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Distribution patterns of groundwater-dependent vegetation species diversity and their relationship to groundwater attributes in northwestern China

JunTao Zhu,[1] JingJie Yu,[1]* Ping Wang,[1] Qiang Yu[2] and Derek Eamus[2]

[1] *Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China*
[2] *Plant Functional Biology and Climate Change Cluster, University of Technology, PO Box 123, Broadway 2007, Sydney, NSW, Australia*

ABSTRACT

The study of the patterns of plant species diversity and the factors influencing these patterns is the basis of ecology and is also fundamental to conservation biology. Groundwater-dependent vegetation (GDV) must have access to groundwater to maintain their growth and function, and this is especially common in arid and semi-arid regions, including north-western China. In this paper, plant species diversity and groundwater attributes (composition and depth) were investigated in 31 plots in the Ejina Delta in north-western China to determine whether groundwater attributes influenced patterns species diversity in GDV. Detrended canonical correspondence analyses and generalised additive models were performed to analyse the data. A total of 29 plant species were recorded in the 31 plots; perennial herbs with deep roots had an advantage over all other groups, and GDV species diversity was primarily affected by groundwater depth (*GWD*), salinity (*SAL*) and total dissolved solids (*TDS*), HCO_3^-, Ca^{2+}, pH, and SO_4^{2-}. The herb layer species diversity and total species diversity reached their maximum in similar, moderate environmental conditions. The diversity of the tree species was influenced by *SAL* and *TDS* and was maximal at large values of *GWD* and low values of *SAL* and *TDS*. The diversity of shrub species was affected by Ca^{2+} and Mg^{2+} and was maximal low *GWD* and high *SAL* and *TDS*. Patrick's and Shannon–Wiener's index of the total community diversity presented a bimodal pattern along gradients of *GWD* and *SAL*, whilst Simpson's and Pielou's index showed a partially unimodal pattern. On the basis of field investigation and the analysis of field data, we concluded that the perfect combination of *GWD* and *SAL* for GDV species diversity is 2 m and $1{\cdot}8\,g\,l^{-1}$, respectively. The appropriate combination range is 2–5 m and $1{\cdot}8$–$4{\cdot}2\,g\,l^{-1}$, and the critical combination for the damaged GDV species diversity is 5 m and $4{\cdot}2\,g\,l^{-1}$. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS distribution pattern; species diversity; groundwater-dependent vegetation; groundwater attributes; in north-western China

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INTRODUCTION

Species diversity, which is defined by the biodiversity of species and their aggregations, is closely related to ecosystem stability (Tilman and Downing, 1994; Tilman, 2000). Studies on species diversity have primarily focused on changes in the number of species and the degree of biodiversity, including pattern, formation and regulation of the small and large-scale temporal and spatial changes in species richness, abundance and distribution (Zhou *et al.*, 2000). The distribution pattern of plant species diversity is the synthetic reflection of all types of ecological gradients, and the pattern of biodiversity along environmental gradients is one of the basic issues in biodiversity research (Kratochwil, 1999). The patterns of plant species diversity and the factors influencing those patterns are the basis of much of ecology and also central to conservation biology (Noss, 1990). It is crucial to understand the composition, changes and development of plant communities as well as the structural and functional stability of ecosystems (Chen *et al.*, 2006).

The distribution pattern of species diversity primarily correlates with climate, community productivity and other factors (such as the historical evolution of regional geography and community succession) (Odland and Birks, 1999; O'Brien *et al.*, 2000). Large-scale studies have shown that the pattern of species diversity is mainly affected by vegetation history and evolution (Ricklefs and Schluter, 1993; Qian and Ricklefs, 1999). A comparison of different layers of species diversity shows that the responses of plant communities to the environment are not consistent at different layers (Rey Benayas, 1995). Furthermore, species at different stages in their life cycle also show different gradients due to limitation by different factors (Hamilton and Perrott, 1981; Ojeda *et al.*, 2000).

Habitat heterogeneity is assumed to be an important factor in maintaining ecosystem biodiversity (Levin, 1981). Many studies have found variations in species diversity with elevation (Baruch, 1984; Wilson *et al.*, 1990; Chawla

*Correspondence to: J. Yu, Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A, Datun Road, Chaoyang District, Beijing, 100101, China.
E-mail: yujj@igsnrr.ac.cn

et al., 2008), water availability (Rundel and Sturmer, 1998; Stromberg, 2007), soil quality (Sebastian *et al.*, 2007) and groundwater (Chen *et al.*, 2006; Jansson *et al.*, 2007; Hao *et al.*, 2010). Along disturbance gradients, species diversity has been found to be highest at intermediate levels (Huston, 1979). However, other studies have found increases (Bailey, 1988; Phillips *et al.*, 1994) or decreases in diversity (Wilson and Tilman, 1991) along gradients of disturbance. Water availability is a key factor that influences plant species diversity, particularly in arid and semi-arid settings (Rundel and Sturmer, 1998). In arid regions, groundwater plays a predominant role in supporting plant species diversity (Chen *et al.*, 2004). Hoffman *et al.* (1994) have shown that in the Karoo desert, species richness increases along a moisture gradient. Hao *et al.* (2010) indicated that the species diversity was the highest where the groundwater level was 2–4 m below the surface, and diversity was lower at sites with deeper and more shallow groundwater depths. Plant species diversity decreased greatly when the groundwater level dropped to below 6 m. The biodiversity of natural vegetation accessing groundwater depends on gradients of both water availability and salt content, and various vegetation types adapt to different characteristics of groundwater level and salinity in arid regions (Zhao *et al.*, 2003; Wang *et al.*, 2010). There are groundwater-dependent ecosystems and groundwater-dependent vegetation (GDV) in arid and semi-arid regions (Eamus *et al.*, 2006; Murray *et al.*, 2006). GDV must have access to groundwater to maintain their growth and function, and this is true for GDV in north-western China. However, information is still lacking on the patterns of GDV species diversity and their relationships to different groundwater characteristics.

The Ejina Delta is an extremely arid oasis in the lower reaches of the Heihe River in north-western China. Groundwater is essential to maintain and conserve plant species diversity (Chen *et al.*, 2004) in arid regions. The dominant vegetation in this area includes *Populus euphratica*, *Tamarix ramosissima* and *Sophora alopecuroides*, and these species primarily depend upon groundwater for their persistence in this environment (Zhu *et al.*, 2009). To effectively conserve regional biodiversity, conservationists need to know how diversity is distributed geographically within the region. Key questions for conservation efforts include: does the region consist of many distinct communities, or is it homogeneous? How different are the communities (Jost *et al.*, 2010)?

In this paper, we selected several plant communities and groundwater attributes [groundwater depth (*GWD*), salinity (*SAL*), total dissolved solids (*TDS*), electric conductivity (*EC*), pH and concentrations of K^+, Ca^{2+}, Na^+, Mg^{2+}, Cl^-, HCO_3^-, SO_4^{2-}, etc.] to determine the factors influencing the patterns and characteristics of GDV species diversity by analysing the following: (1) variations in diversity indices of different community types; (2) the key factors affecting patterns of GDV species diversity; (3) the variations in species diversity along gradients of *GWD* and *SAL*.

MATERIALS AND METHODS

Experimental sites

The study area is located in the lower reaches of the Heihe River, extending between latitudes 40°20′–42°30′N and longitudes 99°30′–102°00′E, in the county of Ejina, Inner Mongolia, Northwest China, with an area of 3×10^4 km^2 (Li *et al.*, 2001). This region has a continental climate with a mean annual temperature of approximately 8 °C, a maximum daily temperature of 41 °C (July) and a minimum of −36 °C (January) (Xie, 1980). The long-term (1957–2003) annual average precipitation at the study site was less than 42 mm and barely recharged the water table. Pan evaporation rate was 2300–3700 mm year (Wen *et al.*, 2005). No perennial run-off originates from the area, and the Heihe River has the only run-off flow through the area (He and Zhao, 2006). The Heihe River, which originates from the Qilian Mountain, flows through the Ejina Basin and divides into two branches at Langxinshan (Wang, 1997). The two branches of the Heihe River flow into East and West Juyan Lake, and the total length of these branches in the basin are approximately 240 km (Feng *et al.*, 2001). Before entering the terminal lakes, the East River and West River form several tributaries, such as the Nalin River, the Longzi River and the Andu River. The Heihe River is the main source of recharge for the groundwater system, and approximately 68% of the groundwater recharge in the Ejina alluvial fan is a vertical percolation of the Heihe River (Feng *et al.*, 2004; Wen *et al.*, 2005).

In this region, plant biodiversity is low, and plant cover is very low. Survey data (Commissione Redactorum Florae Inner Mongolia, 1977–1979), reveal 268 species belonging to 151 genera and 49 families present in this area. Compositae (81 species), Chenopodiaceae (47 species), and Gramineae (33 species) are the dominant families, with 30 or more species. Leguminosae (15 species), Polygonaceae (11 species), Cyperaceae (11 species) and Tamaricaceae (10 species) represent more than ten species. These seven families include the 208 most dominant species, which account for 72% of the total species pool for the area.

Xerophytic, extremely xerophytic and salt-tolerant desert species are also widely distributed in this region. From the distribution patterns, it is clear that mesophytes and hygrophytes, including arbours, bushes and herbs, growing in the Ejina River banks and the fluvial plain, including *P. euphratica*, *Elaeagnus angustifolia*, *T. ramosissima*, *Phragmites communis*, *Achnatherum splendens*, *S. alopecuroides* and *Glycyrrhiza uralensis* are the dominant species of these groups in the region. Various types of desert shrubs and herbs, including *Haloxylon ammodendron*, *Nitraria tangutorum*, *Artemisia oxycephala* and *Agriophyllum arenarium*, are primarily distributed in the outer portions of the oasis. Some sparse and drought-tolerant desert species, such as *Reaumuria soongorica*, *Ephedra przewalskii*, *Zygophyllum xanthoxylon*, *Sympegma regelii*, *Anabasis brevifolia* and *Calligonum mongolicunl*, are mainly distributed in low mountainous and hilly areas and the Gobi desert (Si *et al.*, 2005). The dominant vegetation in the study area, including *P. euphratica*, *T. ramosissima*, and *S. alopecuroides*, primarily depend upon groundwater for sustenance (Zhu *et al.*, 2009).

Plots and measurements

Surveys of natural vegetation were carried out in the same plant plots from June to August in 2009, 2010 and 2011. A total of 31 observation points were selected for water table and *SAL* monitoring. A total of 31 (400 m^2) plant plots and 217 plant quadrats (31 tree quadrats, 93 shrubs quadrats and 93 herb quadrats) were established randomly around the water table observation point (approximately 20 m from the observation point). The height, coverage and diameter at breast height of the trees ($\geq$5 m) were recorded individually. Three (25 m^2) shrub quadrats and three (1 m^2) herb quadrats were established randomly in each plant plot. The species present and the frequency, height and percentage of canopy cover were determined for each quadrat. Vegetation cover data were recorded using the ordinal scale of Van-der-Marel (1979). The location of observation points, including altitude, longitude and latitude, were determined by Global Position System. *GWD* was measured three times each month in each of the 31 wells over a 3-year period. In addition, three groundwater samples were collected every 2 months at each point. Chemical components, including HCO_3^-, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+, were measured at the Institute of Geography Sciences and Natural Resources Research, Chinese Academy of Sciences. Levels of SO_4^{2-} and Cl^- were analysed by ion chromatography, and HCO_3^- anions were analysed by titration (0·01 N H_2SO_4). Cations were analysed by inductively coupled plasma. *TDS* represent the sum of the cations and anions in the water. The major ions in water chemistry contribute to *SAL*, *EC* and pH values that were measured *in situ* using a HANNA HI 98188 waterproof, portable Conductivity Metre as well as CyberScan PC300 Waterproof Portable pH/ORP/ Conductivity Metres. To obtain exact data on the annual changes of *GWD* and *SAL* in this region, 15 Divers and five CTD-Divers (produced by Eijkelkamp) were fixed in 20 wells in April 2010 (Figure 1). The data were recorded by each Diver once every 30 min.

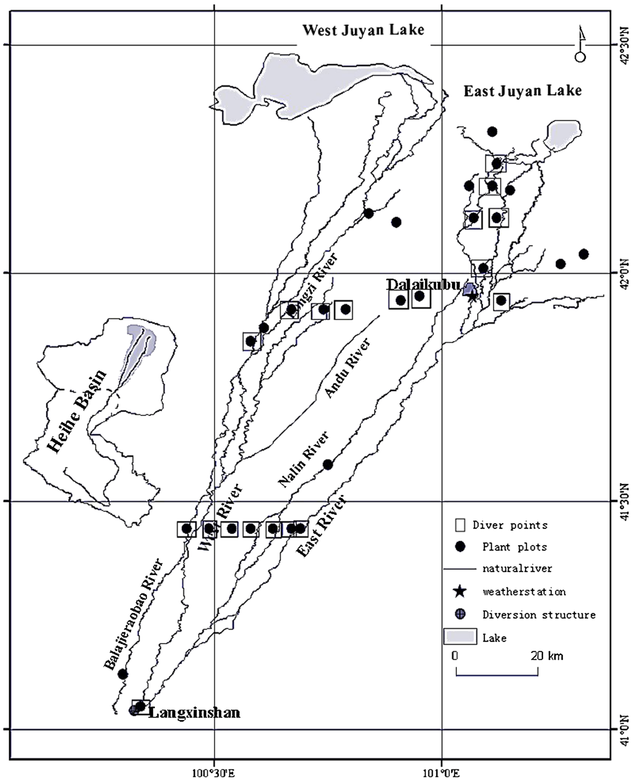

Figure 1. The location of study area, water channels and plant plots (400 m^2).

Statistical analysis

The importance value of each tree, shrub and herb in each plant plot was calculated with the following formulas (Zhang and Oxley, 1994):

$$\text{Tree } IV = (RDen + RF + RDom)/300 \tag{1}$$

$$\text{Shrub-Grass } IV = (RDen + RF + RC)/300 \tag{2}$$

where Tree *IV* is the tree importance value, *RDen* is the relative density, *RF* is the relative frequency, *RDom* is the relative dominance, and *RC* is the relative coverage.

Species diversity indices were determined (Ma *et al.*, 1995) as Shannon–Wiener's index of diversity

$$\mathrm{H} = -\Sigma P_i \ln P_i \tag{3}$$

and Simpson's index of diversity

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

whereas Pielou's index of evenness was calculated as

$$Jsw = \frac{H}{\ln S} \tag{5}$$

and Patrick's index of richness was calculated as

$$R = S \tag{6}$$

Finally, Simpson's index of domination was calculated as

$$C = \Sigma {P_i}^2 \tag{7}$$

where P_i is the relative importance value of species *i* and *S* is the total number of species in the i^{th} plot, and *H*, Shannon–Wiener's index; *D*, Simpson's index; *Jsw*, Pielou's index of evenness; *R*, Patrick's index of richness; *C*, Simpson's index of domination.

The diversity index of various layers can be calculated using the formulae listed earlier. According to the characteristic of community vertical structure, when measuring the total index of community, the indices of different growth types are weighted. The weight is the average of the relative coverage and the thickness of the leaf layer (Fan *et al.*, 2006). We applied the following formula (Gao *et al.*, 1997):

$$W_i = \left(\frac{C_i}{C} + \frac{h_i}{h}\right)/2$$

where C is the total coverage of community ($C = \sum C_i$) ($i = 1$, tree layer; 2, shrub layer; 3, herb layer; the same below), h is the average height of various growth types ($h = \sum h_i$), W_i is the weighted parameter of diversity index of i growth type, C_i is the coverage of the i^{th} growth type and h_i is the average height of the i^{th} growth type. Among them, the thickness of tree leaf layer is calculated at 1/3 the height of the tree layer, the shrub layer is at 1/2 and the herb layer is at 100%.

The total diversity index of the community was calculated according to the following formula:

$$D = W_1 D_1 + W_2 D_2 + W_3 D_3$$

where W_1, W_2 and W_3 are the weighted parameters of the tree layer, shrub layer and herb layer, respectively, and D_1, D_2 and D_3 are the diversity indices of the tree layer, shrub layer and herb layer, respectively.

Finally, all diversity indices were normalised by $D_{\tilde{i}} = (D_i - D_{\min})/(D_{\max} - D_{\min})$, and then the interval value (0–100) was obtained (Shen *et al.*, 2000). $D_{\tilde{i}}$ is the diversity index after normalisation and D_i, $D_{\min}$ and $D_{\max}$ are the original value, the minimum and maximum of the tree layer, shrub layer, herb layer and total community, respectively.

The computer programme WinTWINS (Version 2·3), designed by Hill and Šmilauer (2005), was used to classify vegetation types, and CANOCO (Version 4·5), designed by Ter Braak and Šmilauer (2002), was used for ordination analysis. The ordination diagrams and the response curve of diversity indices to *GWD* and *SAL* modelled by the generalised additive model (GAM) were made with the computer programme CanoDraw (Version4·0), designed by Smilauer. The default cut levels (0, 2, 5, 10 and 20) were used in TWINSPAN, and the default options were also used in the division procedure. The data on groundwater attributes (annual average value) were square root transformed in the analysis. The significance of the resulting ordination was evaluated by 499 Monte Carlo permutations (Petr, 2009; Zhang and Dong, 2010).

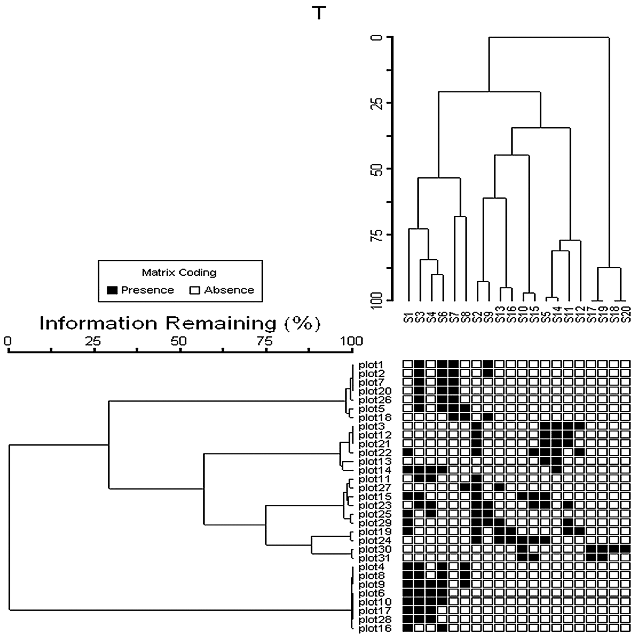

Figure 2. Cluster analysis and two-way dendrogram of plant plots and species. The species: S1, *K. caspica*; S2, *T. ramosissima*; S3, *N. tangutorum*; S4, *A. oxycephala*; S5, *S. alopecuroides*; S6, *R. soongorica*; S7, *E. przewalskii*; S8, *C. mongolicunl*; S9, *A. sparsifolia*; S10, *A. splendens*; S11, *O. glabra*; S12, *S. collina*; S13, *B. dasyphylla*; S14, *P. euphratica*; S15, *G. uralensis*; S16, *E. angustifolia*; S17, *P.communis*; S18, *L. secalinus*; S19, *C. epigeios*; S20, *E. breviaristatus*.

RESULTS

Community types

Desert vegetation was sparsely distributed and species diversity was low in the Ejina Delta due to the harsh environment. Twenty-nine plant species were recorded in 31 plots. Among them, woody plants are very limited. In 31 plots, the tree layer only appeared in eight plots, and the shrub layer appears in 19 plots, whereas the herb layer appeared in all plots. *P. euphratica* and *E. angustifolia* are the only two tree species in this region.

Six plant community types were obtained by TWINSPAN classification in the Ejina Delta (Figure 2). The composition of various plant plots in Ejina Delta is shown in Table I.

Community I was Ass. *Phragmites australis* + herbs and included plots 30 and 31. This community type was distributed on both sides of the Ejina River and the regions of shallow *GWD* (1·30–1·45 m). The species diversity of this community was richer than other communities. The important value of the dominant species (*P. australis*) was at 0·80–0·85. The total community coverage at the highest level was usually in the range of 90–95% (Table I).

Community II was Ass. *P. euphratica–T. ramosissima* + herbs and included plots 3, 12, 13, 14, 21 and 22. This type was distributed mainly in the East River banks and the lake delta. *GWD* was usually 1·6–2·5 m for this community. The importance value of *P. euphratica* and *T. ramosissima* was at 0·80–0·85 and 0·03–0·13, respectively. Total plant cover was in the high range of all communities assessed and was in the range of 20–85% (Table I).

Community III was Ass. *E. angustifolia–T. ramosissima* + herbs and included plots 19 and 24. This type was distributed mainly in the lower reaches of the West River. *GWD* was usually 2·5–2·65 m for this assemblage. The importance value of *E. angustifolia* and *T. ramosissima* was at 0·59–0·61 and 0·09–0·11, respectively. Total plant cover was usually in the range of 35–70% (Table I).

Community IV was Ass. *T. ramosissima*–herbs and included plots 11, 15, 23, 25, 27 and 29. This type was primarily distributed on the beaches of the Ejina River. *GWD* was usually within the range of 2·62–3·50 m, and the importance value of *T. ramosissima* was at 0·45–0·56. Total plant cover was usually in the range of 18–80% (Table I).

Community V was Ass. *Karelinia caspica–N. tangutorum* + *Artemisia* sp. + *Calligonum* sp. and included plots 4, 6, 8, 9, 10, 16, 17 and 28. This type was distributed mainly at the outer margin of the Ejina Delta. *GWD* was usually 3·45–5·36 m, and species diversity was relatively low. The importance value

Table I. The information of plant plots in Ejina Delta.

Plots number	Altitude (m)	Groundwater depth (m)	Coverage (%)	Important value of major species					
				S1	S2	S3	S4	S5	S6
001	1048	4·88	25%	—	—	—	—	—	0·1631
002	920	5·58	8%	—	—	—	—	—	0·1311
003	1029	1·80	80%	—	0·8344	—	0·0323	0·0124	0·0212
004	987	3·59	30%	—	—	—	—	0·3647	—
005	996	4·63	12%	—	—	—	—	—	0·1423
006	1003	3·50	35%	—	—	—	—	0·4063	—
007	1003	4·35	20%	—	—	—	—	—	0·1932
008	958	3·75	30%	—	—	—	—	0·4264	—
009	951	5·36	7%	—	—	—	—	0·2156	—
010	911	4·83	55%	—	—	—	—	0·2645	—
011	919	3·40	40%	—	—	—	0·4643	—	—
012	911	2·25	20%	—	0·7583	—	0·0995	—	—
013	930	2·20	50%	—	0·7843	—	0·0758	—	0·0214
014	944	2·50	40%	—	0·7246	—	0·1273	0·0354	—
015	942	2·80	80%	—	—	—	0·5316	0·1435	—
016	957	4·02	23%	—	—	—	—	0·2982	—
017	958	3·81	15%	—	—	—	—	0·3370	—
018	1009	4·50	28%	—	—	—	—	—	0·1753
019	910	2·50	70%	—	—	0·6123	0·1132	0·0312	—
020	1050	5·80	8%	—	—	—	—	—	0·1124
021	931	1·60	85%	—	0·8554	—	0·0543	0·0311	0·0135
022	919	2·00	65%	—	0·8142	—	0·0314	0·0261	0·0121
023	961	2·62	55%	—	—	—	0·5632	—	—
024	922	2·65	35%	—	—	0·5852	0·0864	—	—
025	971	3·15	45%	—	—	—	0·4753	0·1466	—
026	922	5·50	5%	—	—	—	—	—	0·0634
027	943	3·50	18%	—	—	—	0·4527	—	—
028	919	3·75	20%	—	—	—	—	0·3460	—
029	924	3·10	38%	—	—	—	0·5042	0·1090	—
030	989	1·30	95%	0·8546	—	—	—	—	—
031	984	1·45	90%	0·8052	—	—	—	—	—

Note: S1, *Phragmites communis*; S2, *Populus euphratica*; S3, *Elaeagnus angustifolia*; S4, *Tamarix ramosissima*; S5, *Karelinia caspica* and S6, *Ephedra przewalskii*.

of *K. caspica* was 0·22–0·43 and total plant cover was usually in the range of 7–55% (Table I).

Community VI was Ass. *E. przewalskii–R. soongorica* + *N. tangutorum* + *Alhagi sparsifolia* and included plots 1, 2, 5, 7, 18, 20 and 26. This type was mainly distributed in the wide Gobi plain. *GWD* was usually 4·35–5·80 m, and species diversity and plant cover in this community were the lowest of all assemblages. The importance value of *E. przewalskii* was 0·06–0·19, and total plant cover was usually in the range of 5–28% (Table I).

Species diversity

The species diversity index can directly reflect community structure. The changes in species diversity in six different plant communities are shown in Figure 3 and Table II. In general, species diversity was lower in this region, the community structure was simple, and the species composition was sparse compared with the humid regions. In terms of all assemblages, identified species diversity increased with an increase in species richness. That is, the level of species diversity depended on the richness of species composition. The species composition of communities II and III were relatively abundant, with forest and desert elements; as a result, the Shannon–Wiener diversity index was the largest in these communities (1·10–1·57). In communities I and IV, species composition was relatively poor, but the level of species diversity was higher (0·96–0·97). Species composition was much lower in communities V and VI, and the level of species diversity was the lowest (0·43–0·57).

The trend in the domination index contrasted with that of the diversity index and displayed a close relationship with the number of dominant species. Because of low levels of species diversity, communities V and VI had a low number of species. Therefore, the dominant species made a larger contribution to the diversity index of the community, and the domination index was relatively larger (0·70–0·76). The evenness index reflected the uniformity of species distribution, and this showed the same trend as species diversity. For example, in Community V (simple species composition), the dominant species were often distributed in patches, and its evenness index was usually lower (0·38). The results of significance analysis indicate that there were significant differences only between Community II and all the other communities, which indicates that the forest desert community had significant differences from other desert communities although there

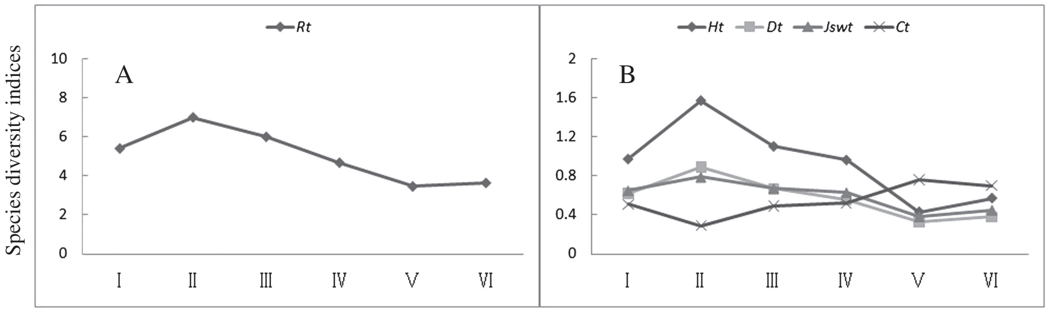

Figure 3. The diversity indices of different plant community types in Ejina Delta. *Rt*, *Ht*, *Dt*, *Jswt* and *Ct* are Patrick richness index, Shannon–Wiener species diversity index, Simpson species diversity index, Pielou evenness index and Simpson domination index of the total plant communities, respectively. I, II, III, IV, V and VI mean different plant community types.

Table II. Species diversity indices on different plant community types.

Community types	*R*	*H*	*D*	J_{sw}	*C*
Ass. *Phragmites australis* + herbs	5.40^{bc}	0.97^{bc}	0.62^{bc}	0.65^{bc}	0.51^{bc}
Ass. *Populus euphratica–Tamarix ramosissima* + herbs	7.00^{a}	1.57^{a}	0.89^{a}	0.79^{a}	0.29^{a}
Ass. *Elaeagnus angustifolia–T. ramosissima* + herbs	6.00^{bc}	1.10^{bc}	0.67^{bc}	0.67^{bc}	0.49^{bc}
Ass. *T. ramosissima*–herbs	4.67^{cd}	0.96^{bc}	0.55^{cd}	0.63^{bc}	0.52^{bc}
Ass. *Karelinia caspica–Nitraria tangutorum* + *Artemisia* sp. + *Calligonum* sp.	3.45^{cd}	0.43^{cd}	0.33^{cd}	0.38^{cd}	0.76^{cd}
Ass. *Ephedra przewalskii–Reaumuria soongorica* + *Nitraria tangutorum* + *Alhagi sparsifolia*	3.63^{cd}	0.57^{cd}	0.38^{cd}	0.45^{cd}	0.70^{cd}

R, Patrick richness index, *H*, Shannon–Wiener species diversity index, *D*, Simpson species diversity index, J_{sw}, Pielou evenness index, *C*, Simpson domination index. Data were the mean of plant plots. Means within lists with different letters (a, bc, cd) differ significantly at the 0.05 level.

were no obvious differences in species diversity between the desert communities (Table II).

DCCA ordination

Detrended canonical correspondence analyses (DCCA) ordination analysis was applied to the tree layer, the shrub layer, the herb layer and the total diversity index in 31 plots. A Monte Carlo test indicated that all of the ordination axes were highly significant ($p < 0{\cdot}01$). The eigenvalues of the four ordination axis were 0·325, 0·046, 0·012 and 0·002, respectively. This accounted for 77·74% of the total eigenvalues. The cumulative variances of the diversity and diversity-environment correlations were 77·74 and 84·5%, respectively (Table III), indicating a significant analysis. The significance test showed that *GWD* and *SAL* were significantly positively correlated with the first axis ($p < 0{\cdot}01$), and the negative correlations were with HCO_3^- and Ca^{2+} ($p < 0{\cdot}01$). There was also a significant positive correlation between *TDS* and the first axis ($p < 0{\cdot}05$). $SO4^{2-}$ was positively correlated with the second axis ($p < 0{\cdot}05$), and pH was negatively correlated with the second axis ($p < 0{\cdot}05$) (Table IV). These results indicated that *GWD*, *SAL*, *TDS*, HCO_3^-, Ca^{2+}, pH and SO_4^{2-} mainly affected the distribution pattern of species diversity among 12 factors in the Ejina Delta.

A two-dimensional DCCA ordination diagram was made using the first two ordination axes (Figure 4). Each of the diversity indices was represented by only one point in the ordination diagram, and its location reflected the fact that this index obtained its maximum at a certain point in the corresponding environmental gradients. The direction of the arrow indicates a positive or negative correlation of various environmental factors with the ordination axes. The length of the arrow reflects the relationship between the environmental factors and the distribution pattern of diversity indices. The length of the line indicates the strength of the correlation, with long lines indicating a strong correlation. The angle formed by the arrow and the ordination axes denotes the correlation between environmental factors and ordination axes. A smaller angle indicates a greater correlation. From left to right, *GWD*,

Table III. Eigenvalues, cumulative percentage variance of DCCA ordination.

	Axes			
	1	2	3	4
Eigenvalue	0·325	0·046	0·012	0·002
Diversity-environment correlations	0·824	0·605	0·313	0·255
Cumulative variance of diversity (%)	64·5	72·2	76·9	77·74
Cumulative variance of diversity-environment correlation (%)	68·3	82·5	84·0	84·5

DCCA, detrended canonical correspondence analyses.

Table IV. The correlation coefficients of DCCA ordination axes and groundwater environmental factors.

	Axes			
	1	2	3	4
Groundwater depth	0·68**	0·06	0·03	−0·05
Salinity	0·52**	0·07	0·04	0·06
Total dissolved solids	0·35*	0·07	0·01	−0·05
Electric conductivity	0·18	0·10	0·04	−0·12
pH	−0·02	−0·34*	−0·02	−0·04
HCO_3^-	−0·47**	−0·07	0·03	0·05
SO_4^{2-}	−0·07	0·32*	−0·05	0·02
Na^+	0·02	0·14	0·04	−0·03
Ca^{2+}	−0·46**	0·05	−0·04	0·02
Mg^{2+}	−0·16	−0·10	0·02	0·03
Cl^-	−0·13	0·15	0·02	−0·03
K^+	−0·10	0·24	0·06	0·02

*$p < 0·05$, **$p < 0·01$. DCCA, detrended canonical correspondence analyses.

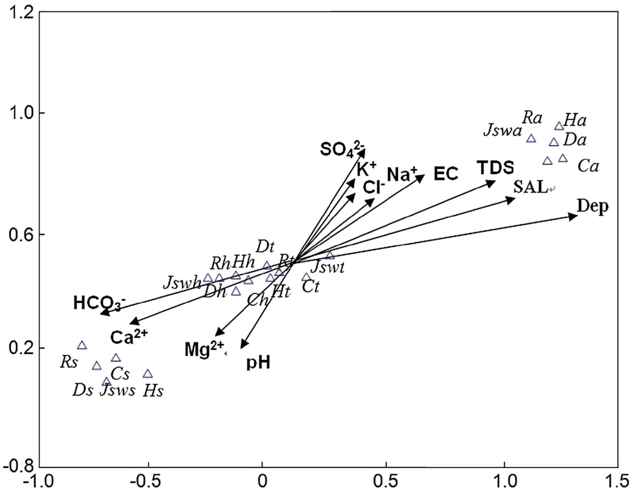

Figure 4. DCCA analysis of species diversity indices in Ejina Delta. *GWD*, groundwater depth; *SAL*, salinity; *TDS*, total dissolved solids; *EC*, electric conductivity; *R*, Patrick richness index; J_{sw}, Pielou evenness index; *H*, Shannon–Wiener species diversity index; *C*, Simpson domination index; *D*, Simpson species diversity index; *a*, tree layer; *h*, herb layer; *s*, shrub layer; *t*, total plant community.

SAL and *TDS* increased gradually along the first axis, whereas HCO_3^- and Ca^{2+} decreased gradually. From top to bottom, pH increased gradually along the second axis, indicating a change from acidic to alkaline conditions. In the DCCA ordination diagram, various diversity indices, including the tree, the shrub, the herb and the total diversity, got together, respectively. Only the herb layer and the total diversity indices were similar, indicating that the total diversity index primarily depended upon the herb layer. The herb layer and the total diversity index obtained their maximum under the same conditions, which took on a neutral characteristic, located in the middle of gradients in *GWD*, *SAL*, *TDS*, HCO_3^-, Ca^{2+}, pH and SO_4^{2-}. The tree diversity index was greatly influenced by *SAL* and *TDS*, and it obtained its maximum under deeper *GWD* and higher *SAL* and *TDS*. The shrub diversity index was greatly influenced by Ca^{2+} and Mg^{2+}, and it obtained its maximum under lower *GWD* and higher Ca^{2+} and Mg^{2+} (Figure 4).

Distribution patterns

Generalised additive model was employed to model the response curve of the species diversity indices to *GWD* and *SAL*, taking the species diversity index as the dependent variable and *GWD* and *SAL* as the independent variables. In contrast to general regression analysis, GAM does not fix the relationship between variables in advance but uses a smoothing function instead of a regression parameter. Thus, the fitting curves of variables obtained by GAM are in accord with the original data (Zhu, 2008), and nonlinearity, bimodality and asymmetrical unimodality in the data can be disclosed easily (Cao *et al*., 2005).

Patrick's richness index and Shannon–Wiener's index of the total community presented a similar, bimodal trend along the gradients of *GWD* and *SAL*. However, the first peak of the Shannon–Weiner's index was higher than that of the second peak, and the latter peak of Patrick's richness index was not as obvious as that of the S–W index [(Figure 5(A), (B) and Figure 6(A), (B)]. The main reason for this difference may be that Patrick's richness index is based on species number in the plots, whereas Shannon–Wiener's index is a comprehensive index of species richness and evenness (Xu *et al*., 2011). The meadow plant community was mainly composed of *P. australis* and *A. splendens* at the lowest *GWD* and at the highest *SAL*, with fewer species and a lower diversity index (Figures 5 and 6). Patrick's richness index and Shannon–Wiener's index reached their first peak at a *GWD* of 2 m and *SAL* of $1·8\ g\ l^{-1}$. This corresponds to the location of the desert riparian forest, which was dominated by *P. euphratica*. The main shrub species were *T. ramosissima* and *H. ammodendron*, and there were some herbs, such as *S. alopecuroides* and *G. uralensis*. The second peak of the two indices appeared at 5 m and $4·2\ g\ l^{-1}$, and the dominant species there were *E. przewalskii*, *R. soongorica* and *N. tangutorum*. Simpson's domination index and Pielou's evenness index showed an asymmetric unimodal curve [Figures 5 (C), (D) and 6(C), (D)]. Simpson's domination index reached the first peak at 3·5 m and $3·2\ g\ l^{-1}$, where the desert herb community dominated by *K. caspica*, *N. tangutorum* and *A. oxycephala*, was located. The first peak in Pielou's evenness index was at 2 m and $2·2\ g\ l^{-1}$, which corresponds to the desert riparian forest dominated by *P. euphratica*.

DISCUSSION

In the Ejina Delta, herbaceous communities (especially perennial herbs) play an important role among plant assemblages. The distribution pattern of the total species diversity was mainly influenced by *GWD*, *SAL*, *TDS*, HCO_3^-, Ca^{2+}, pH and SO_4^{2-}. The herb layer and total species diversity reached their maximum in similar and at moderate environmental conditions. Along disturbance

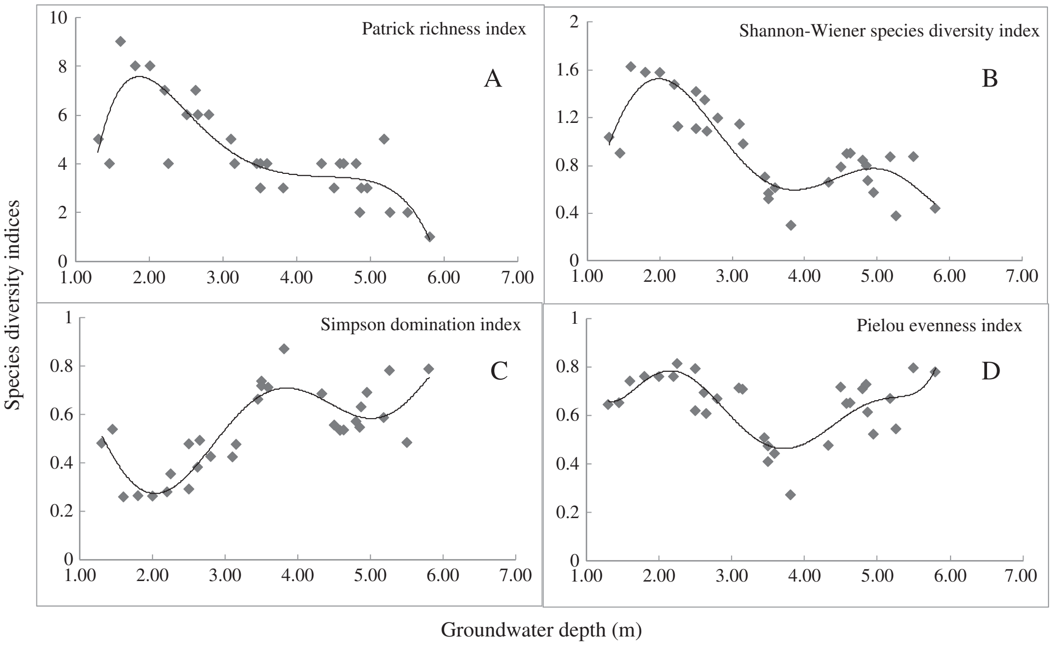

Figure 5. The distribution pattern of species diversity indices along groundwater depth gradient in Ejina Delta.

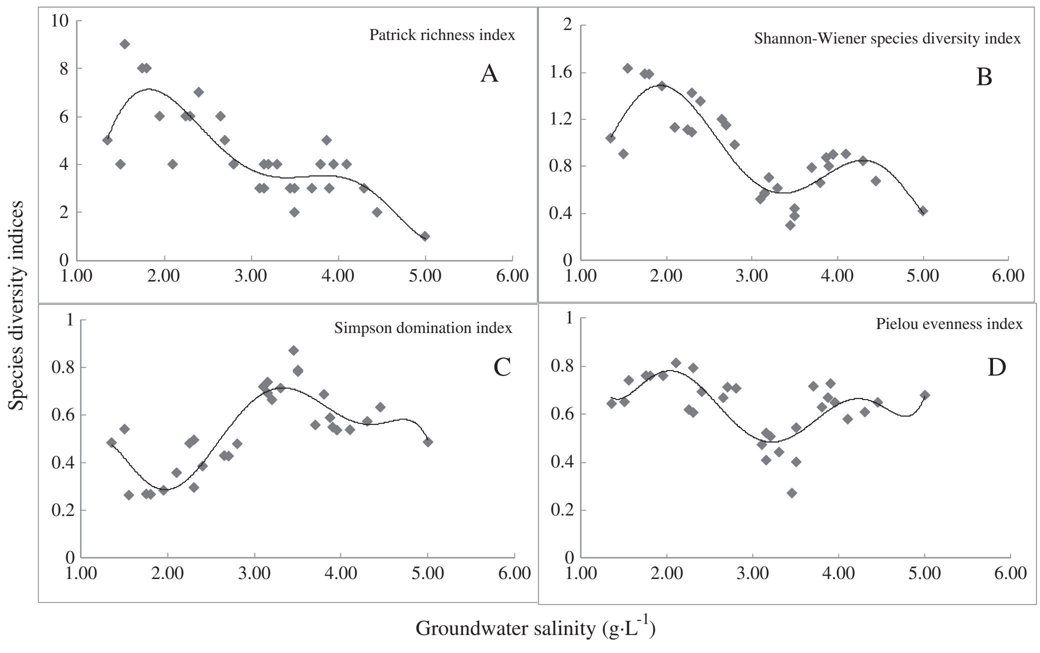

Figure 6. The distribution pattern of species diversity indices along groundwater salinity gradient in Ejina Delta.

gradients, species diversity has been found to be largest at intermediate levels (Huston, 1979; Ward and Stanford, 1983), and this was also the case in our study. The tree diversity index was greatly influenced by *SAL* and *TDS* and was maximal under deep rather than shallow *GWD* and higher *SAL* and *TDS*. The shrub diversity index was greatly affected by Ca^{2+} and Mg^{2+} and was maximal under lower *GWD* and higher Ca^{2+} and Mg^{2+} concentrations. The herbaceous plant community was dominant in the Ejina Delta, especially perennial, herbaceous plants with deep roots, which accounted for 45·3% of vascular plants in this district (Feng *et al*., 2009). They were widely distributed in arid and hilly desert plains and oases. As a result of the extremely arid climate and low precipitation in this area, perennial herbs with clonal reproduction and deep roots are better adapted to the environment in the long-term.

In this study, Patrick's richness index and Shannon–Wiener's index of the plant communities presented a bimodal pattern along *GWD* and *SAL*, and they reached peaks at 2 m, 1·8 g l^{-1} and 5 m, 4·2 g l^{-1} simultaneously. In contrast, Simpson's domination index and Pielou's evenness index showed a partially unimodal pattern, reaching peaks at 3·5 m, 3·2 g l^{-1} and 2 m, 2·2 g l^{-1}, respectively. Some studies have found that diversity increases (Bailey, 1988; Phillips *et al*., 1994) or decreases (Wilson and Tilman, 1991) along disturbance gradients. Spatial heterogeneity in the physical environment (e.g. substrate, nutrients, soil moisture and structure) has been positively and linearly correlated with diversity at a number of spatial scales (Pringle, 1990, Scarsbrook and Townsend, 1993). Hoffman *et al*. (1994) have shown that in the Karoo desert, species richness increases along a moisture gradient. Hao *et al*. (2007) indicated that the species richness index and the diversity index decreased with the increase in *GWD* in the lower reaches of Tarim River. These findings were different from those reported here, and this difference may be due to the variations of habitat conditions and community species composition in different regions.

In the bimodal pattern of species diversity, the *GWD* was lower (it meant water condition was better) at the first peak of the curve, where the desert riparian forest was located. The first peak was dominated by *P. euphratica*, and *P. euphratica* had the highest species richness and diversity index. The community gradually changed into communities IV and V with increasing depth to groundwater. In contrast, community V usually developed into the single dominant community when species richness and diversity index were reduced. When *GWD* increased moderately (from 3·5 to 5 m), this community changed into community VI, and species richness and the diversity index increased slightly, forming the second peak. When modelled by GAM, the response curves of Patrick's richness index and Shannon–Wiener's index along *GWD* and *SAL* were more strongly correlated with field *GWD* and *SAL* gradients and perfectly reflected the changing process of the diversity indices along these gradients. Xu *et al*. (2011) indicated that Patrick's index and Shannon–Wiener's index of plant communities presented a bimodal pattern along a gradient of altitude, and Simpson's index and Pielou's index showed a partially unimodal pattern. This is consistent with our study. Elevation is a major factor in mountain habitat reflecting the differences that influenced the distribution, structure and species diversity of the plant community (Wang, 2002). Similarly, *GWD* and *SAL* also played a decisive role in the composition and structure of plant communities, as well as in changes in species diversity in arid region (Chen *et al*., 2006). The spatial patterns of species diversity are determined by many ecological factors, and the bimodal pattern and partially unimodal pattern of species diversity along gradients of *GWD* and *SAL* largely depend on the covariation and interaction of the groundwater environmental variables considered in this study (Lomolino, 2001).

In this study, species diversity was largest at the 2 m level and was smaller at more shallow and deeper groundwater depths. A sharp decline in diversity occurred at a *GWD* of 5 m and *SAL* 4·2 g l^{-1}, and most species diversity indices were distributed at the interval *GWD* of 2–5 m. However, Hao *et al*. (2010) indicated that species diversity was the highest at the 2–4 m level, followed by the 4–6 m level, and then the 0–2 m level, in the lower reaches of the Tarim river, and plant species diversity decreased greatly when the water table dropped to below 6 m. Wang *et al*. (2010) found that the biodiversity of natural vegetation depends on gradients of both water availability and groundwater salt content and that various vegetation types adapt to different characteristics of groundwater level and *SAL* in arid regions. On the basis of our current field investigation and analysis, we conclude that the optimal combination of *GWD* and *SAL* for GDV species diversity is 2 m and 1·8 g l^{-1}, the appropriate combination range is 2–5 m and 1·8–4·2 g l^{-1}; and the critical combination for damaged GDV species diversity is 5 m and 4·2 g l^{-1}. Therefore, when managing the environment in Ejina Delta or other similar arid regions in the world, we must simultaneously keep the *GWD* and *SAL* at an appropriate range (2–5 m and 1·8–4·2 g l^{-1}) to ensure biodiversity and ecosystem function are maintained.

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