

Response of reed community to the environment gradient-water depth in the Yellow River Delta, China

Baoshan CUI (✉), Xinsheng ZHAO, Zhifeng YANG, Bin CHEN, Na TANG, Xuejie TAN

State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China

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Abstract We investigated and monitored a reed community in the fields. Data on the bio-ecological characteristics and β -diversity of reed communities in different environmental gradients (mainly based on water depth) of the Yellow River Delta were collected through multi-analysis, extremum analysis and β -diversity index analysis. In accordance with the square sum of deviations (Ward) cluster analysis, 10 sampling plots were divided into six types with the dominant plants in different plots varying according to the change in environmental gradients. The dominant plants in these plots varied from aquatic plants to xerophytes and salt tolerant plants as water depth decreased. The average height and diameter of the reeds at breast level were significantly correlated with the average water depth. The fitness curves of average density and coverage with average water depth were nonlinear. When the average water depth was 0.3 m, the average density and coverage of reeds reached the apex value, while the height and diameter of the reeds at breast level increased with the water depth. There were obvious changes to the environmental gradient in the Yellow River Delta. The transitional communities were also found to exist in the Yellow River Delta by β -diversity analysis. Vicarious species appeared with the change in water depth. The occurrence of substitute species is determined by the function of common species between adjacent belts. The different functions of common species led to differences in community structure and function and differences in dominant plants. The result reflects the variations of species present in different habitats and directly reflects environmental heterogeneity. The values of β -diversity indices of adjacent plots were higher than those of nonadjacent plots. There are transition zones between the xerophytes and aquatic plants in the Yellow River Delta. In an aquatic environment, the similarity of

reed community is higher than that of xeromorphic plants. The β -diversity index can reflect plant succession trends caused by the change in environmental gradients in the Yellow River Delta. The β -diversity index reveals plant responses to changes in environmental gradient and is helpful in observing changes in patterns of species diversity in relation to environmental gradient change and evolving trends in the future, which in turn plays a prominent role when environmental water requirements of wetland are discussed.

Keywords reed, β -diversity, environmental gradient, wetland, the Yellow River Delta

1 Introduction

With the development of research on the ecological water requirement of wetlands, discussions on their mechanisms are gradually developed (Cui et al., 2002, 2003, 2005; Li et al., 2004; Sun et al., 2004; Yang et al., 2003; Zhao et al., 2005; Zhao et al., 2005). The responses of wetland plants to environmental gradients, an important research direction, is the basis for determining minimum, suitable and ideal ecological water requirements, and for correctly deducing temporal and spatial changes in the ecological water requirement of wetland (Cui et al., 2003; 2005). Wetland plants, which exist in a watery environment, are influenced by such environmental factors as water gradient, flow conditions, water transparency, biological competition and nutrients (Chen et al., 2003; Duan et al., 2004; Xu et al., 2003; Xu et al., 2004; Zhao et al., 2003; Middleton, 1990; Keedy and Constabel, 1986; Bart and Hartman, 2000; Bodensteiner and Gabriel, 2003). Wetland plants' spatial distribution is somewhat related to the differences in their response to water (Middleton, 1990; Keedy and Constabel, 1986; Bart and Hartman, 2000; Bodensteiner and Gabriel, 2003; Jiang et al., 2003; Kurt and Richard, 2005; Meyerson et al., 2000).

At present, research on the response of wetland plants to environmental gradients has been specific to such plants as *Phragmites communis*, *Vetiveria zizanioides*, *Sagittaria wuyiensis*, *Sagittaria potamogetifolia* and *Scirpus triqueter* L. As to the response of the reed to environmental gradient, researchers focused on photosynthesis, water treatment, biomass, ecotype, physiological and biochemical characteristics and ecological service function, while less attention was paid to community characteristics and β -diversity (Chen et al., 2003; Duan et al., 2004; Xu et al., 2003; Xu et al., 2004; Zhao et al., 2003; Middleton, 1990; Keedy and Constabel, 1986; Bart and Hartman, 2000; Bodensteiner and Gabriel, 2003; Jiang et al., 2003; Kurt and Richard, 2005; Meyerson et al., 2000; Nedeau and Merritt, 2003; Wu et al., 1994; Yang and Li, 2003; Zhang et al., 2003; Zhu et al., 2003; Chen et al., 1999; Wang et al., 1999; Jing et al., 2001).

Phragmites communis, an important wetland plant, is the constructive species of most wetland plants communities. The reed community, spreading broadly over the Yellow River Delta, is the direct beneficiary of ecological restoration engineering for the wetland (Zhao et al., 2005; Wu et al., 1994; Xi et al., 2002; Liu et al., 2001). Research on the response of a reed community to the environmental gradient of water depth has become the springboard on which to conduct ecological water replenishing engineering (Yang et al., 2004; Zhao et al., 2005). To specify the reed community, we analyzed the bio-ecological characteristics and β -diversity of a reed community in different environmental gradients of water depth by using multivariable statistics, function extreme analysis, and β -diversity index analysis. The results are expected to provide the scientific basis for defining the ecological water requirement range of reed wetland, revealing the mechanism behind the ecological water requirements of wetland, and enabling the technical conduct of wetland restoration engineering, management of reed production, and maximization of productive benefits.

2 Experiment design and method

2.1 Survey of study area

The study area (37°35'–38°12' N, 118°33'–119°20' E) is located in the Yellow River Delta Natural Reserve, situated at the entrance of the Yellow River to the Bohai Sea, in Shandong Province, China (Fig. 1). This natural reserve is home to a protected wetland ecosystem and rare and endangered waterfowl, and is characterized by a temperate, continental monsoon climate, distinct seasons, and contemporary rain and heat. The annual average air temperature is 12.1°C, with 196 frostless days,

and annual average rainfall and evaporation are 551.6 mm and 1962 mm, respectively. The total area of the Yellow River Delta is 153000 ha.

Wetland-covered secular water, including river, lake, estuary, pond, reservoir, aqueduct, saline, shrimp or crab pond and shoal, takes 63.06% of the total areas, while wetland-covered seasonal water, embracing tideland, reed swamp, other swamps, sparse wetland, shrub wetland, meadow and paddy land, occupies the remaining areas. Compared to other estuaries, the Yellow River Delta wetland is a newly formed and fragile ecosystem with low resistance to environmental disturbance and vulnerable to loss balance, as well as an important transferring station for migrating birds.

2.2 Sampling strategy

The study areas are located in the region governed by Dawenliu Management Station of the Yellow River Delta in Shandong province, China (Fig. 1). When selecting sampling regions, we considered different environmental gradients, dominant species, geomorphic characteristics and the broadness of spatial distribution to allow the sampling scheme to take into account real conditions. In accordance with long-term observation of water depth, the sampling regions were divided into 10 gradient ranges (10 groups), that is, > 1.5 m, 1.0–1.5 m, 0.9–1.0 m, 0.6–0.8 m, 0.4–0.7 m, 0.2–0.4 m, 0–0.3 m, –0.2–0 m, –0.6––0.2 m and < –0.6 m. A big quadrat, situated in the representative location of each group, was set up in each group. Ten smaller quadrats were then set up randomly within this big quadrat (the area was standardized when the number of species remained steady). Finally, 500 data units were obtained by sampling 5 times in all of the small quadrats. Each quadrat is labeled in detail in the location map (Fig. 1).

The study region was chosen because it had sustained reed growth over many years, since the research objective was to study a relatively permanent reed community.

2.3 Monitored variables and data processing

Monitored variables consisted of vegetation composition, types and quantities of plants, water depth of reed habitation, ecological characteristics, height above water surface, cover and density, etc. The cover and density of reed were estimated, which did not influence the findings. The monitoring period was January 2004–December 2005. Monthly changes in water depth were recorded by the Odyssey water level recording system developed in New Zealand. The annual average values of water depth were analyzed.

Arcview v3.3 and CorelDraw X3 were used to process schematic diagrams and create graphs of sampling points. Microsoft Excel v2003 (fitting curves and statistics description), SYSTAT v11 (cluster analysis of

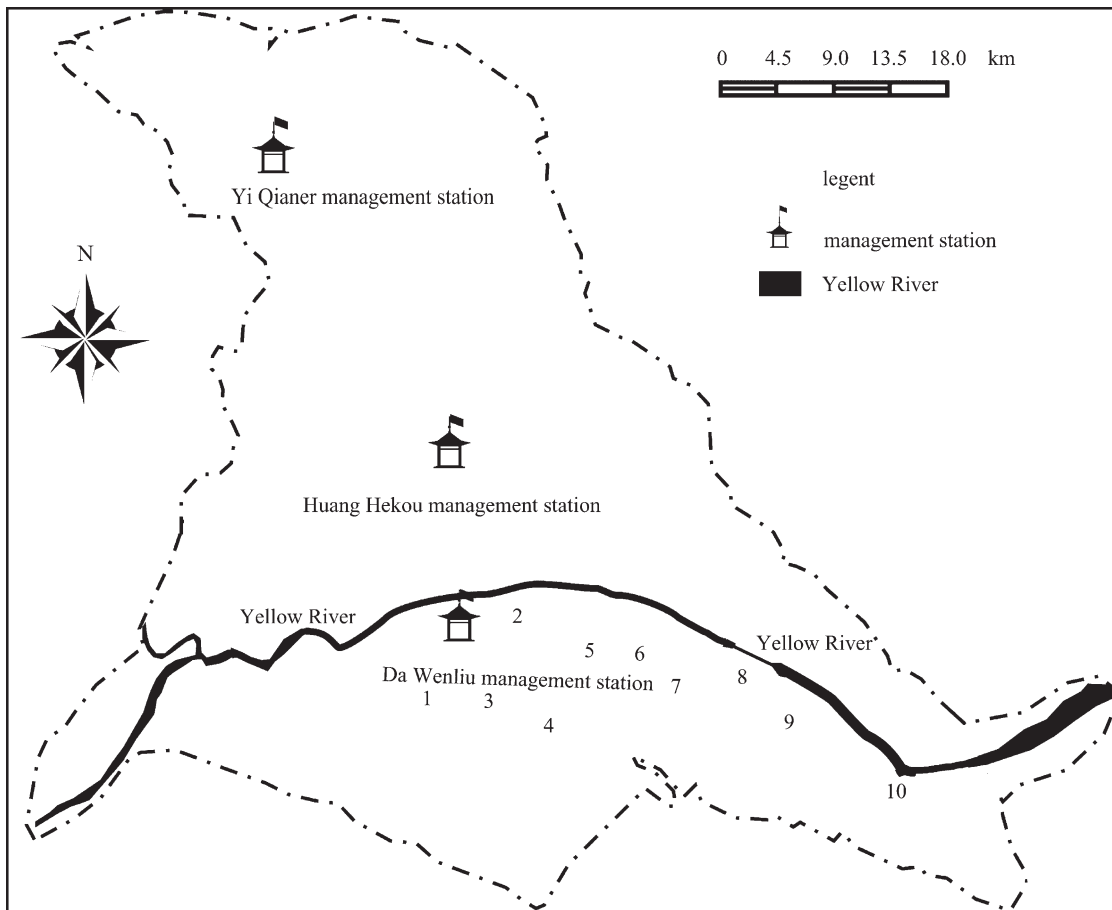


Fig. 1 Study area and experiment sites

deviation square) and Z-BioD v1.0 (calculation of β -diversity) were used for data input and statistical analysis.

2.4 Statistical analysis

Environmental gradient is defined as the variability of environmental conditions in relation to spatial changes. It is influenced by factors such as slope gradient, slope aspect, slope height, water, human disturbance and terrain, etc. The environmental gradients of the Yellow River Delta were mainly produced by water conditions, water depth and salinity. For the reed community in the ecological restoration engineering, water conditions were the main environmental factors, and water depth was the key factor that determined the distribution and characteristics of the reed community. Therefore, considering the inundation conditions, we chose regions with fresh water or little variability of salinity changes as our sampling objects, and the water depth was the main parameter of environmental gradient. Afterwards, the influence of changes in water depth on the characteristics of the reed community was discussed. (Defining soil surface as the benchmark, water depth is used above soil

surface and buried depth is used beneath soil surface, but in this paper, both were called water surface).

3 Results and discussion

3.1 Ecological characteristics of reed community in different environmental gradients

3.1.1 Structures of reed community in different environmental gradients

The ecological characteristics of the reed community refer to its phenomenal characteristics of reed community (plant height, stem diameter) and community composition. Five hundred units of data were collected with their statistical description listed in Table 1. Data from the 10 sample plots was processed by cluster analysis of deviation square, and the results are shown in Figure 2. Square Euclidean distance was used to calculate distances between samples in the method of deviation square, which tends to cluster samples with small quantity and finds classes that are approximate in size and shape. Like the group average linkage method, deviation square is a

Table 1 The statistical description of reed community in different sampling sites

No.	parameters					
	height/m	density/m ²	coverage%	diameter/cm	species sum	water depth
1	1.06 ± 0.02	< 1	< 1	1.00 ± 0.02	93	< -0.6
2	1.50 ± 0.01	4 ± 1	5	1.01 ± 0.01	89	-0.6--0.2
3	2.00 ± 0.01	89 ± 7	60	0.40 ± 0.01	90	-0.2-0
4	1.98 ± 0.04	344 ± 21	98	0.38 ± 0.01	41	0-0.3
5	2.17 ± 0.04	302 ± 12	95	0.35 ± 0.01	39	0.2-0.4
6	2.37 ± 0.02	177 ± 5	75	0.45 ± 0.01	33	0.4-0.7
7	2.59 ± 0.02	67 ± 3	55	0.50 ± 0.01	19	0.6-0.8
8	2.60 ± 0.04	16 ± 1	20	0.67 ± 0.02	15	0.9-1.0
9	2.70 ± 0.01	10 ± 2	8	0.82 ± 0.01	13	1.0-1.5
10	2.70 ± 0.02	< 1	1	0.87 ± 0.01	6	> 1.5

Note: 1): The serial numbers of sampling sites were different from those in the table; the values similar to "2.70 ± 0.02" were denoted as "average value ± error".

good clustering method for classification and was therefore used widely in ecology. According to the distance index (distance = 1.3206) determined by the clustering analysis of deviation square, the No.1 sample plot was classified under w1, the No.2 and 3 sample plots were classified under w2, the No.9 and 10 sample plots were classified under w6, the No.6 and 7 plots were classified under w4, the No.4 and 5 plots under w3 and the No.8 was classified to w5. The characteristics of the reed community after classification are listed in Table 2.

As shown in Table 2, aquatic plants dominate the entire community, provided that the lowest water depth within one year was above 0 m. Below 0 m, xerophytes, mainly saline-alkali proofing plants and halophytes, gradually occupied the dominant position. When the lowest water depth in one year was above 1 m, aquatic plants were still the dominant species, consisting mainly of *Myriophyllum spicatum*, *Potamogeton crispus*, and

Hydrilia vertillata (L.f.) Royle. Moreover, unique populations dotted with a single reed plant were found in the study area. In the habitat with the water depth fluctuating in the range of 0.9–1.0 m, aquatic plants gained ascendance in the community. The dominant species were *Myriophyllum spicatum*, *Ceratophyllum submersum* and *Phragmites communis*, while the accompanying species were *Polygonum hydropiper* and *Lepiironia articulate* (Retz) Domin, etc. In the habitat with the water depth fluctuating at a range of 0.4–0.8 m, aquatic plants gained a stronghold in the community, with the dominant species being *Lepiironia articulate* (Retz) Domin and *Phragmites communis*, and the accompanying species *Myriophyllum spicatum*, *Hydrilia vertillata* (L.f.) Royle and *Ceratophyllum submersum*, etc. In the habitat with the water depth fluctuating in the range of 0–0.4 m, aquatic plants proliferated in the community, with the dominant species *Phragmites communis* and the accompanying species *Polygonum hydropiper*, *Lepiironia articulate* (Retz) Domin, *Glycine sojasieb* and *Imperata cylindrica* var. major, etc. In the habitat with the water depth fluctuating in the range of -0.6–0 m, xerophytes flourished in the community, with the dominant species being *Phragmites communis*, *Tamarix chinensis* Lour, and *Polygonum lapathifolium* Linn, each of which formed its community based on natural spreading in the local area, while the accompanying species were *Cynanchum sibiricum* Willd, *Polygonum lapathifolium* Linn, *Setaria viridis*, *Setaria glauca* (L.) Beauv, *Herba Artemisiae Annuae*, *Glycine sojasieb* and *Imperata cylindrica* var. major, etc. In the habitat with the water depth fluctuating in the range of under -0.6 m, xerophytes gained ascendance in the community, and the dominant species were *Tamarix chinensis* Lour, *Suaeda heteroptera*, and *Suaeda glauca* Bge, each of which formed its community based on natural spreading in the local area, while the accompanying species were *Phragmites communis*, *Cynanchum sibiricum* Willd, *Setaria viridis*, *Herba Artemisiae Annuae* and *Glycine sojasieb*, etc.

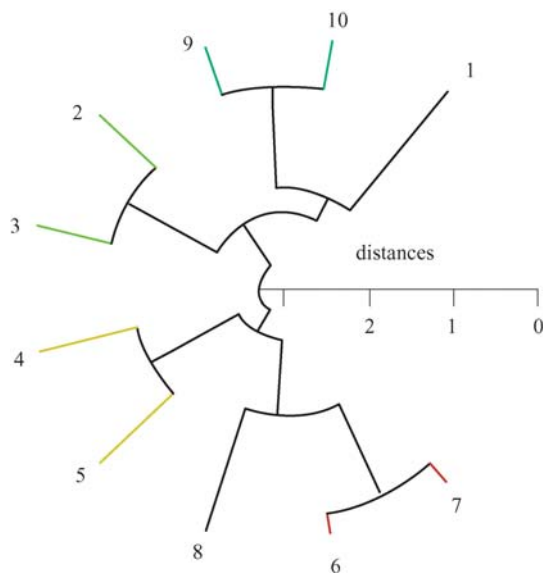


Fig. 2 The result of square sum of deviations (ward) cluster analysis

Table 2 The reed biological characters on different water depth after square sum of deviations (Ward) cluster analysis¹⁾

No.	parameters (average value)				water depth/m	main dominant species
	height/m	density/m ²	coverage/%	diameter/cm		
W1	1.06 ± 0.02	< 1	< 1	1.00 ± 0.02	< -0.6	<i>Tamarix chinensis</i> Lour, <i>Suaeda heteroptera</i> , <i>Suaeda glauca</i> Bge
W2	2.00 ± 0.10	89 ± 7	60	0.4 0 ± 0.01	-0.6-0	<i>Phragmites communis</i> , Chinese <i>Tamarisk</i> , <i>Polygonum lapathifolium</i> Linn
W3	2.17 ± 0.04	336 ± 12	95	0.35 ± 0.01	0-0.4	<i>Phragmites communis</i>
W4	2.59 ± 0.02	67 ± 3	55	0.50 ± 0.01	0.4-0.8	<i>Lepiironia articulata</i> (Retz) Domin, <i>Phragmites communis</i>
W5	2.60 ± 0.04	16 ± 1	20	0.67 ± 0.02	0.9-1.0	<i>Myriophyllum spicatum</i> Linn, <i>Ceratophyllum submersum</i> , <i>Phragmites communis</i>
W6	2.70 ± 0.01	10 ± 2	8	0.82 ± 0.01	> 1.0	<i>Myriophyllum spicatum</i> Linn, <i>Potamogeton crispus</i> , <i>Hydrilia vertillata</i> (L.f.) Royle

Note: see Table 1

3.1.2 Change of the ecological characteristics of the reed with different environmental gradients

With the increase in the annual average water depth, the average plant height and the diameter at breast level of the reed both indicated an upward trend. The R^2 of the reed height-water depth curve and that of the diameter at breast level-water depth curve are 0.7048 and 0.6664, respectively. This indicated that there was a significant correlation between average reed height, diameter at breast level and water depth (Fig. 3). Figures 4 and 5, meanwhile, showed that there was a non-linear correlation between the average reed density, the average coverage and the water depth, which means that too low or too high water depth was the restrictive factor affecting the reed growth. The increase of the reed diameter at breast level was conducive to the growth of the reed in water and prevented it from being broken off. At the annual average water depth of 0.3 m, both the average reed density and the coverage clearly peaked (Figure 4 and 5) while at the same time gradually decreasing along the two sides of the peak, which possibly also indicates that too low or high

water depth limits reed growth. Near the water depth of 0.3 m, the density of the reed community also gradually decreased with the change in the water depth. This may have been caused by a natural thinning (a compensation for the reed height and the radial growth, which can also increase the biomass of the low-water reed community). However, it was not enough to affect the trend that biomass increased with the rise in water depth. The increase in reed diameter at breast level was the main reason for the smaller biomass change, which was beneficial to the growth of the reed in the water. The fact that the reed height increased with the rise in water depth can be attributed to the fact that the reed, as a large-scale emerging plant, needs to emerge out of the water surface in order to obtain CO₂ and light exposure for photosynthesis, and also to transmit O₂ to its root system for transpiration and oxidation of the root. Reeds living in deeper water which had to compete for less resources usually develop a much greater height (Duan et al., 2004). The reed begins to germinate in spring and lives in lower-water habitats. Large-scale change in the water depth is deleterious to the growth of the reed. Extreme

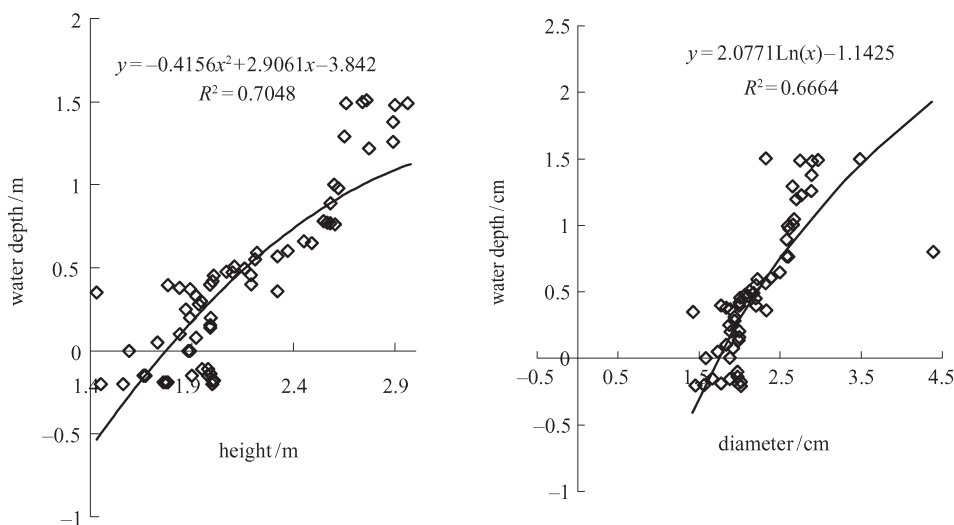


Fig. 3 The linear fit curves of reed height, diameter at breast height and water depth in reed meadow

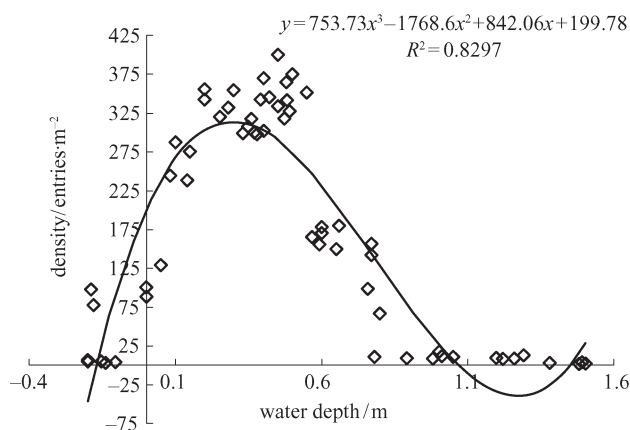


Fig. 4 The non-linear fit curve of reed density and water depth in reed meadow

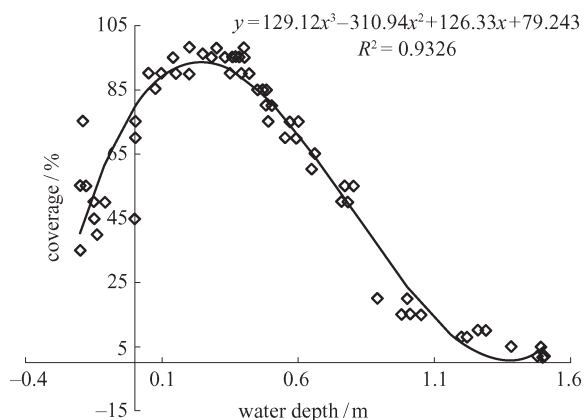


Fig. 5 The non-linear fit curve of reed coverage and water depth in reed meadow

water conditions (too low or too high water depth) have restricted the physiological and ecological characteristics of the reed to a certain degree, and at the same time, they have caused an adjustment in the plant’s morphological features, which is proven by the increase in the diameter at breast level with the rise in water depth.

In a condition with proper water depth, the water is no longer the restrictive factor. The demands of the reed’s metabolism for water would have already been satisfied by the reed’s root system and the horizontal rhizome, thus the reed community thrives and grows well. The “hydraulic lift” action of the reed’s vertical rhizome changes with the depth of groundwater, and with the increase in depth of groundwater, this correlation between “hydraulic lift” and groundwater depth declines. This indicates that the space distribution of wetland vegetations is related to its different responses to the changes of water depth (Chen et al., 2003; Xu et al., 2003; Xu et al., 2004; Zhao et al., 2003; Zhu et al., 2003). The underground environmental gradient also has a great effect on the vegetation’s ecological characteristics (Xu et al., 2003; Xu et al., 2004; Zhao et al., 2003), especially

the effect of groundwater depth which can also be proved by the fact that the ecological characteristics of the single reed vary greatly.

3.2 Change in the β -diversity of reed communities along different environmental gradients according to the sum of deviations (Ward) cluster analysis

β -diversity means the diversity of species formation among communities in different habitats, or the plant succession rate according to the environmental gradient. It also reflects the change in the constitution of the species along an environmental gradient or a series of habitats that is called “between-habitat diversity”. The dominant ecological factors controlling β -diversity are water, soil, geomorphic features, disturbance and others (Wang et al., 1997; Koleff and Gaston, 2001; Loreau, 2000; Patricia et al., 2003; Wilson and Shmida, 1984).

We used the Sorensen and Cody indices to measure β -diversity. The Sorensen index reflects the similarity of the species between different communities and plots. The similarity is usually seen through the differences in species composition among communities caused by the environmental gradients (Loreau, 2000; Patricia et al., 2003; Wilson and Shmida, 1984). Less similarity in species composition in different types of habitat is reflected in a smaller β -diversity indices in the research field. The Cody index, however, reflects the succession rates of the species in the samples along the environmental gradients. The measurement of β -diversity of different environmental gradients can also indicate the degree of segmentation of the habitats (separated by the species), habitat diversity in different locations, species turnover and replacement rate and the rate of biotic change (Koleff and Gaston, 2001). In addition, β -diversity can directly reflect the discrepancy in species composition in different sample strips (Koleff and Gaston, 2001; Loreau, 2000; Patricia et al., 2003; Wilson and Shmida, 1984).

When introducing the environmental gradient variable into our research on β -diversity, we can conclude that the study on the scale is also one of the most important issues. Hence, we used the Sorensen and Cody indices as the quantity indices and analyzed the β -diversity in detail according to the different environmental gradients in the research field.

We used the six integrated results from the cluster analysis to calculate the Sorensen index, and the formula is as follows:

$$Si = \frac{2c}{a+b} \tag{1}$$

Where the a, b in the equation represent the total numbers of the species in the two communities, respectively; c represents the number of species shared by both communities;

The calculation of the Cody index is as follows:

$$\beta_c = \frac{a+b-2c}{2} \tag{2}$$

where the meanings of the references *a*, *b* and *c* are the same as those of the equation (1).

Table 3 showed that the Sorensen diversity indices of all the adjacent plots were greater than those of the non-adjacent plots. Because of geographical segregation and the obvious change in the environmental gradients, the species of vegetation in each sample field had distinctly changed. The Sorensen index of the similarity of the reed communities between the sample w1 and w5 and between sample w1 and w6 were both equal to zero. The Sorensen index between sample w2 and w6 was also zero. This indicated that the longer the distance between the samples was, the nearer the β -diversity index was to zero while at the same time implying that there exists great differences in the species composition in each sample field sharing fewer common species. That the degree of the similarity was comparatively lower reflected the prominence of the heterogeneity of the vegetation habitats according to different environmental gradients.

Table 3 The species similarity indexes (Sorensen) of reed habitats on different environment gradients

No.	w1	w2	w3	w4	w5	w6
w1	1.00	–	–	–	–	–
w2	0.69	1.00	–	–	–	–
w3	0.43	0.74	1.00	–	–	–
w4	0.16	0.24	0.72	1.00	–	–
w5	0.00	0.07	0.18	0.35	1.00	–
w6	0.00	0.00	0.10	0.13	0.50	1.00

There is a distinct change in environmental gradient in the Yellow River Delta: with the increase in water depth, there appears an obvious succession relationship caused by the mutual species action in different sample strips. The distinctive action of the mutual species leads to a discrepancy in the structure, function and dominant species of different communities. In this study, the maximum Sorensen index of the adjacent plots appeared between the sample w2 and w3, and the indices between the sample w1 and w4 changed little, which indicated that the structures of the communities were similar. The smallest Sorensen index appeared between sample w4 and w5 which implied that these two plots were the regions where the reed communities changed significantly. The result of the field research (Table 2) shows that the sample field w4 and w5 were the transition zones between the xerophytes and aquatic plants. Figure 6 shows that the Cody index (Table 4) reduced gradually with the increase in water depth, while the Cody index fluctuated between sample field w4 and w5. This indicated that the region of these plots served as the transition zones between the

xerophytes and aquatic plants (the Sorensen index can also prove this). Moreover, these regions significantly differed from their adjacent regions (Table 2). The difference was caused by the change in water depth and the disturbance of the salient change caused by the water content (Wu et al., 1994; Yang and Li, 2003; Zhang et al., 2003). The smaller the Cody index is, the more similar the different communities are. However, the further the distance between plots, the greater the Cody index and the differences between communities (Wilson and Shmida, 1984). As shown in Fig. 6, we discovered that the similarity between the communities of aquatic plants was greater, while that of the xerophytes was smaller. This was relative to fewer species adapting to deepwater depth compared with those living in the xeric environment (Table 2).

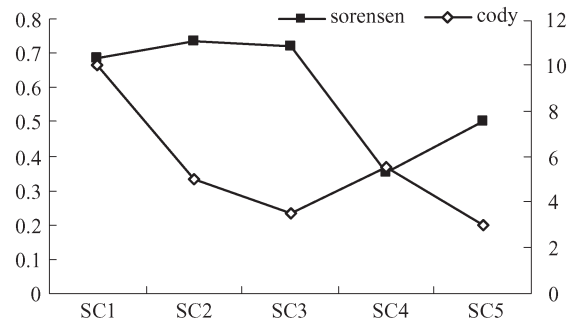


Fig. 6 The change of Sorensen index and Cody index with the environmental gradient of water depth. Note: SC1 denotes calculating of index between sampling plots w1 and w2, others are the same

Table 4 The replacement rates (cody) of reed habitats on different environmental gradients

No.	w1	w2	w3	w4	w5	w6
w1	1.00	–	–	–	–	–
w2	10.00	1.00	–	–	–	–
w3	16.00	5.00	1.00	–	–	–
w4	21.50	12.50	3.50	1.00	–	–
w5	24.00	14.00	9.00	5.50	1.00	–
w6	23.00	14.00	9.00	6.50	3.00	1.00

4 Conclusions

(1) According to the square sum of deviations (Ward) cluster analysis, we divided 10 sampling plots into 6 types, i.e., sample 1 was singly separated as one type, sample 2 and 3 as another, then sample 9 and 10, sample 6 and 7, sample 4 and 5, then sample 8. With the change in the water depth, the dominant plants in different plots also changed in relation to the xerophytes such as salt-tolerant plants changing to aquatic plants.

(2) The average height and diameter at breast level of reeds were significantly correlated to average water depth. The fitness curves of reed average density and

coverage with average water depth were nonlinear. When the average water depth was 0.3 m, the average density and coverage of reeds reached apex values, while the height and diameter at breast level increased along with the increase in water depth.

(3) There were clear changes of environmental gradients in the Yellow River Delta. With the increase in water depth, a distinct succession trend was observed that was determined by the action of common species between adjacent belts. The different actions of common species led to the difference in community structure, function and variations in the type of dominant plants. The values of β -diversity indices of adjacent plots were higher than those of distant plots. There was a transition zone between xerophytes and aquatic plants in the Yellow River Delta. In an aquatic environment, the homogeneity of the reed community was higher than that of xenomorphic plants.

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