ECOHYDROLOGY
Ecohydrol. (2011)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/eco.249

Interpreting the groundwater attributes influencing the distribution patterns of groundwater-dependent vegetation in northwestern China

Juntao Zhu, Jingjie Yu,* Ping Wang, Yichi Zhang and Qiang Yu
Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China

ABSTRACT

Groundwater-dependent vegetation (GDV) must have access to groundwater to maintain their growth and function. GDV distribution patterns are an important issue in arid vegetation ecology. Using groundwater attributes to explore the distribution patterns of GDV have been very limited. In this article, we selected the Ejina Desert Oasis as an area to investigate GDV and groundwater attributes. Twenty plant species and 31 plant plots of data were collected. Two-way indicator species analysis (TWINSPAN) was performed to determine GDV types. Detrended correspondence analysis (DCA) and detrended canonical correspondence analysis (DCCA) were performed to analyse the relationships between GDV and groundwater attributes. The results indicated that (1) six plant community types were classified by TWINSPAN; (2) DCA ordination analyses showed that the groundwater depth (Dep) was the main factor restricting the distribution patterns of GDV, and the distribution of the dominant species and corresponding vegetation types had strong similarities; (3) in the DCCA diagram, the first axis represented variations of Dep, while the second axis was related to the pH values; (4) with increased Dep, the community types made the transition from I to VI; and (5) the DCCA diagram was similar to the DCA. However, the distribution patterns of GDV were more compact in the DCCA, while the DCA showed that each association group appeared within a limited range and had a clear border against other communities. This study shows that ordination methods can be used to explain the relationships between the distribution patterns of GDV and groundwater attributes. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS distribution pattern; groundwater-dependent vegetation; groundwater attributes; quantitative classification; the extremely arid region

Received 14 December 2010; Accepted 20 June 2011

INTRODUCTION

The Heihe River is an extremely arid inland river where the ecological environment is fragile. It is the second largest river in northwestern China (Guo *et al.*, 2009). Due to the overexploitation of the water resources in the middle reaches of the Heihe River in the 1960s, discharge to the lower reaches decreased, resulting in degradation of the ecological environment. For example, there has been a decline in the groundwater level and degeneration of water quality (Qi and Luo, 2005). The decline in groundwater level has caused large changes in vegetation patterns and led to ecological deterioration and desertification of the Ejina Oasis, which plays a protective role in blocking sandstorms in northwest China (Guo *et al.*, 2009). Several studies have examined changes in groundwater level, which are likely to affect vegetation distribution patterns indirectly and directly (Sun *et al.*, 1994; Li *et al.*, 2003). Zhang *et al.* (2005) showed that both biotic and abiotic factors influence the distribution patterns of plant communities in arid regions. Research focusing on the relationships between plant communities and groundwater attributes has become increasingly important in understanding the ecology of arid regions (Jiang *et al.*, 1994; Wang, 1997; Zhang *et al.*, 2001).

Since the 1980s, the development of ecological theory and application has led to vegetation patterns gradually becoming a focus in vegetation ecology research (Burke, 2001). Quantitative classification and ordination, which are effective multivariate techniques, have been widely used for analyses of community structures and understanding the relationships between communities and the environment in vegetation ecology (Zhang, 1995; Mucina, 1997; Leps and Šmilauer, 2003; Zhang *et al.*, 2008). Many studies have reported the relationships between vegetation and the environment in the inland river basin. Sun *et al.* (1994) indicated that groundwater depth (Dep), mineralization, soil salinity and Cl^- content, not pH values, were the main limiting factors for the growth of *Populus euphratica*. Li *et al.* (2003) revealed that the Dep, mineralization and salinity were important factors that influenced vegetation composition and patterns in the middle reaches of the Tarim River. In addition, Zhang *et al.* (2005) suggested that the dominating factors for vegetation distribution in the lower reaches of the Tarim River were Dep, soil water content, pH value, salinity and mineralization. Wang *et al.* (2007) also showed that Dep was the determining factor for community distributions on the banks of the Ejina River. Gui

* Correspondence to: Jingjie 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, P. R. China.
E-mail: yujj@igsnrr.ac.cn

et al. (2010) proposed that the main factors restricting the distribution of communities in the Cele River Basin were altitude and pH.

Because it affects both vegetation distribution and species composition, a small change in groundwater level can have major impacts on vegetation (Zhou *et al.*, 2007). The amount and frequency of rainfall is highly variable and scarce in arid regions, and the direct effects of precipitation on vegetation growth can be very weak (Chen *et al.*, 2004; Elmore *et al.*, 2006). Therefore, groundwater plays a predominant role in supporting plant communities in arid regions (Chen *et al.*, 2004). There are groundwater-dependent ecosystems (GDEs) and groundwater-dependent vegetation (GDV) in arid regions (Eamus *et al.*, 2006; Murray *et al.*, 2006). To date, there have been few attempts to study the distribution patterns of GDV and its relationship with groundwater attributes.

The Ejina Desert Oasis is an extremely arid oasis and is the natural safeguard of the Hexi corridor in northwest and North China. In recent years, the discharge of the Heihe River has declined due to an increase in the Dep. For the purpose of rehabilitating and reconstructing the ecosystems in the Ejina Oasis, water diversions to the lower reaches of the Heihe River were created in 2000, which caused a large change in water resources. To evaluate the influence of the water diversions on GDV in this region, it is necessary to understand the plant community types and establish relationships between the GDV and groundwater attributes (Dep and chemical characteristics). In this article, TWINSPAN classification was used to determine the GDV types. Detrended correspondence analysis (DCA) and detrended canonical correspondence analysis (DCCA) ordination methods were applied to analyse the relationships between the GDV and groundwater attributes.

MATERIALS AND METHODS

Experimental sites

The study area was 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; Zhang *et al.*, 2005). This region has a continental climate; it is extremely hot in the summer and severely cold in the winter. The mean annual temperature is approximately 8 °C, with a maximum daily temperature of 41 °C (July) and a minimum of −36 °C (January) (Xie, 1980). According to local meteorological data from 1957 to 2003, the annual average precipitation at the study site was less than 42 mm and scarcely recharged the groundwater, and the mean potential evaporation rate was 2300–3700 mm year^{-1} (Wen *et al.*, 2005). No perennial runoff is generated in this region and the Heihe River sustains the only perennial flow through the area (He and Zhao, 2006).

The Heihe River, which arises in the Qilian Mountain, flows through the Ejina Basin and divides into two branches at Langxinshan (Wang, 1997). The two branches of the Heihe River mingle in the 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 has been the main recharge source for the groundwater system, and approximately 68% of the groundwater recharged by vertical percolation from the Heihe River (Wu *et al.*, 2002; Feng *et al.*, 2004; Wen *et al.*, 2005).

In this region, plant biodiversity is low and plant cover is very low. According to investigations and statistics (Flora of Inner Mongolia, 1977–1979), 268 species belonging to 151 genera and 49 families are distributed in this area. Compositae (81), Chenopodiaceae (47) and Gramineae (33) are the dominant families, with 30 or more species. Leguminosae (15), Polygonaceae (11), Cyperaceae (11) and Tamaricaceae (10) represent more than ten species. These seven families include 208 species, and account for 72% of the total species present. Xerophytic, extremely xerophytic and salt-tolerant desert species are widely distributed in this region. From the distribution patterns, it can be seen that mesophytes and hygrophytes, including arbours, bushes and herbs, have grown in the Ejina river banks and flood plain, with the dominant species being *P. euphratica, Elaeagnus angustifolia, Tamarix ramosissima, Phragmites communis, Achnatherum splendens, Sophora alopecuroides* and *Glycyrrhiza uralensis*. Various types of desert shrubs and herbs, including *Haloxylon ammodendron, Nitraria tangutorum, Artemisia oxycephala* and *Agriophyllum arenarium*, are mainly distributed in the outer frontier 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 the low mountain hilly area and the Gobi Desert (Si *et al.*, 2005). The predominant vegetation in the study area, such as *P. euphratica*, *T. amosissiman* and *S. alopecuroides*, mainly depend on groundwater for sustenance (Guo *et al.*, 2009; Zhu *et al.*, 2009).

Plots and measurements

Natural vegetation investigations were carried out from June to August in the Ejina Desert Oasis. Five transects were positioned along the river course. At the five transects, 31 sites were selected for water table and salinity monitoring. Thirty-one (400 m^2 plots) plant plots and 217 squares (31 tree squares, 93 shrubs squares and 93 herb squares) were established randomly around the water table monitoring sites (Figure 1). The breast height, coverage and diameter of the trees ($\geq$5 m) were recorded individually. Three (25 m^2) shrub squares and three (1 m^2) herb squares were established randomly in each plot. The species present and the frequency,

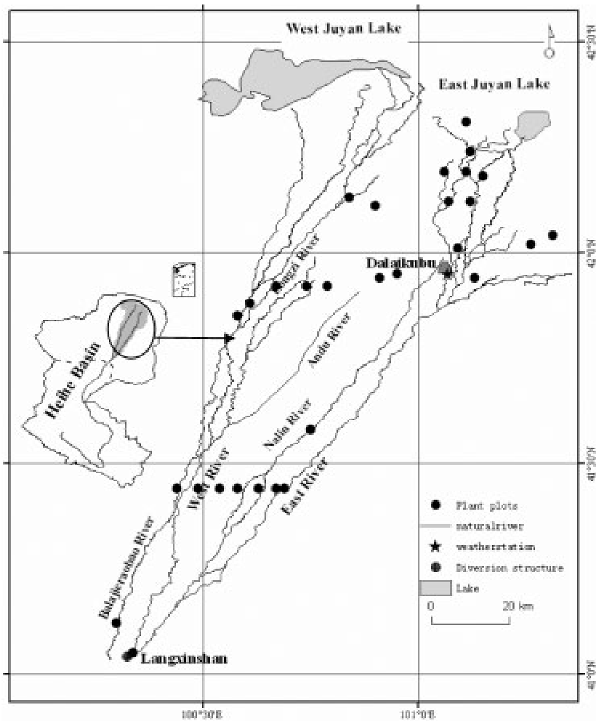

Figure 1. The location of study area, water channels and plant plots (400 m^2).

height and canopy cover percentage were determined for each square. Vegetation cover data were recorded using the ordinal scale of Van-der-Marrel (1979). The location of the sites, including altitude, longitude and latitude, were determined by Navigation Satellite Timing and Ranging Global Position System (GPS). The Dep was measured every 3 days in 31 wells between June and August. In addition, three groundwater samples were collected at each site. Chemical components, including HCO_3^-, CO_3^{2-}, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+, were measured at the Institute of Geography Sciences and Natural Resources Research, CAS. Levels of SO_4^{2-} and Cl^- were analysed by ion chromatography (IC), and HCO_3^- anions were analysed by titration (0·01 N H_2SO_4). Cations were analysed by inductively coupled plasma (ICP). The total dissolved solids (TDS) represent the sum of cations and anions in the water. The major ions in water chemistry contribute to the total salinity (SAL), electrical conductivity (EC) and pH values that were measured *in situ* using a HANNA HI 98188 waterproof, portable Conductivity Meter as well as CyberScan PC300 Waterproof Portable pH/ORP/Conductivity Meters.

Statistical analyses

Using the importance value as the index of dominance, the function status and distribution patterns of different species were evaluated for each plant community. Calculations were made according to the formulas (Zhang and Oxley, 1994)

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

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

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

Twenty-nine species were recorded in 217 squares. Considering the effects of the dominant species and common species on plant communities, species whose frequency was less than 5% were removed and species whose frequency was equal or more than 5% were preserved (Leps and Šmilauer, 2003). The average importance values of trees, shrubs and herbs were calculated individually in each plant plot. Finally, a group from the original matrix (31 × 20) between plots and species was obtained. Environmental data included Dep, SAL, TDS, EC, pH and HCO_3^-, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+ concentrations. Using these data, a group from the original matrix (31 × 12) between plots and groundwater attributes was obtained.

The plant community types in the Ejina Desert Oasis were classified by two-way indicator species analysis (WinTWINSPAN, version 2.3) (Hill and Šmilauer, 2005). The distribution patterns in this study area were analysed by CCA, DCA and DCCA. The CCA, DCA and DCCA were constrained unimodal ordination methods that stressed patterns in relative abundance (Leps and Šmilauer, 2003) and have been widely used to analyse the relationships between vegetation distributions and environmental factors (da Silva and Batalha, 2008; Zuo *et al*., 2009). The importance value of each species in each square was used for the CCA, DCA and DCCA. To test whether the important environmental factors were omitted, the ordination eigenvalues of the DCA and DCCA were compared (Liu, 1996). Due to the influence of redundant variables, CCA exhibited an obvious 'bowing effect' (Leps and Šmilauer, 2003). To avoid the effects of redundant variables, a forward selection method and the Monte Carlo test (1000 permutations) were used (Jafari *et al*., 2004; Franklin *et al*., 2006). A group of proxy variables was determined for further analyses. The forward selection, Monte Carlo test, CCA, DCA and DCCA were performed using CANOCO 4·5 (ter Braak and Šmilauer, 2002).

RESULTS

TWINSPAN classification

Using the results of the TWINSPAN classification combined with practical ecological significance, six plant community types were obtained in the Ejina Desert Oasis (Figures 2 and 3). Community I (1) contained *P. communis* and weeds and includes plots 30 and 31. This community type was mainly distributed on both sides of the Ejina River and the regions of lower Dep, which included the river, lake, marsh wetland and meadow landscapes. Hygrophytic and halophytic herb species existed in this ecosystem, which included *P. communis*, *A. splendens, Leymus secalinus, Calamagrostis epigeios, Elymus breviaristatus* and *Kalimeris indica*, among others. The


```
                  1      221      1112112222122 11233
                  8125706446890678153579942323101

6   S6            -2212223112112-----------------   0000
7   S7            4444443------------------------   0000
1   S1            -------455555555-4-4-42-4------   0001
3   S3            -212211322222-12344------------   0001
4   S4            -------4-2-12-122-33-----------   0001
8   S8            2--2----2-21--------3----------   0001
9   S9            211---------------32-4---------   0010
2   S2            ----------------55555543555-5--   00110
13  S13           --------------------1221-------   00110
16  S16           ----------------------55-------   00110
5   S5            -----------------34----334354--   00111
11  S11           ------------------3--33--33-3--   00111
12  S12           ----------------------2-23-----   00111
14  S14           -------5----------------55555--   00111
15  S15           -----------------23----23-----3   01
10  S10           -----------------2-----3-----24   10
17  S17           -----------------------------55   11
18  S18           -----------------------------3-   11
19  S19           -----------------------------54   11
20  S20           -----------------------------4-   11

                  0000000000000000000000000000011
                  00000000000000001111111111111
                  00000001111111110000000011111
                  11111110111111110000001111111
```

Figure 2. TWINSPAN classification results of plant communities in Ejina Desert Oasis. Note: The top of the classification matrix is the plot number and the bottom is the classification results of the plots. The left is the species number and the right is the classification results of 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*.

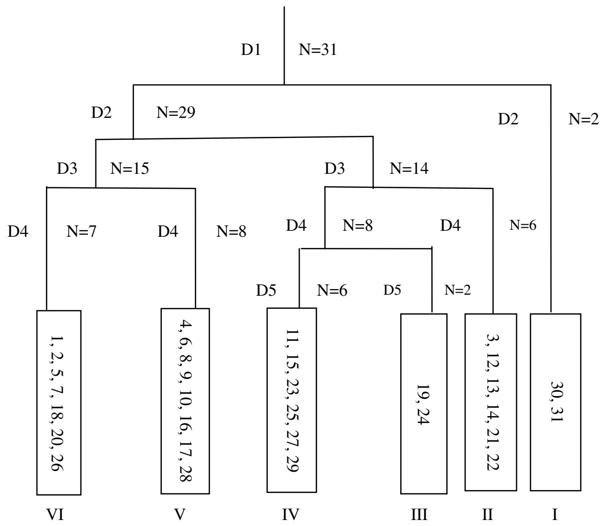

Figure 3. Dendrogram of the TWINSPAN classifications of 31 plant plots (217 squares) in the Ejina Desert Oasis.

total community coverage at the higher level was usually in the range of 70–90%.

Community II (0111) was composed of *P. euphratica*, *T. ramosissima* and weeds and included plots 3, 12, 13, 21 and 22. Plot 14 (0010) was also placed in Community II according to the practical conditions. This community type was mainly distributed in the East River banks and the lake delta. The forest of *P. euphratica* mostly presented strip and plaque distribution characteristics on both sides of the Ejina River. There was an abundance of aeolian sand under the forest and was present in the formation of dunes. Some herb species, such as *S. alopecuroides*, *P. communis, Oxytropis glabra* and *Karelinia caspica,* were grown under the forest canopy. *T. ramosissima* was the only shrub. The total community coverage in the higher levels was usually in the range of 40–70%.

Community III (0101) was composed of *E. angustifolia*, *T. ramosissima* and weeds and included plots 19 and 24. This community type was mainly distributed in the lower reaches of the West River. The shrubs, including *T. ramosissima* and *C. mongolicunl,* were predominant under the forest canopy. Herbaceous companion species mainly included *S. alopecuroides*, *G. uralensis, Alhagi sparsifolia* and *K. caspica*. The total community coverage was usually in the range of 40–70%.

Community IV (0100) was composed of *T. ramosissima* and weeds and included plots 11, 15, 23, 25, 27 and 29. This community type was mainly distributed on the beaches of the Ejina River. The major soil types were sandy soil, meadow soil and grey brown desert soil. *T. ramosissima* had absolute predominance in this community. The companion species, *N. tangutorum* and *Lycium ruthenicum,* were mainly distributed in the region of higher soil salinization, while *A. oxycephala* and *S. alopecuroide* were mainly distributed in the region of higher desertification. The total community coverage is usually in the range of 40–60%.

Community V (0011) was composed of *K. caspica*, *N. tangutorum*, *A. oxycephala* and *C. mongolicunl* and included plots 4, 6, 8, 9, 10, 16, 17 and 28. This community type was mainly distributed at the outer margin of the Ejina Oasis, which consisted of desert plant communities and Gobi landscapes. The composition and structure of the plant communities were simple. The natural vegetation cover was lower. The total community coverage was usually in the range of 15–30%.

Community VI (0001) was composed of *E. przewalskii*, *R. soongorica*, *N. tangutorum* and *A. sparsifolia* and included plots 1, 2, 5, 7, 18, 20 and 26. This community type was mainly distributed in the wide Gobi plain. The major soil types included desert soil, sandy soil and saline soil. In this community, only one plant species existed in a partial section, and other plots were absolutely bare. The ground surface was usually covered with gravel and pebbles. The Gobi desert environment often supported low vegetative cover. This community coverage was usually less than 10%.

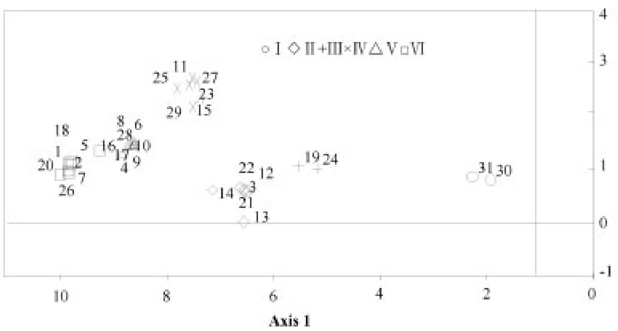

Figure 4. Two-dimensional DCA ordination diagram of 31 plant plots in the Ejina Desert Oasis.

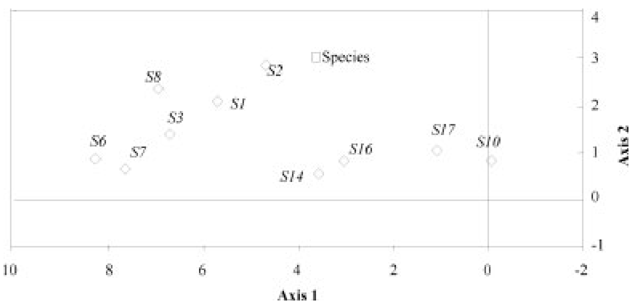

Figure 5. Two-dimensional DCA ordination diagram of the main plant species in the Ejina Desert Oasis.

DCA ordination

Species-plot dates were analysed using DCA. Then the lengths of the gradient (the first axis) were compared. If the value was larger than 4, a single peaked model was selected; if the value was situated between 3 and 4, both a single peaked and linear model were selected; if the value was less than 3, a linear model was selected (RDA, PCA) (Leps and Šmilauer, 2003). In our study, the value (8·071) was greater than 4, and a single peaked model was thus selected (CCA, DCA and DCCA).

The distribution patterns of plant communities were analysed by DCA. The eigenvalues of the four ordination axes were 0·954, 0·411, 0·083 and 0·041. The cumulating contribution rates of the first 2 axes were 76·5%. The basic outlook of one variable could be well reflected if the cumulating contribution rate was larger than 70% (Zhang and Zhang, 2000). This indicated that the results of the DCA ordination were good. The eigenvalues of the first axis was the maximum, and most of ecological information was reflected; this was followed by the second axis. Therefore, a two-dimensional DCA ordination diagram was made according to the first 2 axes (Figure 4). The results of the TWINSPAN classification were almost consistent with the results of the DCA ordination. Six plant community types were classified by WinTWINSPAN in the Ejina Desert Oasis.

In terms of ordination axes, the plant communities clearly changed along the first axis. The vegetation types in this region included marsh meadow, desert riparian trees, desert riparian shrubs, drought desert shrubs and extremely drought desert shrubs. This indicated that the first axis mainly represented variations of Dep and SAL. From right to left, Dep increased gradually along the first axis, and SAL changed correspondingly. The natural landscapes made the transition from marsh meadow to the Gobi desert. Along the second axis, Communities I, III, V and VI were approximately located on the same horizontal line (Figure 4). Their pH values presented the same trend. Among them, the pH value of Community IV was the highest and that of Community II was the lowest. Therefore, we concluded that the second axis mainly represented variations in pH value.

On the basis of the plant community types, the various communities were distributed regularly in the DCA ordination diagram. Six plant communities varied sequentially from right to left (Figure 4). Community I, IV, V and VI were distributed at both ends. Community II and III were located in the centre. Moreover, Community I, III and VI were far apart from each other. The results showed that obvious changes in species composition and environmental gradients took place among these communities. Community II together with III belonged to the desert riparian trees, and they had many common characteristics in species composition and environmental gradients. Due to the components of the drought that appeared in Community IV, the differences between IV, V and VI were relatively small. For this reason, the three communities were mainly distributed in the left, and they were located in close proximity to one another (Figure 4).

The distribution of the dominant species in the DCA ordination diagram is presented in Figure 5. This shows that the distribution patterns of the dominant species and corresponding vegetation types have good similarity. For instance, Community I, with the dominant species (S10 and S17) and S10 and S17 are all distributed on the right of Figure 4. Other dominant species and their corresponding communities were also distributed near the same location in the DCA ordination diagram.

Distribution pattern of the plant communities

To examine the relationships between the distribution patterns of plant communities and groundwater attributes, CCA ordination was used. CCA is a constrained unimodal ordination method and has been widely used as an analytical method (Leps and Šmilauer, 2003; da Silva and Batalha, 2008). In particular, the ordination diagram of samples, species and environmental variables derived from the CCA optimally displayed the variation of the object composition in connection with the environmental factors (Zuo *et al*., 2009). An obvious 'bowing effect' from Figure 6 can be seen due to the effects of redundant variables. To eliminate the effects of redundant variables, a forward selection method and a Monte Carlo test (1000 permutations) were used for 12 groundwater environmental variables. We obtained a group of proxy variables for the DCCA. Marginal and conditional effects of various variables were determined through the Monte Carlo test in the process of forward selection. Meanwhile, the statistical correlation was deeply understood between various variables and plant communities (Leps and Šmilauer, 2003).

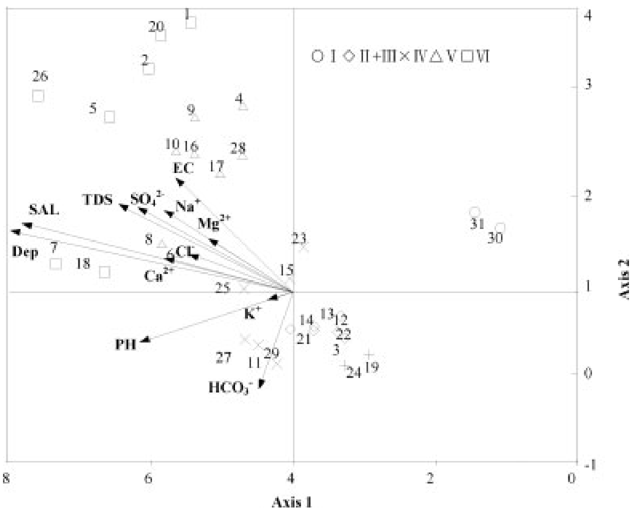

Figure 6. Two-dimensional CCA ordination diagram of 31 plant plots in the Ejina Desert Oasis.

Table I shows the changing conditions of marginal and conditional effects of 12 variables under the Monte Carlo test in the process of forward selection. Marginal effects reflected the effects of the environmental variables on the species composition. However, conditional effects reflected the effects of the environmental variables on the community after the anterior variable was eliminated. Both marginal and conditional effects were expressed by canonical eigenvalues (Leps and Šmilauer, 2003). The Dep variable had the largest influence on the plant communities. The Dep conditional effects were also the highest (0·86). Thus, the Dep variable was the first among the environmental variables. The marginal effects of the SAL variable were in second place (0·85). After the Dep variable was put forward under the Monte Carlo test, the conditional effects of SAL immediately dropped to 0·35. This indicated that a strong correlation existed between SAL and Dep. The conditional effects of other variables also dropped significantly after the Dep variable was put forward. This also indicated that a strong correlation existed between other variables and Dep. Nevertheless, pH, SAL, TDS, EC and HCO_3^- still passed the Monte Carlo test in the process of forward selection ($P < 0{\cdot}05$). These six groundwater attributes were composed of a group of proxy variables (Table II). A total of 78% of the environmental information was extracted, and the Dep variable offered the most information (27%) (Table I).

DCCA is a constrained unimodal ordination method that eliminates the 'bowing effect' and calculates ordination values combined with vegetation and environment data. DCCA could be more beneficial when interpreting the ecological significance of ordination axes and has become the most advanced technology of multivariate analysis in regards to the relationships between vegetation and the environment (Zhang and Oxley, 1994; Shen *et al*., 2000). Figure 7 shows the relationships between vegetation patterns and groundwater attributes through DCCA after six proxy variables were determined. The

Table I. Marginal and conditional effects obtained from the summary of forward selection.

Marginal effects		Conditional effects		*P* value	*R* value	*F* value
Environmental factors	λ 1	Environmental factors	λ 2			
Dep	0.86	Dep	0.86	0.002[a]	0.27	8.49
SAL	0.85	pH	0.71	0.002[a]	0.23	8.12
TDS	0.79	SAL	0.35	0.002[a]	0.11	3.15
EC	0.78	TDS	0.31	0.005[a]	0.06	3.41
pH	0.75	EC	0.27	0.036[b]	0.06	1.58
HCO_3^-	0.64	HCO_3^-	0.18	0.032[b]	0.05	1.98
SO_4^{2-}	0.64	Ca^{2+}	0.12	0.226	—	1.29
Na^+	0.61	Na^+	0.11	0.318	—	1.13
Ca^{2+}	0.52	SO_4^{2-}	0.08	0.284	—	1.23
Mg^{2+}	0.35	Cl^-	0.08	0.698	—	0.62
Cl^-	0.18	Mg^{2+}	0.07	0.682	—	0.67
K^+	0.07	K^+	0.06	0.716	—	0.64

R value represents relative percentage.
λ1, the eigenvalues of marginal effects; λ2, the eigenvalues of conditional effects. [a] The impact of environmental factors on community types is significant at the 0·01 level. [b] The impact of environmental factors on community types is significant at the 0·05 level.

Table II. Variation characteristics of six groundwater environmental proxy variables.

Type	Dep (m)	pH value	SAL (%)	TDS (mg l^{-1})	EC (μs cm^{-1})	HCO_3^- (mg l^{-1})
I	1·10–1·85	7·22–7·42	1·32–1·65	583·15–753·85	635·72–894·25	114·37–146·52
II	2·28–3·56	7·38–7·8	1·80–2·52	947·64–1385·37	856·21–1285·36	173·85–233·42
III	2·33–4·25	7·32–7·65	1·75–2·30	665·42–1063·55	774·55–1095·36	135·25–196·73
IV	2·81–5·15	7·46–7·9	2·41–3·25	1223·58–1745·26	1130·83–2216·15	201·36–347·70
V	3·32–5·54	7·55–8·25	3·15–3·87	1574·54–2512·75	1578·86–2653·24	279·09–382·15
VI	4·25–6·86	7·64–9·29	3·70–5·15	1885·35–3643·71	2156·33–3497·56	315·48–457·50

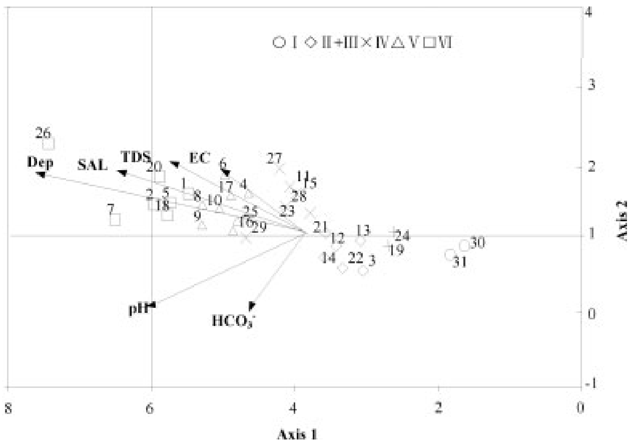

Figure 7. Two-dimensional DCCA ordination diagram of 31 plant plots in the Ejina Desert Oasis.

eigenvalues of the first 2 axes were 0·925 and 0·247. The contribution rates were 59·5 and 17·8%, respectively. The cumulating contribution rate of the first 2 axes was 77·3%. This meant that the first 2 axes could represent 77·3% of the environmental information. This indicated that the results of DCCA ordination were also good. The relationships between the plant communities and environmental factors are shown in Figure 7. Plots could be interpreted quantitatively using the length of the arrow to indicate how much variance was explained by that factor; the direction of the arrows for an individual environmental factor indicated an increasing weighting of that factor; the angle between the arrow and ordination axis reflected the correlation of that factor and the environmental factor. The smaller the angle, the higher the correlation was between the axis and the environmental factor (Zhang and Zhang, 2000).

Figure 7 shows that the Dep arrow is pointed in approximately the same direction as the SAL, TDS and EC arrows, in contrast to the pH and HCO_3^- arrows Moreover, the length of Dep arrow was the longest, and the angle was the smallest. Among all environmental factors, Dep exhibited the greatest influence on community distributions, followed by pH, SAL, TDS, EC, and HCO_3^-. In the DCCA ordination diagram, the first axis represents the variations of Dep conditions, while the second axis is related to pH values. As a result, it is not difficult to show that Dep is the most important factor influencing community distributions. With increased Dep, SAL and TDS, there was also an obvious increasing trend along the first axis. From right to left, distribution patterns of plant communities varied along the first axis, and the community types made the transition from I to VI. There were significant differences in pH levels in community I, II and VI; these differences were mainly in the second axis. Conclusively, the DCCA ordination diagram was similar to the DCA diagram. However, distribution patterns of the communities were more compact in the DCCA ordination diagram, while the DCA ordination diagram showed that each association group appeared within a limited range and had a clear border against other communities.

DISCUSSION

Six plant community types were classified by Win-TWINSPAN in the Ejina Desert Oasis, including *P. communis* and weeds; *P. euphratica*, *T. ramosissima* and weeds, *E. angustifolia*, *T. ramosissima* and weeds, *T. ramosissima* and weeds, *K. caspica, N. tangutorum, A. oxycephala* and *C. mongolicunl*, and *E. przewalskii, R. soongorica*, *N. tangutorum* and *A. sparsifolia*. The vegetation types in these regions were marsh meadow, desert riparian trees, desert riparian shrubs, drought desert shrubs and extreme drought desert shrubs. The results of the TWINSPAN classifications reflected the changing trends in vegetation types. This study expanded on the quantitative classification and ordination of the natural vegetation of the *P. euphratica* forest, which grew on the banks of the Ejina River (Wang *et al.*, 2007). In this study, the vegetation types were investigated on a regional scale. Vegetation classifications qualitatively reflected the relationships between vegetation types and the environment. The Ejina Desert Oasis belongs to the dry continental climate of the warm temperate zone, and the zonal vegetation type is arid desert. Due to the effects of the water from the upper reaches of the Heihe River, intrazonal vegetation appeared in the Ejina Desert Oasis, such as saline meadows, saline marsh, *P. euphratica* forests and *E. angustifolia* forests, and finally the formation of the intrazonal forest.

The results of the TWINSPAN classifications were almost consistent with the DCA ordination. The rationality of TWINSPAN classifications were well verified in this study. The results showed that each association group appeared within a limited range and had a clear border against other communities in the two-dimensional ordination diagram. This indicated that the relationships between the plant communities and environment could be well reflected through DCA ordination, which is in agreement with previously reported DCA ordinations for this area (Zhang *et al.*, 2003; Gui *et al.*, 2010). Figure 5 shows that the dominant species and their corresponding communities are essentially distributed at the same location in DCA ordination diagram. For instance, Community I with the dominant species (S10 and S17) and S10 and S17 were all distributed to the right of the diagram. This indicated that the distribution patterns of the dominant species determined the distribution of the community types to some degree (Zhang *et al.*, 2003).

The results of the DCA ordination suggested that Dep was an important factor that influenced the distribution patterns of species and communities in the Ejina Desert Oasis. Wang *et al.* (2007) also concluded that Dep played a determinative role on the distribution of plant communities. In addition, in the arid inland river basin, similar conclusions were also obtained by other scholars (Sun *et al.*, 1994; Li *et al.*, 2003; Zhang *et al.*, 2005).

Studies on the relationships between vegetation and environment showed that considering more environmental factors was not necessarily better. Because there were complex correlations among the environmental factors, even collinearity relationships appeared (Li *et al.*, 2008). Due to the effects of redundant variables, results appeared with large deviations. Therefore, it was necessary to choose decisive environmental variables for community distribution patterns to study the relationships between the communities and the environment. Li *et al.* (2003) adopted correlation coefficient methods to eliminate redundant environmental variables; Qian *et al.* (2004) and Liu *et al.* (2010) used principal component analysis (PCA) to avoid the problem of collinearity. However, Gui *et al.* (2010) suggested that a forward selection method and the Monte Carlo test could determine the environmental factors efficiently while eliminating the problem of collinearity. In this study, a forward selection method was used for 12 groundwater attributes. We obtained a group of proxy variables (Dep, pH, SAL, TDS, EC and HCO_3^-) that influenced community distribution patterns significantly. Seventy-eight percent of the environmental information was extracted from six proxy variables. The Dep variable offered the most information (27%). Furthermore, the Monte Carlo test also indicated that it was reasonable to select the group of proxy variables. Forward selection combined with the Monte Carlo test was a reliable and practical method to study vegetation distribution patterns (Gui *et al.*, 2010). The DCCA ordination diagram was similar to the DCA ordination diagram. However, distribution patterns of the communities were more compact in the DCCA ordination diagram, while the DCA ordination diagram showed that each association group appeared within a limited range and had a clear border against other communities (Zhang, 1995; Gui *et al.*, 2010). Dep exhibited the largest influence on plant community distributions in the first axis. The variation in pH values caused the differentiations in the second axis (Zhang *et al.*, 2003). The influence of the other four proxy variables on community distribution patterns was relatively weak. This can be seen from the conditional effects and in the DCCA ordination diagram (Gui *et al.*, 2010).

Zhang *et al.* (2005) proposed that both biotic and abiotic factors influence the distribution patterns of plant communities. Inter-relationships between plant communities and environmental factors are complex, reflecting simultaneous changes in factors such as Dep, soil moisture, salt content and soil stability; it is thus necessary to quantitatively examine their relationships (Zhang *et al.*, 2001; Jafari *et al.*, 2004). In this study, only groundwater attributes such as Dep, SAL, TDS and others were used for investigating the relationships between the distribution patterns of the GDV and, to a certain degree, explaining the relationships between the GDV and groundwater attributes. However, more work will be done with soil environmental interpretation in future research.

Few attempts have been made to explain the distribution patterns of GDV in the Ejina Desert Oasis. Understanding GDV types and the relationships between the distribution pattern of the GDV and groundwater attributes can provide guidance to rational water transport, vegetation restoration and construction in the Ejina Desert Oasis. In this study, these results increase our understanding of the relationships between the distribution patterns of the GDV and groundwater attributes in this region. The results will also provide a theoretical base for evaluating the influence of water diversions on the GDV in this region or other similar inland river basins.

ACKNOWLEDGEMENTS

This study was funded by the National Basic Research Program of China (2009CB421305) and National Natural Science Fund Project of China (91025023). The authors are also grateful to Professor Guobin Fu, Dr Lili Mao, Leilei Min, Fei Ao, Zhiyong Wang, Yongliang Xu and Runliu Song for their valuable comments and participation in the field work.

REFERENCES

Burke A. 2001. Classification and ordination of plant communities of the Naukluft mountains, Namibia. *Journal of Vegetation Science* **12**: 53–60.

Chen YN, Zhang XL, Zhu XM, Li WH, Zhang YM, Xu HL, Zhang HF, Chen YP. 2004. Analysis on the ecological benefits of the stream water conveyance to the dried-up river of the lower reaches of Tarim River, China. *Science China Series D—Earth Sciences* **47**: 1053–1064.

Commissione Redactorum Florae Inner Mongolia. 1977–1979. *Flora of Inner Mongolia (Tomus 2, 3 & 4)*. Inner Mongolia People's Publishing House: Hohhot, China.

da Silva DM, Batalha MA. 2008. Soil-vegetation relationships in cerrados under different fire frequencies. *Plant and Soil* **31**: 87–96.

Eamus D, Froend R, Loomes R, Hose G, Murray B. 2006. A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. *Australian Journal of Botany* **54**: 97–114.

Elmore AJ, Manning SJ, Mustard JF, Craine JM. 2006. Decline in alkali meadow vegetation cover in California: the effects of groundwater extraction and drought. *Journal of Applied Ecology* **43**: 770–779.

Feng Q, Cheng GD, Endo KN. 2001. Towards sustainable development of the environmentally degraded River Heihe basin, China. *Hydrological Sciences Journal* **46**: 647–658.

Feng Q, Liu W, Su YH, Zhang YW, Si JH. 2004. Distribution and evolution of water chemistry in Heihe River basin. *Environmental Geology* **45**: 947–956.

Franklin J, Wiser SK, Drake DR, Burrows LE, Sykes WR. 2006. Environment, disturbance history and rain forest composition across the island of Tonga, Western Polynesia. *Journal of Vegetation Science* **17**: 233–244.

Gui DW, Lei JQ, Zeng FJ, Jiang Y, Mu GJ, Yang FX. 2010. Effect of ecological factors on plant communities of the Cele River Basin on the north slope of the middle Kunlun mountains. *Acta Prataculturae Sinica* **19**: 38–46. (in Chinese with English Abstract).

Guo Q, Feng Q, Li J. 2009. Environmental changes after ecological water conveyance in the lower reaches of Heihe River, northwest China. *Environmental Geology* **58**: 1387–1396.

He ZB, Zhao WZ. 2006. Characterizing the spatial structures of riparian plant communities in the lower reaches of the Heihe River in China using geostatistical techniques. *Ecological Research* **21**: 551–559.

Hill MO, Šmilauer P. 2005. *TWINSPAN for Windows version 2.3. Centre for Ecology and Hydrology & University of South Bohemia*. Huntingdon and Ceske Budejovice.

Jafari M, Zare Chahouki MA, Tavili A, Azarnivand H, Zahedi Amiri Gh. 2004. Effective environmental factors in the distribution of vegetation types in Poshtkouh rangelands of Yazd Province (Iran). *Journal of Arid Environment* **56**: 627–641.

Jiang H, Huang JH, Chen LZ, Yang XQ. 1994. DCA ordination, quantitative classification and environment interpretation of plant communities in Dongling Mountain. *Acta Botanica Sinica* **36**: 539–551. (in Chinese with English Abstract).

Leps L, Šmilauer P. 2003. *Multivariate Analysis of Ecological Data Using CANOCO*. Cambridge University Press: New York; 202–210.

Li GQ, Wang XA, Guo H, Zhu ZH. 2008. Effects of ecological factors on plant communities of Ziwuling Mountain, Shaanxi Province. *Acta Ecologica Sinica* **28**: 2463–2471. (in Chinese with English Abstract).

Li T, Yin LK, Yan C. 2003. Quantitative classification and ordination analysis on vegetation in the middle reaches of Tarim River. *Arid Land Geography* **26**: 173–179. (in Chinese with English Abstract).

Li X, Lu L, Cheng GD, Xiao HL. 2001. Quantifying landscape structure of the Heihe River Basin, north-west china using FRAGSTATS. *Journal of Arid Environment* **48**: 521–535.

Liu GS. 1996. *Soil Physical and Chemical Analysis and Description of Soil Profiles*. Standards Press of China: Beijing; 50–112. (in Chinese).

Liu WD, Ding Y, Zang RG, Su JR, Yang M, Cai DL, Li RC, Chen SW. 2010. Quantitative classification and ordination of low-altitudinal tropical forests in Bawangling, Hainan Island. *Chinese Journal of Ecology* **29**: 1526–1532. (in Chinese with English Abstract).

Mucina L. 1997. Classification of vegetation: past, present and future. *Journal of Vegetation Science* **8**: 751–760.

Murray BR, Hose GC, Eamus D, Licari D. 2006. Valuation of groundwater-dependent ecosystems: a functional methodology incorporating ecosystem services. *Australian Journal of Botany* **54**: 221–229.

Qian YB, Wu ZN, Zhang LY, Shi QD, Jiang J, Tang LS. 2004. Impact of ecoenvironment on vegetation community pattern in Gurbantunggut Desert. *Acta Geographica Sinica* **59**: 895–902. (in Chinese with English Abstract).

Qi SZ, Luo F. 2005. Water environmental degradation of the Heihe River basin in arid northwestern China. *Environmental Monitoring and Assessment* **108**: 205–215.

Shen ZH, Zhang XS, Jin YX. 2000. Gradient analysis of the influence of mountain topography on vegetation pattern. *Acta Phytoecologica Sinica* **24**: 430–435.

Si JH, Feng Q, Zhang XY, Su YH, Zhang YW. 2005. Vegetation changes in the lower reaches of the Heihe River after its water import. *Acta Botanica Boreali-Occidentalia Sinica* **25**: 631–640.

Sun XX, L Yi, Kang XY. 1994. The quantitative classification and the ordination of *Populus euphratica* Oliv's natural forest stand in Jiuquan. *Journal of Arid Land Resources and Environment* **8**: 61–67. (in Chinese with English Abstract).

ter Braak CJF, Šmilauer P. 2002. *Canoco Reference Manual and CanoDraw for Windows User's Guide: Software for Canonical Community Ordination (version 4.5)*. Microcomputer Power: Ithaca, New York.

Van-der-Marrel E. 1979. Transformation of cover-abundance values in phyto-sociology, its effects on community similarity. *Vegetation* **39**: 97–114.

Wang LB, Yu WL, Yang WB, Hu XL, Li GT, Li JT. 2007. The quantitative classification and ordination of natural vegetation *Populus euphratica* Oliv. Forests growing on the banks of Ejina River. *Journal of Northwest Forestry University* **22**: 45–48. (in Chinese with English Abstract).

Wang X. 1997. Multivariate analysis of desert in Anxi. *Acta Botanica Sinica* **39**: 461–466.

Wen X, Wu Y, Su J, Zhang Y, Liu F. 2005. Hydrochemical characteristics and salinity of groundwater in the Ejina Basin, Northwestern China. *Environmental Geology* **48**: 665–675.

Wu J, Hobbs R. 2002. Key issues and research priorities in landscape ecology: an idiosyncratic synthesis. *Landscape Ecology* **17**: 355–365.

Xie Q. 1980. *Regional hydrogeological survey report of the People's Republic of China (1 : 200 000): Ejina K-47-[24] [R] (Jiuquan)*. (in Chinese).

Zhang JT. 1995. *Methods of Vegetation Quantitative Ecology*. Science and Technology Press of China: Beijing; 217–226. (in Chinese).

Zhang F, Zhang JT. 2000. Research progress of numerical classification and ordination of vegetation in China. *Journal of Shanxi University (Natural Science Edition)* **23**: 278–282. (in Chinese with English Abstract).

Zhang F, Zhang JT, Zhang F. 2003. Pattern of forest vegetation and its environmental interpretation in Zhuweigou, Lishan Mountain Nature Reserve. *Acta Ecologica Sinica* **23**: 421–427. (in Chinese with English Abstract).

Zhang JT, Dong YR, Xi YX. 2008. A comparison of SOFM ordination with DCA and PCA in gradient analysis of plant communities in the midst of Taihang Mountains China. *Ecological Informatics* **3**: 367–374.

Zhang JT, Oxley ERB. 1994. A comparison of three methods of multivariate analysis of upland grasslands in North Wales. *Journal of Vegetation Science* **5**: 71–76.

Zhang YM, Cao T, Pan BR. 2001. Quantitative classification and ordination analysis on bryophyte vegetation in Bogda Mountain, Xinjiang. *Acta Phytoecologica Sinica* **26**: 10–16.

Zhang YM, Chen YN, Pan BR. 2005. Distribution and floristics of desert plant communities in the lower reaches of Tarim River, southern Xinjiang, People's Republic of China. *Journal of Arid Environment* **63**: 772–784.

Zhou ZQ, Wei XX, Liu T. 2007. The numerical classification of desert vegetation and soil interpretation in Qitai County, Xinjiang. *Biodiversity Science* **15**: 264–270. (in Chinese with English Abstract).

Zhu Y, Ren L, Skaggs T, Lu H, Yu Z, Wu Y, Fang X. 2009. Simulation of *Populus euphratica* root uptake of groundwater in an arid woodland of the Ejina Basin, China. *Hydrological Processes* **23**: 2460–2469.

Zuo XA, Zhao XY, Zhao HL, Zhang TH, Guo YR, Li YQ, Huang YX. 2009. Spatial heterogeneity of soil properties and vegetation–soil relationships following vegetation restoration of mobile dunes in Horqin Sandy Land, Northern China. *Plant and Soil* **318**: 153–167.

