the causes of the distribution of saline–alkaline plant communities in the Hexi Corridor remains relatively scarce. Under the combined influence of uneven precipitation distribution, an arid climate, and frequent human activities, desertification in the Hexi Corridor has intensified and has been accompanied by large-scale soil salinization[10]. The presence of salt-tolerant plants can, on the one hand, ameliorate soil salinization[11], and, on the other hand, effectively reduce soil salt content[12]. Some salt-tolerant plants can lower soil pH and electrical conductivity, making the soil more suitable for plant growth[13]. However, most studies in this region have focused on the physicochemical properties of saline–alkaline soils[14] and the improvement of saline–alkaline land[15], and most have examined changes in a single plant species at small spatial scales. Few studies have addressed the relationships between saline–alkaline plants and environmental factors such as soil and climate across the entire region; studies of the distribution patterns of saline–alkaline plants and changes in species diversity at large spatial scales remain limited.

On this basis, this study combines field investigation with laboratory analysis, and uses TWINSPAN, DCA, and CCA to classify and ordinate saline–alkaline plant communities in the desert–oasis transition zone of the Hexi Corridor. The aims are to explore the relationships between the distribution patterns of saline-alkaline plant communities and environmental factors in this region, and to reveal the patterns of change in species diversity. The results can provide a scientific basis for the improvement, conservation, and sustainable management of saline–alkaline plant communities in the Hexi Corridor.

1 Materials and Methods

1.1 Overview of the study area

The study area is located in the eastern section of the Hexi Corridor, mainly distributed across three places: Wuwei City (37°23′–38°12′ N, 101°59′–103°23′ E), Zhangye City (37°51′–39°53′ N, 97°23′–102°37′ E), and Jinchang City (37°47′–39°00′ N, 101°04′–102°43′ E). It lies in northwestern Gansu Province and has a typical temperate continental climate, with scarce precipitation, an arid climate, and large diurnal temperature differences. The mean annual precipitation ranges from 119 to 344 mm, mean annual evaporation reaches 2197 mm, mean annual potential evaporation ranges from 2000 to 3000 m, and mean annual temperature ranges from 4.8 to 9.2 ℃. Soil types include brown desert soil, gray-brown desert soil, gray desert soil, light brown desert soil, and sierozem. Natural vegetation is relatively simple in species composition, consisting mainly of drought-resistant shrubs and herbs, with few tree species. The main shrubs include red sand (*Reaumuria soongarica*), pearl shrub (*Caroxylon passerinum*), and white-thorn (*Nitraria tangutorum*); the main herbs include *Salsola passerina*, *Bassia dasyphylla*, crested wheatgrass (*Agropyron cristatum*), and reed (*Phragmites australis*).

1.2 Field survey and sampling

This study adopted a combination of field and laboratory methods. In the preliminary stage, sampling points were pre-arranged according to remote-sensing data and the NDVI index, then adjusted and finalized based on field conditions; finally, a total of 113 sampling points were selected. Field investigation and sampling were conducted from August to September 2024. At each sampling point, one large 10 m × 10 m quadrat was established for the investigation of shrub species, and indices such as plant species, number of individuals, coverage, frequency, and crown width within the quadrat were recorded. Along the diagonal of the quadrat, three sampling positions were determined at equal intervals, and soil samples from the 0–20 cm soil layer were collected separately; these were then mixed evenly and bagged as the soil sample for that sampling point. At the same time, the five-point plum-blossom positioning method was used within the quadrat: 1 m × 1 m small quadrats were set at the four corners and the center of the large quadrat to investigate herbaceous plants within the quadrats, and related indices such as herb species and number of individuals were recorded. GPS equipment was then used to record the longitude, latitude, elevation, and other data for each sampling point. After all samples were brought back to the laboratory, they were air-dried naturally, plant roots and gravel were removed, and the samples were passed through a 0.25 mm sieve for the determination of soil pH, soil electrical conductivity (EC), and the contents of soluble salt ions in the soil.

1.3 Acquisition of soil and meteorological data

Soil pH was determined by the potentiometric method (soil:water ratio 1:2.5); soil electrical conductivity was determined by the electrode method (soil:water ratio 1:5); soil moisture content was determined by the oven-drying method; and soluble salt ion content was determined by extraction at a soil:water ratio of 1:5

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. Monthly precipitation data for China over the past 20 a at 1 km resolution and monthly mean temperature data over the past 20 a at 1 km resolution were downloaded from the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn). Using the Kriging method in the spatial interpolation analysis module of ArcGIS 10.8, the meteorological data were interpolated, and meteorological factor data for each sampling point were extracted.

The calculation method for total soil salt content is:

$$TSC = W_{\mathrm{Ca^{2+}}} + W_{\mathrm{Mg^{2+}}} + W_{\mathrm{K^{+}}} + W_{\mathrm{Na^{+}}} + W_{\mathrm{CO_3^{2-}}} + W_{\mathrm{HCO_3^{-}}} + W_{\mathrm{SO_4^{2-}}} + W_{\mathrm{Cl^{-}}} \quad (1)$$

The calculation method for soil alkalization degree is:

$$ESP = \frac{ES}{CEC} \times 100\% \quad (2)$$

where W is the mass fraction of salt ions ($\mathrm{g \cdot kg^{-1}}$); ES is exchangeable sodium ion ($\mathrm{cmol \cdot kg^{-1}}$); and CEC is cation exchange capacity ($\mathrm{cmol \cdot kg^{-1}}$).

1.4 Calculation of diversity indices

This study adopted the Margalef richness index from the α-diversity indices.

indices (D_{Ma}), Simpson diversity index (D), Shannon-Wiener diversity index (H'), and Pielou evenness index (P) were used to compare the variation characteristics of diversity among communities. Sorenson' s similarity index and Jaccard' s similarity index were used to measure the diversity of communities or habitats and to compare the similarity characteristics among communities. The calculation formulas are as follows:

Margalef richness index (D_{Ma}):

$$D_{\mathrm{Ma}} = \frac{S-1}{\ln N} \quad (3)$$

Simpson dominance index (D):

$$D = 1 - \sum P_i^2 \tag{4}$$

Shannon–Wiener index (H'):

$$H' = -\sum P_i \ln P_i \tag{5}$$

Pielou evenness index (P):

$$P = \frac{(-\sum P_i \ln P_i)}{\ln S} \tag{6}$$

$$P_i = \frac{N_i}{N} \tag{7}$$

where S is the total number of species in the quadrat; N is the total number of individuals in the quadrat; N_i is the number of individuals of the i-th plant species; and P_i is the proportion of individuals of the i-th plant species in the total number of individuals.

Sorenson' s similarity index:

$$S = \frac{2S_{12}}{2S_{12} + S_1 + S_2} \tag{8}$$

Jaccard' s similarity index:

$$J = \frac{S_{12}}{S_1 + S_2 - S_{12}} \tag{9}$$

where S_{12} is the number of species occurring in both communities, and S_1 and S_2 are the numbers of species in community 1 and community 2, respectively.

The calculation formula for importance value is as follows:

$$\text{Importance value} = \frac{\text{abundance} + \text{frequency} + \text{coverage}}{3} \tag{10}$$

1.5 Data Analysis

In this study, the importance values of shrubs and herbs in each quadrat were calculated as the basis to construct a quadrat–species importance-value matrix for the numerical classification and ordination of TWINSPAN. During the classification process, the sample sites and species were first divided into two major classes, 0 and 1, and then these two classes were successively divided level by level until the preset classification level was reached. Afterwards, Excel 2010 was used for data statistics and analysis, and the α index and β index of species were calculated. SPSS 26 was used for one-way analysis of variance to compare differences among communities. PCORD-5 software was used to establish matrices for sample sites–species and sample sites–environmental factors, and DCA ordination and CCA analysis were performed. The environmental factors were annual mean precipitation, annual mean temperature, soil pH, soil electrical conductivity, altitude, soil total salt content, soil water content, and soil alkalization degree. Soil total salt content and alkalization degree are important soil properties that can reflect the degree of soil salinization and alkalization. Soil pH is an important indicator reflecting the chemical properties of soil; it can affect the availability of nutrients in soil as well as the growth conditions of plants [17]. In DCA ordination, when the length of the first axis is > 4.0, a unimodal model should be selected; when it is between 3.0 and 4.0, either a unimodal or linear model may be selected; if it is < 3.0, a linear model should be selected. In CCA ordination analysis, arrows represent the various environmental factors, and the quadrant in which an arrow lies represents the positive or negative correlation between the environmental factor and the ordination axes. The magnitude of the correlation between community distribution and that environmental factor can be judged from the length of the arrow line: the longer the line, the greater the correlation, and conversely the smaller the correlation. In addition, the included angle between two arrows also reflects the strength of the correlation between two environmental factors: the smaller the angle, the greater the correlation.

2 Results and Analysis

2.1 Classification of Community Numbers

Using TWINSPAN hierarchical classification, 113 sample sites were divided into 15 groups. Combined with the actual conditions of the field investigation and the habitat characteristics of the communities, the fourth-level community classification criterion was adopted, and the communities were finally merged into 11 association types, as shown in Fig. 1.

Association I was the *Peganum harmala* + *Halogeton arachnoideus* association, including sample sites 13, 70, 71, 75, 82, and 84, distributed in Liangzhou District, Shandan County, and Ganzhou District. The altitude was 1453–1772 m, the annual mean precipitation was 190.5 mm, the annual mean temperature was 7.4 ℃, and the mean coverage of the association was 47.89%. Associated species included *Lycium ruthenicum* and *Suaeda salsa*.

Association II was the *Kalidium foliatum*-Suaeda salsa association, including sample sites 11, 44, 46, 49, 51, 53, 54, 55, 57, 59, 61, 63, 64, 66, 68, 72, 73, 81, and 83, distributed in Minle County, Yongchang County, Shandan County, and Ganzhou District. The altitude was 1602–2347 m, the annual mean precipitation was 208 mm, the annual mean temperature was 6.6 ℃, and the mean coverage of the association was 33.82%. Associated species included Reaumuria and

Peganum harmala.

Association III was the *Asterothamnus centraliasiaticus*-Salsola + *Peganum harmala* association, including sample sites 37, 56, 58, 60, 62, 65, 67, 69, 74, 77, 90, 91, 92, 94, 95, 110, and 113, distributed in Liangzhou District, Linze County, Ganzhou District, Minle County, Shandan County, Yongchang County, and Gulang County. The altitude was 1397–2337 m, the annual mean precipitation was 200 mm, the annual mean temperature was 7.2 ℃, and the mean coverage of the association was 22.1%. Associated species included *Peganum harmala* and *Artemisia desertorum*.

Visible text in the cluster classification tree diagram

- **Level I:** $D1\ N = 114,\ E = 0.7451$
- **Level II:** $D2\ N = 71,\ E = 0.624$; $D3\ N = 43,\ E = 0.8608$
- **Level III:** $D4\ N = 43,\ E = 0.6865$; $D5\ N = 28,\ E = 0.6865$; $D6\ N = 33,\ E = 0.7397$; $D7\ N = 10,\ E = 0.7162$; $D8\ N = 6,\ E = 0.6357$; $D9\ N = 37,\ E = 0.6866$; $D10\ N = 22,\ E = 0.5370$; $D11\ N = 6,\ E = 0.6575$; $D12\ N = 23,\ E = 0.7446$; $D13\ N = 10,\ E = 0.6853$; $D14\ N = 4$; $D15\ N = 6,\ E = 0.4879$
- **Level IV:** $D16\ N = 1$; $D17\ N = 5,\ E = 0.5622$; $D18\ N = 19,\ E = 0.4748$; $D19\ N = 18,\ E = 0.7329$; $D20\ N = 6,\ E = 0.6706$; $D21\ N = 16,\ E = 0.5465$; $D22\ N = 2$; $D23\ N = 4$; $D24\ N = 7,\ E = 0.6499$; $D25\ N = 16,\ E = 0.5677$; $D26\ N = 8,\ E = 0.6327$; $D27\ N = 2$; $D28\ N = 4$; $D29\ N = 2$

Terminal groups shown in the diagram:

- **Association I:** 13; 70, 71, 75, 82, 84
- **Association II:** 11, 44, 46, 49, 51, 53, 54, 55, 57, 59, 61, 63, 64, 66, 68, 72, 73, 81, 83
- **Association III:** 37, 56, 58, 60, 62, 65, 67, 69, 74, 77, 90, 91, 92, 94, 95, 110, 113
- **Association IV:** 7, 39, 40, 85, 106, 109
- **Association V:** 2, 8, 22, 30, 45, 48, 50, 52, 80, 86, 89, 93, 96, 99, 101, 107
- **Association VI:** 17, 32; 6, 15, 23, 26
- **Association VII:** 14, 24, 97, 100, 103, 105, 112
- **Association VIII:** 1, 3, 9, 10, 16, 18, 20, 21, 36, 38, 47, 76, 78, 79, 88, 102
- **Association IX:** 12, 19, 25, 27, 28, 33, 42, 111; 31, 35
- **Association X:** 5, 29, 87, 98
- **Association XI:** 4, 41, 104, 108; 34, 43

Note: E is the eigenvalue; D_K is the K-th classification; N is the number of plots; 1–113 are plot numbers.

Figure 1. Cluster classification tree diagram

Fig. 1 Cluster classification tree diagram

Association IV is the red-sand shrub + *Nitraria sphaerocarpa* association. It contains plots 7, 39, 40, 85, 106, and 109, distributed in Minqin County, Jinchuan District, Ganzhou District, Linze County, and Gaotai County. The elevation is 1337–1471 m, mean annual precipitation is 129 mm, mean annual temperature is 8.8 °C, the mean cover of the association is 16.68%, and the associated species include wubingli and zhumaocai.

Association V is the red-sand shrub + pearl shrub association. It contains plots 2, 8, 22, 30, 45, 48, 50, 52, 80, 86, 89, 93, 96, 99, 101, and 107, distributed in Gaotai County, Linze County, Ganzhou District, Minqin County, and Liangzhou District. The elevation is 1260–1632 m, mean annual precipitation is 140 mm, mean annual temperature is 8.7 °C, the mean cover of the association is 20.43%, and the associated species include *Nitraria sibirica* and black-fruited wolfberry.

Association VI is the black-fruited wolfberry + salt-claw association. It contains plots 6, 15, 17, 23, 26, and 32, distributed in Minqin County. The elevation is 1224–1380 m, mean annual precipitation is 110 mm, mean annual temperature is 9.3 °C, the mean cover of the association is 25.44%, and the associated species include red-sand shrub and camel grass.

Association VII is the *Tamarix ramosissima* + *Calligonum mongolicum* association. It contains plots 14, 24, 97, 100, 103, 105, and 112, distributed in Minqin County, Linze County, and Gaotai County. The elevation is 1226–1410 m, mean annual precipitation is 125 mm, mean annual temperature is 9.3 °C, the mean cover of the association is 21.47%, and the associated species include *Alhagi camelorum* and white thorn.

Association VIII is the *Haloxylon ammodendron* + white thorn–wubingli association. It contains plots 1, 3, 9, 10, 16, 18, 20, 21, 36, 38, 47, 76, 78, 79, 88, and 102, distributed in Linze County, Ganzhou District, Shandan County, Minqin County, and Liangzhou District. The elevation is 1362–1588 m, mean annual precipitation is 133 mm, mean annual temperature is 8.9 °C, the mean cover of the association is 21.09%, and the associated species include black-fruited wolfberry and *Caryopteris mongholica*.

Association IX is the sand sagebrush–zhumaocai association. It contains plots 12, 19, 25, 27, 28, 31, 33, 35, 42, and 111, distributed in Gulang County, Liangzhou District, and Minqin County. The elevation is 1355–1749 m, mean annual precipitation is 135 mm, mean annual temperature is 8.8 °C, the mean cover of the association is 17.46%, and the associated species include *Echinops davuricus* and *Agriophyllum squarrosum*.

Association X is the *Zygophyllum xanthoxylum*–ice-grass association. It contains plots 5, 29, 87, and 98, distributed in Linze County, Ganzhou District, Liangzhou District, and Minqin County. The elevation is 1306–1464 m, mean annual precipitation is 137 mm, mean annual temperature is 9.1 °C, the mean cover of the association is 19.31%, and the associated species include red-sand shrub and reed.

Association XI is the slender-branch salt-claw-reed association. It contains plots 4, 34, 41, 43, 104, and 108, distributed in Minqin County, Linze County, and Gaotai County. The elevation is 1343–1415 m, mean annual precipitation is 136 mm, mean annual temperature is 8.9 °C, the mean cover of the association is 35.74%, and the associated species include salt-claw and white thorn.

2.2 Characteristics of changes in plant diversity of the communities

Through analysis of changes in the four indices of α-diversity for the 11 associations classified by TWINSPAN, the results are shown in Figure 2, and it was found that the overall change

Fig. 2 Variation characteristics of α-diversity indices among different associations

Panels: (a) Simpson diversity index (D); (b) Margalef richness index (D_{Ma}); (c) Pielou evenness index (P); (d) Shannon–Wiener diversity index (H).

Note: Different lowercase letters indicate significant differences in the indices among associations ($P < 0.05$).

Fig. 2 Variation characteristics of α-diversity indices among different associations in the subtropical forest

The changes were consistent, all showing a trend of first increasing and then decreasing. The Simpson index of the associations followed the order: association III > association VI > association X > association II > association V > association VIII > association I > association XI > association IV > association IX > association VII. The Simpson index of association III was significantly higher than those of associations IX and VII ($P \leq 0.05$), and association IX was significantly higher than association VII. For the Margalef richness index, association XI had the lowest richness index, while the richness index of association X was significantly higher than that of association XI. The Pielou evenness index of association VII was significantly lower than those of the other associations; moreover, the Shannon–Wiener diversity index of association VII was also the lowest compared with the other associations. The Shannon–Wiener diversity indices of associations II, III, VI, and X were significantly higher than that of association VII.

As shown in Fig. 3, altitude, soil water content, and electrical conductivity were positively correlated with the Shannon–Wiener diversity index, Margalef richness index, Simpson index, and Pielou evenness index. Alkalization degree and total salinity were positively correlated with the Shannon–Wiener diversity index and Simpson index, whereas soil pH showed a negative correlation with all four diversity indices.

Fig. 3 RDA analysis plot of diversity indices

Note: *Ait* denotes altitude; *Pre* denotes annual precipitation; *Tem* denotes annual mean temperature; *EC* denotes soil electrical conductivity; *SWC* denotes soil water content; *ESP* denotes soil alkalization degree; *TSC* denotes soil total salinity. The same applies below.

Fig. 3 RDA analysis plot of diversity indices

As shown in Tables 1 and 2, the similarity between association II and association III was the highest, with Sorenson' s index and Jaccard' s index of 0.300 and 0.273, respectively. The next highest was between association V and association VII, with Sorenson' s index and Jaccard' s index of 0.296 and 0.267, respectively. The lowest inter-association similarities occurred between association I and associations VII and IX, association II and association XI, association III and association XI, association V and association IX, association VI and association IX, and association IX and association XI, with index values of 0.

2.3 Relationship between community distribution patterns and the environment

Using the species-plot matrix data, DCA ordination was performed for the 11 associations classified by TWINSPAN (Fig. 4). The gradient length of the first axis was found to be 5.74 > 4.0, satisfying the unimodal model; therefore, this study selected the unimodal model to conduct DCA ordination analysis of the 113 sample plots. The results showed that,

Table 1. Similarity comparison among various clusters of Sorenson' s
Tab. 1 Similarity comparison among various clusters of Sorenson' s

Sorenson' s similarity	Cluster I	Cluster II	Cluster III	Cluster IV	Cluster V	Cluster VI	Cluster VII	Cluster VIII	Cluster IX	Cluster X
Cluster II	0.114									
Cluster III	0.121	0.300								
Cluster IV	0.077	0.213	0.222							
Cluster V	0.222	0.150	0.200	0.229						
Cluster VI	0.154	0.186	0.195	0.222	0.286					
Cluster VII	0.000	0.121	0.129	0.214	0.296	0.286				

Sorenson's similarity	Cluster I	Cluster II	Cluster III	Cluster IV	Cluster V	Cluster VI	Cluster VII	Cluster VIII	Cluster IX	Cluster X
Cluster VIII	0.242	0.174	0.182	0.205	0.222	0.216	0.207			
Cluster IX	0.000	0.108	0.205	0.133	0.000	0.000	0.100	0.229		
Cluster X	0.190	0.211	0.263	0.148	0.231	0.160	0.211	0.200	0.095	
Cluster XI	0.125	0.000	0.000	0.167	0.261	0.167	0.250	0.160	0.000	0.133

Table 2. Similarity comparison among various clusters of Jaccard' s
Tab. 2 Similarity comparison among various clusters of Jaccard' s

Jaccard's similarity	Cluster I	Cluster II	Cluster III	Cluster IV	Cluster V	Cluster VI	Cluster VII	Cluster VIII	Cluster IX	Cluster X
Cluster II	0.069									
Cluster III	0.074	0.273								
Cluster IV	0.043	0.156	0.167							
Cluster V	0.167	0.097	0.143	0.174						
Cluster VI	0.100	0.129	0.138	0.167	0.250					
Cluster VII	0.000	0.074	0.080	0.158	0.267	0.250				
Cluster VIII	0.190	0.118	0.125	0.148	0.167	0.160	0.150			
Cluster IX	0.000	0.065	0.148	0.083	0.000	0.000	0.059	0.174		
Cluster X	0.125	0.154	0.217	0.095	0.176	0.105	0.154	0.143	0.056	
Cluster XI	0.077	0.000	0.000	0.111	0.214	0.125	0.200	0.105	0.000	0.083

CCA plot

Figure 1: CCA plot

Legend: Cluster I; Cluster II; Cluster III; Cluster IV; Cluster V; Cluster VI; Cluster VII; × Cluster VIII; + Cluster IX; Cluster X; Cluster XI

Axes: horizontal axis, First axis; vertical axis, Second axis.

Figure 4. DCA analysis plot
Fig. 4 DCA plot

The eigenvalues of the four ordination axes were 0.840, 0.7509, 0.6356, and 0.5562, respectively. Among them, the eigenvalue of the first ordination axis was the largest, followed by that of the second ordination axis. Therefore, the first two ordination axes were selected as the two-dimensional ordination axes. As shown in Fig. 4, the DCA ordination results were basically consistent with the various cluster types generated by TWINSPAN classification, and they could be displayed well in the two-dimensional ordination diagram. The ordination results showed a high degree of similarity with the plant-cluster classification results.

To gain a deeper understanding of the correlations between the vegetation of the 113 sampling sites and environmental factors, CCA analysis was conducted on the 113 plots in the study area together with 8 environmental factors (Fig. 5). The eigenvalues of the four ordination axes were 0.7323, 0.4504, 0.2811, and 0.2245, respectively. It can be seen that the eigenvalues of the first two axes were relatively high, and the cumulative contribution of the species–environment variance of the first two axes reached 57.05%, indicating that the CCA ordination axes could effectively reflect the relationship between plant-community distribution and environmental factors. As shown in Fig. 5, the environmental factors most strongly correlated with cluster distribution were elevation, precipitation, total salt content, and air temperature, with significance levels of $P = 0.002$, $P = 0.002$, $P = 0.016$, and $P = 0.036$, respectively, and explanatory rates of 4.6%, 2.8%, 1.5%, and 1.4%, respectively. Elevation and precipitation had extremely significant correlations with cluster distribution ($P < 0.01$), while total salt content and air temperature

Fig. 5 CCA plot

···had a significant correlation with the distribution of the associations ($P < 0.05$). Moreover, elevation, precipitation, and total salt content made the largest contributions to the first and second axes, at 33.3%, 20.2%, and 11.2%, respectively.

From the CCA ordination of the sample plots, it can be seen that most associations are distributed along the second axis. The *Zhenzhuchai* + *Yanzhuazhua-Suaeda salsa* association is mostly in the fourth quadrant and occurs in areas with relatively high elevation, being strongly affected by elevation. The Central Asian aster-shrub-*Salsola* + *Peganum harmala* association is mostly distributed in the first and second quadrants and is strongly affected by precipitation. The *Reaumuria soongorica* + *Zhenzhuchai* association, *Lycium ruthenicum* + *Yanzhuazhua* association, *Tamarix ramosissima* + *Calligonum* association, *Haloxylon ammodendron* + *Nitraria-Bassia dasyphylla* association, *Artemisia-Salsola* association, *Zygophyllum xanthoxylum-Agropyron cristatum* association, and slender-branched *Yanzhuazhua*-reed association are mainly distributed in the second and third quadrants and are more strongly affected by air temperature, total salt content, and alkalinity. Soil water content, soil pH, and soil electrical conductivity have relatively small effects on the distribution of the associations.

3 Discussion

3.1 Quantitative classification and ordination of communities

As one of the most commonly used methods internationally for classifying plant communities, two-way indicator species analysis (TWINSPAN), with its accurate and scientific classification approach, can reflect certain ecological patterns and is suitable for the classification of plant communities at different spatial scales[18]. Yang Guodong et al.[19] used TWINSPAN to divide 24 plant communities of short-filament osmanthus in Donglashan into 12 community types. Zhang et al.[20] used TWINSPAN to divide the plants in 41 quadrats in the Wuling Mountain Nature Reserve into 8 community types. In this study, however, hierarchical classification using TWINSPAN divided the plants in 113 saline-alkali land quadrats in the Hexi Corridor into 11 plant associations, and the classification results were consistent with the ordination of the plant quadrats on the DCA. This indicates that the TWINSPAN classification method is also suitable for classifying saline-alkali land plant communities in the Hexi Corridor region. However, judging from the classification results, a single community is often distributed in different regions, spanning a relatively large area. This is consistent with the classification results of Yang Xiaoju et al.[21] for plant communities in northwestern Tibet, showing discontinuity in spatial distribution. This is because habitats that are far apart may have similar soil, climatic, hydrological, and other conditions, satisfying the growth requirements of the plant communities[22]. Regarding the ecological meaning contained in DCA ordination axes, different scholars have found different ecological information in their studies. Huo Xinru[23], in a study of the Ningxia Luoshan Nature Reserve, considered that the first DCA axis represented changes in alkali-hydrolyzable nitrogen, while the second axis represented changes in soil water content. Pei Yuan[24], in a study of stand-structure characteristics of spruce forests in the western Tianshan Mountains, considered that the first DCA axis represented topographic variation in the environment where the communities occurred, while the second axis represented the elevational gradient of the communities. The results of the present study show that the first axis reflects variation in the elevational gradient, while the second axis reflects variation in the moisture gradient. Among them, the elevation of the *Zhenzhuchai* + *Yanzhuazhua*–*Suaeda salsa* association is higher than that of the *Zygophyllum xanthoxylum*–*Agropyron cristatum* association and the slender-branched *Yanzhuazhua*–reed association, and the precipitation at the sample sites of the *Artemisia*–*Salsola* association is higher than that of the *Reaumuria soongorica* + *Zhenzhuchai* association. This may be because the dominant driving factors of environmental heterogeneity in the study area differ. In addition, research scale, quadrat-setting range, the types of environmental factors selected, and measurement precision may also influence the interpretation of the ecological significance of ordination axes, indicating that DCA ordination axes contain different ecological meanings in different studies[25].

3.2 Changes in plant-community diversity

Species diversity is an important indicator reflecting the structure and function of a community. It is the basis for maintaining ecosystem stability and provides the fundamental conditions for the operation and maintenance of ecosystem functions[26]. Various diversity indices are used to measure the attributes of community structure, and diversity indices can provide information on species rarity and commonness[27]

. In this paper, the distribution pattern of saline-alkali land plants in the Hexi Corridor was studied by analyzing various diversity indices among the associations. A study of four indices of α-diversity for the 11 associations found that the Shannon diversity index, Simpson diversity index, and Pielou evenness index of Association VII were significantly lower than those of the other associations. This is because the sample plots where Association VII occurs have the lowest precipitation, while the mean annual temperature is high, evaporation is large, the climate is relatively dry, and plants absorb relatively little water from the soil, making it difficult for them to survive

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. This in turn leads to relatively few shrub individuals and herbaceous plants in Association VII, indicating that climate change has an important influence on plant diversity and distribution. This is consistent with the study by Chen Ziyan et al.

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on the spatiotemporal pattern of plant species richness in Inner Mongolian grasslands. However, the Margalef richness index of Association XI was significantly lower than that of the other associations, because the sample sites included in Association XI…

In these areas, shrub species were few, forming single-dominant communities with the herbaceous plant *Phragmites australis* as the dominant species[30-31], which held absolute dominance in the community. Analysis of the two β-diversity indices, Sorenson' s and Jaccard' s, showed that the similarity between association II and association III was the highest. This is because the environments in which associations II and III occur have higher elevations than those of the other associations; moisture and nutrients in the soil are difficult to accumulate, limiting species richness and dispersal capacity and favoring the growth of plants of the same type[32]. Analysis of the changing trends in plant diversity indices with environmental factors in the saline–alkaline lands of the desert–oasis transition zone in the Hexi Corridor showed that elevation, soil water content, and electrical conductivity were positively correlated with the Shannon diversity index, Simpson diversity index, Pielou evenness index, and Margalef richness index. Plant growth cannot occur without water, and the climate of the Hexi region is arid; therefore, soil water content largely limits plant growth[33]. In areas with higher water content, water stress is alleviated, allowing more species to grow and thereby increasing the diversity indices. Changes in soil electrical conductivity affect plant physiological processes; appropriate electrical conductivity can promote the absorption of soil nutrients by plants, thereby influencing plant growth and increasing diversity within the region[34]. Soil pH was negatively correlated with the Shannon diversity index, Simpson diversity index, Pielou evenness index, and Margalef richness index. An increase in plant diversity indices can effectively improve the physicochemical properties of soil, increase soil nutrients, and thereby stabilize soil acidity and alkalinity[35].

3.3 Effects of environmental factors on the distribution of plant communities

The distribution and diversity of plant communities are influenced by the combined effects of multiple factors. Zhang Hongnan et al.[36], in their study of plant community distribution patterns in eastern Tibet, found that topographic factors were the most important factors affecting plant community distribution. Li et al.[37], in their study of plant community distribution patterns on the eastern shore of Taihu Lake, found that soil factors had an important influence on plant community distribution. In the present study, CCA analysis of plant-environment factors showed that the most important factor affecting the distribution of plant associations in the saline-alkaline lands of the desert-oasis transition zone in the Hexi Corridor was elevation, followed by precipitation, total salt content, air temperature, and other factors. This is consistent with the findings of Worthy et al.[38] along the Andes. Elevation is an important factor affecting plant community distribution, and its variation causes changes in other environmental factors under natural conditions, such as air temperature, precipitation, and evaporation. Plant growth and development are greatly affected by environmental factors, thereby influencing the structure and distribution of the entire plant community[39]. Precipitation and air temperature are the main limiting factors for plant growth in arid and semi-arid regions[40]. The spatial differentiation of mean annual precipitation and mean annual temperature reflects spatial variation in hydrothermal factors; the greater the spatial differentiation, the greater the hydrothermal gradient in space. For plants, this means that habitats along moisture and heat gradients are more diverse or more complex[41]. Soil salt content has important effects on plant growth, development, and distribution. Halophytes refer to plant groups that can develop normally under conditions in which sodium chloride content exceeds 200 mmol·L−1, such as *Tamarix ramosissima* and *Suaeda salsa*. A notable characteristic of these plants is that a certain amount of salt can significantly promote their growth and development[42]. Different levels of soil salinity have important effects on plant distribution. For example, *Nitraria* is a typical halophyte and can germinate in mildly and moderately saline environments; *Phragmites australis*, *Kalidium foliatum*, and other plants can likewise grow in saline environments. These plants differ in their tolerance to salinity and alkalinity, thereby affecting their distribution within the region[43]. Soil pH had a relatively small effect on the distribution of associations in the saline-alkaline areas of the Hexi Corridor because all selected plots were saline-alkaline lands, with surface soil pH ranging from 7.5 to 9.0. The soils were alkaline, and the differences in soil pH among associations were not large; therefore, variation in soil pH was not reflected in the distribution of the associations[44]. Soil water content also had a relatively small effect on the distribution of vegetation associations because the measured soil water content was the surface soil water content. The overall characteristics of the study area are an arid climate, low precipitation, and high evaporation, making it difficult for water to accumulate in the surface soil. In addition, the sample points included in the associations were widely distributed, leading to small differences in water content among associations and thus weakening the effect of soil water content on vegetation distribution across the entire region. This indicates that soil pH and soil water content are not important factors affecting the distribution of plant communities in the saline-alkaline lands of the Hexi Corridor.

4 Conclusion

This study took the plant communities of the saline-alkaline lands in the desert-oasis transition zone of the Hexi Corridor as the research object. Based on field survey sampling and laboratory data analysis, TWINSPAN was used to divide 113 plant quadrats in the saline-alkaline lands of the Hexi Corridor into 11 plant communities. The classification results were consistent with the DCA ordination, further demonstrating the reliability of the classification results and revealing the distribution pattern of saline-alkaline land plants in the Hexi Corridor. The diversity survey of plant associations showed that the Shannon diversity index, Simpson diversity index, and Pielou evenness index of association VII were lower than those of the other associations; the Margalef richness index of association XI was the lowest. Elevation, soil water content, and soil electrical conductivity were positively correlated with the Shannon diversity index, Simpson diversity index, Pielou evenness index, and Margalef richness index, while pH was negatively correlated with them. CCA analysis of quadrats, species, and environmental factors showed that the environmental factor with the greatest influence on the distribution of plant communities in the saline-alkaline lands of the Hexi Corridor was elevation, followed by precipitation, total salt content, and air temperature.

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Plant distribution and diversity in relation to environmental factors across saline-alkali lands in the Hexi Corridor' s desert-oasis ecotone

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Abstract: We investigated the distribution patterns of plant communities in saline-alkali lands within the desert-oasis ecotone in the Hexi Corridor, as well as the environmental factors influencing such distribution, by using the importance value of each species as an indicator. To explore the relationship between plant diversity and environmental factors, plant communities in the Hexi Corridor region were classified and ordinated using two-way indicator species analysis (TWINSPAN), detrended correspondence analysis (DCA), and canonical correspondence analysis (CCA). Based on the results of TWINSPAN, plants from 113 sampling sites were classified into 11 distinct types of plant communities. Among them, Association VII had the lowest diversity index, Association XI had the lowest richness index, and Associations II and III had the highest similarity index. Redundancy analysis revealed that elevation, soil water content, and soil electrical conductivity were positively correlated with the Shannon-Wiener diversity index, Margalef richness index, Simpson index, and Pielou evenness index, whereas pH was negatively correlated with these indices. Ordination analysis of the sampling sites via CCA indicated that elevation, precipitation, and total salt content explained 4.6%, 2.8%, and 1.5% of the community distribution, with contribution rates of 33.3%, 20.2%, and 11.2%, respectively. In conclusion, the most significant environmental factors affecting the distribution of plant communities in the saline-alkali lands of the Hexi Corridor desert-oasis ecotone are elevation, precipitation, and total salt content, in this order. Different plant communities exhibit specific distribution patterns along the elevation gradient. This study provides a scientific basis for understanding the distribution and diversity of plant communities in the saline-alkali lands in the Hexi Corridor and may significantly contribute to the protection and restoration of plant ecosystems in these areas.

Keywords: Hexi Corridor; saline-alkali land; quantitative classification and ordination; species diversity

Note: Figure translations are in progress. See original paper for figures.