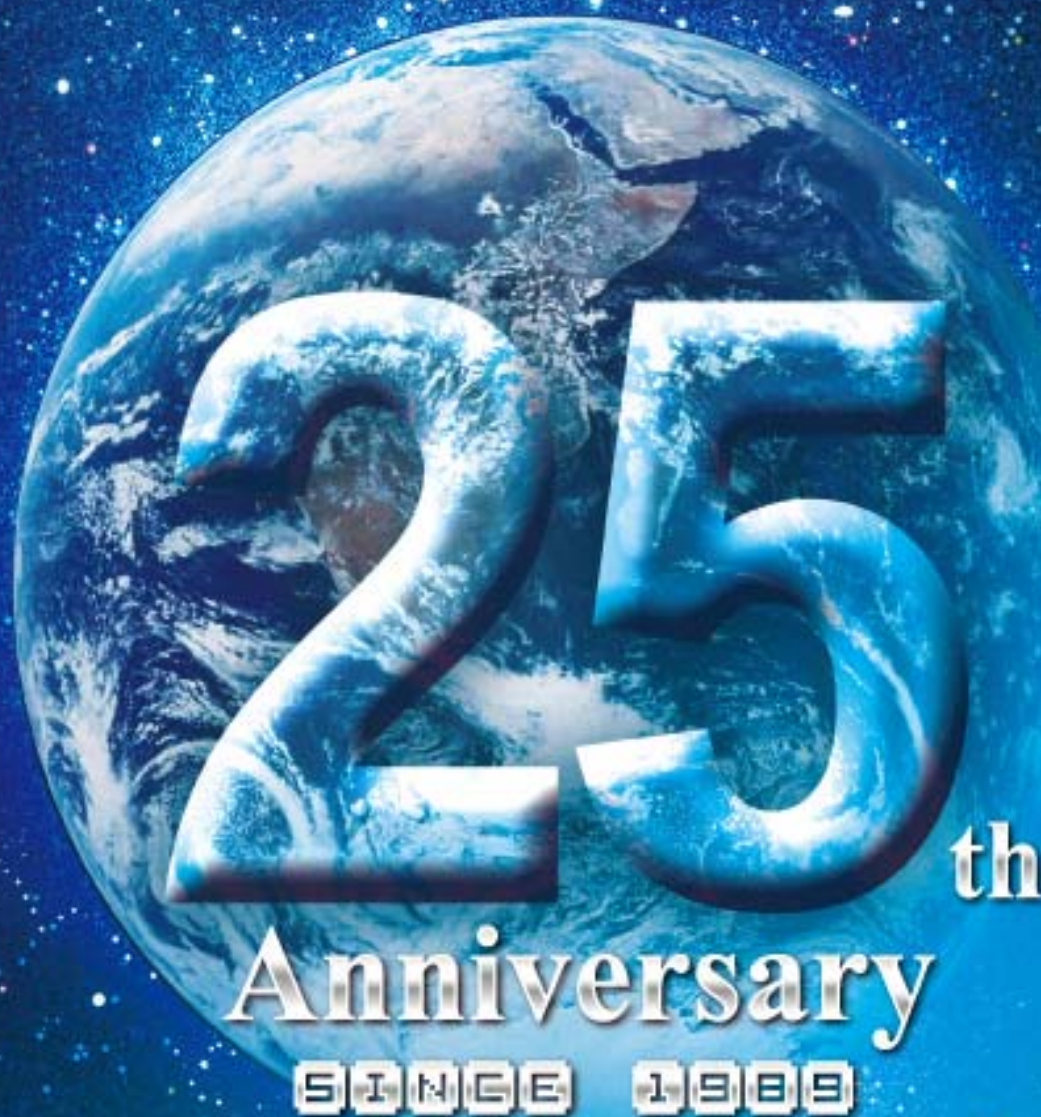


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Growth and nutrient accumulation of *Phragmites australis* in relation to water level variation and nutrient loadings in a shallow lake

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Abstract

Shallow lake eutrophication is a global environmental issue. This study investigated the effects of water level variation and nutrient loadings on the growth and nutrient accumulation of *Phragmites australis* (reed) by field samplings in Baiyangdian Lake, the largest shallow lake of northern China. The field samplings were conducted in two sites of different nutrient loadings during the whole growth period of reeds, and three types of zones with different water depths were chosen for each site, including the terrestrial zone with water level below the ground, the ecotone zone with the water level varying from belowground to aboveground, and the submerged zone with water level above the ground. The result showed that reed growth was more limited by water level variation than nutrient loadings. The average stem lengths and diameters in terrestrial zones were about 26.3%–27.5% and 7.2%–12.0% higher than those in submerged zones, respectively. Similarly, the terrestrial status increased the aboveground biomass of reeds by 36.6%–51.8% compared with the submerged status. Both the nutrient concentrations and storages in the aboveground reeds were mainly influenced by the nutrient loadings in surface water and sediment rather than the water level variation of the reed growth environment, and the nutrient storages reached their maxima in late August or early September. It was observed that the maximum nitrogen storage occurred in the terrestrial zone with higher nutrient loadings, with the value of 74.5 g/m². This study suggested that water level variation and nutrient loadings should be considered when using reeds to control and remediate eutrophication of shallow lakes.

Key words: water level variation; nutrient loadings; *Phragmites australis*; reed growth; nutrient accumulation

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Introduction

Eutrophication is a global environmental issue. Nowadays, it has been recognized as the most common and severe environmental hazard in lake ecosystems (Smith and Schindler, 2009). In shallow lakes, the eutrophication is often most serious, which is heavily influenced by large external nutrient loads, frequent sediment resuspension and resultant high turbidity, nutrient exchange of the highly active sediment-water column and nutrient regeneration (Xia et al., 2004, 2009; Schindler et al., 2008; Zhang et al., 2010). In addition, their eutrophication processes are particularly complicated due to strong lake-land, air-water and water-sediment interactions (Qin et al., 2007).

Reed is a cosmopolitan emergent macrophyte species occurring in a wide range of shallow lakes. It is characterized by a high growth rate and great capacity for nutrient accumulation in its stems, roots, and rhizomes (Asaeda et al., 2002; Baldaton et al., 2003; Tian et al., 2009). Thus,

it has been widely investigated as a potential remediation plant for its functions of nutrient accumulation to remove nutrients from point and non-point pollution sources (Brix and Schierup, 1989; Kiedrzyńska et al., 2008). Hydrology is considered to be the most influential factor determining the structures and functions of wetlands (Mitsch and Gosselink, 2007). With respect to the water regime, three types of reed stands were distinguished. The first is the water-submerged stand with the water level above the ground. The second is the aquatic-terrestrial ecotone stand with the water level varying from belowground to aboveground. The third is the terrestrial stand with the water level below the ground. These stands exhibit significant differences in primary productivity parameters, composition and depth of the soil layer, and nutrient cycling (Gaberšček et al., 2000; Urbanc-Berčič and Gaberšček, 2001; Vanesa et al., 2011). Thus, reed growth may be influenced by water level variation.

In addition, in constructed wetlands, when the nutrient loadings are higher, the macrophytes may retain more nutrients (Coveney et al., 2002; Meuleman et al., 2003),

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and the denitrification process may remove more nitrogen from soil or sediment, compared with environments having lower nutrient loadings. On this basis, it is speculated that similar effects could occur in shallow lakes. Therefore, when considering reeds as remediation plants in eutrophic shallow lakes, the effects of water level variation and nutrient loadings on reeds should be emphasized. However, their effects have rarely been studied and are still not well understood.

In China, there are more than 2700 lakes, with a total area of 91,000 km², and one third of them are shallow lakes. In recent decades, most of the shallow lakes have been confronted with the threat of eutrophication. World-wide experience on eutrophication of shallow lakes shows that after controlling external nutrition inputs, the internal loadings release and ecological remediation should be carried out at the same time (Qin et al., 2004). Thus, understanding the characteristics of reed growth and its nutrient accumulation in shallow lakes are of significance in the control of lake eutrophication with reeds.

In this study, we investigated the effects of water level variation and nutrient loadings on the growth and nutrient accumulation of reed in a shallow lake. Baiyangdian Lake, which is the largest lake in the North China Plain and where the reed is a dominant emergent plant, was chosen as a model shallow lake. Specifically, the objectives of this study were to: (1) analyze the seasonal variations of reed growth and its nutrient accumulation; (2) examine the effects of water level variation and the nutrient loadings in surface water and sediment on the reed growth; (3) explore the effects of water level variation and nutrient loadings in the environment on the nutrient uptake of reed tissues; (4) propose the most favorable growth environment of reed for its largest aboveground nutrient storage and offer remediation suggestions for controlling lake eutrophication.

1 Materials and method

1.1 Description of study site

Baiyangdian Lake (38°43'N–39°02'N, 115°45'E–116°07'E) is the largest shallow fresh water lake in northern China (Fig. 1), and plays an important role in providing habitats for native plant and animal species, in water supply, in regional climate regulation and in flood control. The lake consists of 143 lakes that are linked together by thousands of ditches, covering a total area of 366 km² within a catchment of 31,200 km² (Guo et al., 2011). In the lake, waterbody, water-land ecotone and terrestrial zones account for about 50%, 36% and 14% of the lake area, respectively. Most parts of the lake are less than two meters in depth, and the monthly variation of average water depth in the lake ranges between 0.05 and 0.30 m (Zhao et al., 2011). Baiyangdian Lake is also a famous natural wetland with high ecological, fishing and tourist value. It includes 39 types of aquatic plants,

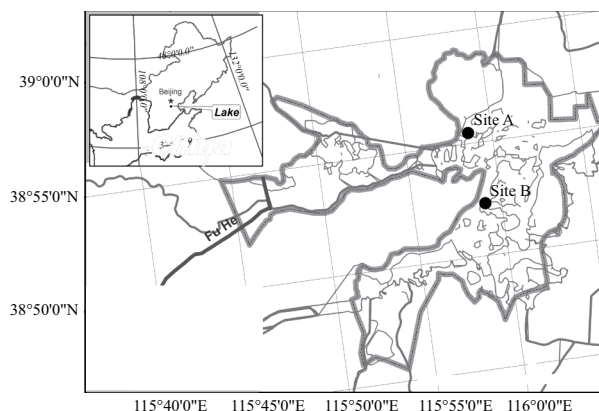


Fig. 1 Location of Baiyangdian Lake and the sampling sites A and B.

and reed is a dominant emergent wetland species. In Baiyangdian Lake, the buds of reeds begin to emerge in April, and then the stems grow rapidly. After that, the reeds senesce and are traditionally harvested at the end of October.

In recent decades, the lake has endured serious pollution as a result of increasing pressures from population expansion and economic development. Eutrophication has been considered as the major problem of Baiyangdian Lake. From 2000 to 2009, monthly averaged total nitrogen (TN) concentrations in the lake varied from 2.56 to 5.6 mg/L, and monthly averaged total phosphorus (TP) concentrations were from 0.08 to 0.61 mg/L (Zhao et al., 2011). They were much higher than the standard levels (1.0 mg/L for TN and 0.05 mg/L for TP) for Grade III of the Chinese water quality grade scale, in which Grade I is the best and Grade V is the worst (SEPA, 2002). Thus, it is imperative to control water pollution and manage water resources for the lake.

1.2 Field sampling

The field sampling was carried out once a month from June 2010 to December 2010 to study the seasonal variation of reed biomass, stem length, stem diameter and nutrient concentrations of reeds. The field sampling was conducted at two sites with different nutrient loadings in surface water and sediment of Baiyangdian Lake (Fig. 1). Site A was located in the northern part of the lake with worse water quality, where the Fuhe River flows into Baiyangdian Lake. Fuhe River, a major pollution source for the lake, receives almost all the domestic sewage and some industrial wastewater from the nearby Baoding City. In Site A, three reed stands with different water levels were chosen according to the different growth environment of reeds, including the terrestrial zone, the water-land ecotone zone and the submerged zone. During the sampling period, the water depth of terrestrial zone, ecotone zone and the submerged zone was -0.30 ± 0.10 , 0.05 ± 0.10 and 0.35 ± 0.10 m, respectively. The reeds acclimatize to grow in a wide range of water depths, which varies from -0.6 to about 1.0 m (Liu, 2009). Therefore, when the water depth

was lower than -0.6 m or higher than 1 m, reed growth was inhibited. In this research, the water depths of the two sites were suitable for reed growth. Site B was located in the central part of the lake, and the water quality was much better than in Site A. In Site B, only terrestrial zone and submerged zone were chosen and sampled for comparing the characteristics of reed growth and nutrient accumulations with those in Site A.

Reeds, surface water of the growth environment and sediment around the reed rhizomes (15 – 20 cm) were collected from $1\text{ m} \times 1\text{ m}$ quadrants, conducted in triplicate. In each 1 m^2 quadrant, there were 100 – 120 reeds, and five reeds with the same stem length as the average length of the sampling zone were sampled. The aboveground biomass (stems and leaves) were harvested at the ground level, and the belowground biomass (roots and rhizome) were collected from a depth of 20 cm. The reed rhizomes extend to a depth of 0 – 80 cm below the ground, but their biomass decreases with increasing soil depth. In Baiyangdian Lake, the reed rhizomes mainly exist at the depth of 0 – 20 cm under the ground, and their biomass accounts for 60% of the total biomass (0 – 80 cm) (Liu et al., 2004). Surface water and sediment (or soil) samples were collected simultaneously from each quadrant. All the samples were hermetically sealed and stored in a cooling box, then transported to the laboratory and kept at 4°C for later analysis.

1.3 Nutrient analysis

Surface water samples were analyzed for TN, TP, ammonium nitrogen ($\text{NH}_4^+\text{-N}$), nitrite ($\text{NO}_2^-\text{-N}$), nitrate ($\text{NO}_3^-\text{-N}$), and phosphate ($\text{PO}_4^{3-}\text{-P}$) according to standard methods recommended by the State Environmental Protection Administration of China (SEPA, 2002). The water samples were filtered through a $0.45\text{ }\mu\text{m}$ filter before nutrient analysis. The Nesslerization colorimetric method was used for $\text{NH}_4^+\text{-N}$ analysis. $\text{NO}_2^-\text{-N}$ was determined by colorimetry through the formation of a reddish-purple produced at pH 2.0 to 2.5 by coupling diazotized sulfanilamide with N -(1-naphthyl)-ethylenediamine. $\text{NO}_3^-\text{-N}$ was determined by the phenol disulfonic acid ultraviolet spectrophotometric method. $\text{PO}_4^{3-}\text{-P}$ was determined by the Mo-Sb-Vc spectrophotometric method. Before TN and TP analysis, water samples were digested with basic potassium peroxydisulfate ($\text{K}_2\text{S}_2\text{O}_8$). Then, TN in the digested solution was determined by ultra-spectrophotometry. TP in the digested solution was determined with the same method as that for PO_4^{3-} analysis.

The reed samples were washed thoroughly with tap water and cleaned with deionized water, then dried at 70°C for 48 hr to measure the biomass dry weight. The dry plant samples were ground to a powder with a mechanical grinder. For TN and TP analysis, a total of 0.100 – 0.200 g reed sample was added in a digestion flask and digested with $5\text{ mL H}_2\text{SO}_4$ (98% , V/V) and $2\text{ mL H}_2\text{O}_2$ (30% , V/V)

on a heating block until the digestion solution turned clear. After the digested solution cooled to room temperature, it was diluted to a final volume of 100 mL with deionized water. After homogenizing the samples, the supernatant was analyzed by using the Nesslerization colorimetric and Mo-Sb-Vc spectrophotometric methods as mentioned above for TN and TP concentrations, respectively.

The sediment (or soil) samples were divided into two fractions. A part of each sample was dried at 105°C for 24 hr, and ground to powder with a mechanical grinder to facilitate total nutrient analysis. For TN content analysis, 2 g catalyst and $5\text{ mL H}_2\text{SO}_4$ (98% , V/V) were added to 1.000 g sample. The solution was heated for 30 min at 150°C followed by 2 hr at 380°C . When the sample was clear and green, TN in the digested solution was measured by semimicro-Kjeldahl determination. For TP content analysis, 0.500 – 1.000 g sample was digested with $8\text{ mL H}_2\text{SO}_4$ (98% , V/V) and 1 mL HClO_4 (70% , V/V) on a heating block for 60 min. After digestion, the samples were diluted, filtered and analyzed by the Mo-Sb-Vc spectrophotometric method.

The other part of the fresh samples were extracted with KCl or NaHCO_3 solution within 24 hr after collection, then the supernatant was used for inorganic nutrient analysis. For $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ analysis, 20 g fresh sample was extracted with $100\text{ mL } 0.2\text{ mol/L KCl}$ solution and shaken for 30 min. The extracted solution was then filtered and analyzed by the Kjeldahl method for $\text{NH}_4^+\text{-N}$ concentration and phenol disulfonic acid spectrophotometric method for $\text{NO}_3^-\text{-N}$ analysis, respectively (Pao, 1999). For PO_4^{3-} analysis, 2.5 g sample was extracted with $50\text{ mL } 0.5\text{ mol/L NaHCO}_3$ solution and shaken for 30 min. After filtration, the extracted solution was measured by the same method as above for TP analysis.

1.4 Data analysis

All statistical analyses were performed using SPSS 13.0. (SPSS Inc., Chicago, USA). Analysis of the variance (ANOVA, one factor) was carried out to test differences between the compared groups. Difference was considered significant when the value of significant difference was smaller than 0.05 .

2 Results and discussion

2.1 Effects of water level variation and nutrient loadings in the lake on reed growth

2.1.1 Seasonal variation of reed growth

As shown in Fig. 2, both the stem length and diameter increased during the growing season of reeds in the two study sites. The maximum stem lengths were 319.0 and 342.5 cm in the terrestrial zones of Site A and Site B, respectively. Correspondingly, the highest stem diameters were 9.2 and 9.8 mm , respectively. The aboveground

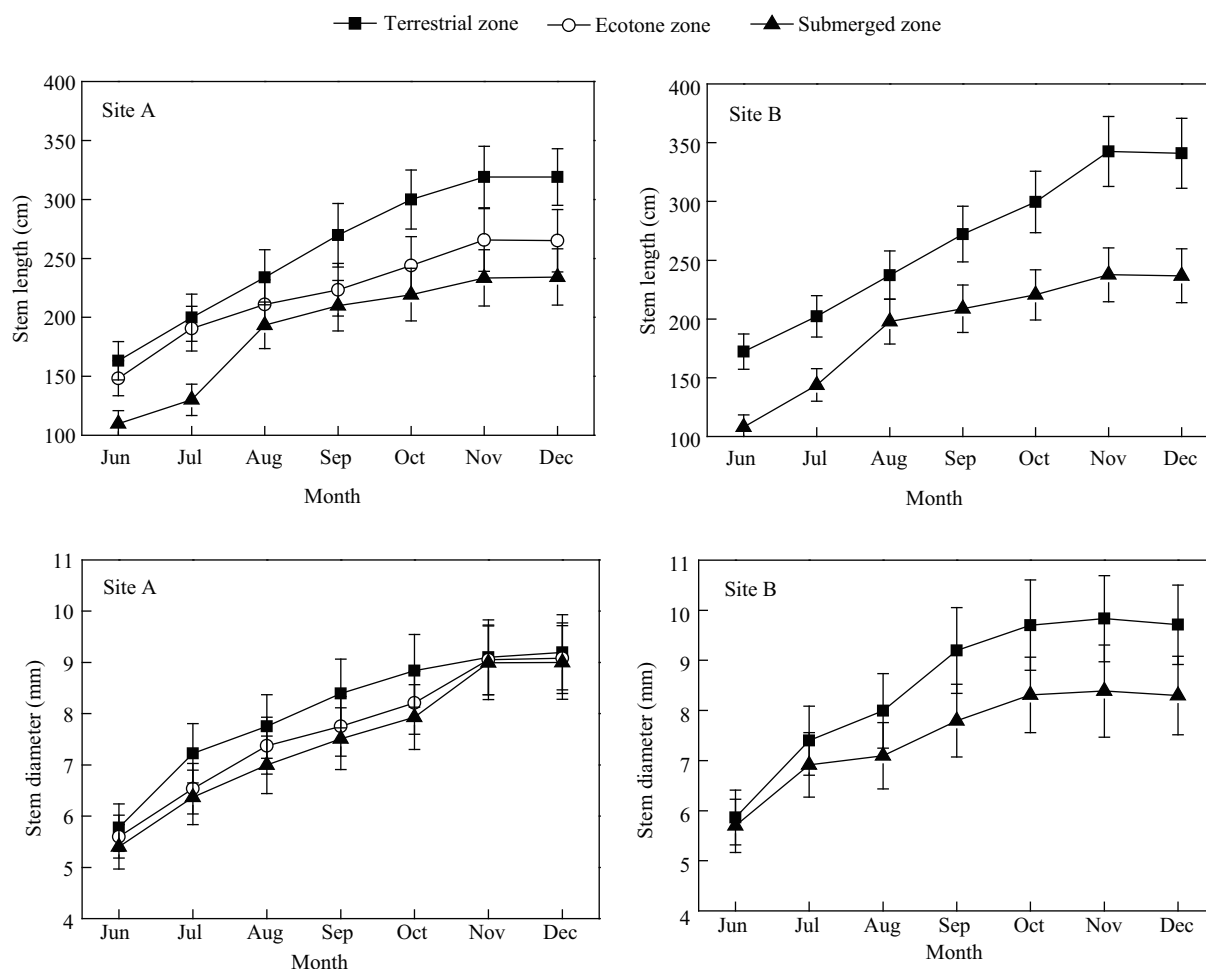


Fig. 2 Variations of reed stem lengths and diameters during the growing season in different zones of the two sampling sites.

biomass of reeds increased gradually and reached the maximum in September, when the values were 2647.0 and 3863.3 g/m² in the terrestrial zones for Site A and Site B, respectively (Fig. 3). Then, reductions were observed in the subsequent months.

Some researchers have indicated that the shoot growth of macrophyte species starts in March, and the aboveground biomass peaks in summer, then the plants start to senesce, causing decrease of the aboveground biomass (Karunaratne et al., 2003; Windham et al., 2003). Similar seasonal variations of reed aboveground biomass were also described by Sollie and Verhoeven (2008) and Quan et al. (2007).

By observing the belowground biomass of reeds, we found that the intense rhizome growth occurred in summer, with increasing belowground biomass from June to October and decreasing in November and December (Fig. S1). The maximum values were 1229.7 and 1464.7 g/m² for Site A and Site B, respectively. According to Karunaratne et al. (2003, 2004), a steady increase of rhizome biomass was also recorded in summer and a decrease in winter. Therefore, summer is the best season for the rhizomes to assimilate more nutrients, which were used for nutrient

reservation and the growth of aboveground reed tissues.

2.1.2 Effects of water level variations on reed growth

Figure 2 shows that the stem length and diameter in the three types of zones varied in the following order: the terrestrial zone > the ecotone zone > the submerged zone. The averaged stem length and diameter in the terrestrial zones of the two sites were about 26.3%–27.5% and 7.2%–12.0% higher than those in the submerged zone, respectively; the stem lengths in the terrestrial zone were significantly longer compared to the submerged zone for both sites ($p < 0.05$) (Table 1). Dinka (1986) also proved that significant differences in stem height existed between reed samples from different water depths. Hellings and Gallagher (1992) reported a decrease in stem height when the flooding level was increased.

The influences of water level variation on aboveground biomass were similar to its effects on stem length and diameter. It was observed that the terrestrial status significantly increased the average aboveground biomass of reeds by 36.6% and 51.8% compared with the submerged status in Site A ($p < 0.05$) and Site B ($p < 0.01$), respectively (Table 1). Armstrong et al. (1999) indicated

Table 1 Comparisons of reed growth in different water level zones

	Site	Terrestrial zone (TZ)	Ecotone zone (EZ)	Submerged zone (SZ)	<i>p</i> (TZ vs. EZ)	<i>p</i> (TZ vs. SZ)	<i>p</i> (EZ vs. SZ)
Stem length (cm)	A	257.79 ± 60.97	221.06 ± 42.39	190.01 ± 50.23	0.215	0.042*	0.235
	B	266.71 ± 66.25	–	193.29 ± 49.27	–	0.037*	–
Stem diameter (cm)	A	8.04 ± 1.23	7.66 ± 1.28	7.46 ± 1.33	0.580	0.412	0.779
	B	8.53 ± 1.50	–	7.50 ± 0.99	–	0.157	–
Aboveground biomass (g/m ²)	A	1828.54 ± 542.41	1570.28 ± 560.76	1158.91 ± 415.42	0.398	0.024*	0.145
	B	2755.01 ± 914.58	–	1327.38 ± 513.42	–	0.004**	–
Belowground biomass (g/m ²)	A	660.17 ± 180.17	1041.16 ± 292.18	545.51 ± 135.88	0.012*	0.204	0.002**
	B	1043.69 ± 288.65	–	924.41 ± 256.75	–	0.430	–

** $p < 0.01$; * $p < 0.05$.

that permanent submergence of young reed seedlings could reduce shoot emergence based on a laboratory experiment. Several studies also confirmed that shoot density was higher in drier than in wetter habitats (Bodensteiner and Gabriel, 2003; Ostendorp et al., 2003; Engloner, 2004). Thus, when water levels were higher, the shoot emergence and density of reeds would decrease, which caused the lower aboveground biomass of reeds. Besides that, Vretare et al. (2001) suggested that the relative growth rates of reeds were higher in shallow than in deep water. On this basis, the lower relative growth rates of reeds in deep water could be another factor in their lower aboveground biomass.

The effects of water level variation on the belowground biomass of reeds were different from aboveground biomass, and their values in the three different zones varied in the order: the ecotone zone > the terrestrial zone > the submerged zone (**Fig. S1**). In Site A, the belowground biomass of reeds in the ecotone zone was significantly higher than in the submerged zone ($p < 0.05$) and terrestrial zone ($p < 0.01$), respectively (**Table 1**). These results were consistent with that reported by Sollie (2007), who indicated that the belowground biomass of reeds was higher in the water level fluctuation zones than in the submerged zones. It is suggested that the performance of vegetation may be influenced by many negative factors in the permanently inundated locations, such as low redox conditions in the sediment (Brock et al., 1987; van den Brink et al., 1995), toxic state of several ions and low internal oxygen availability (Yamasaki and Tange, 1981). In this study, the environment of water-submerged zones was potentially unfavorable for the growth of belowground reeds. In ecotone zones with water level fluctuation, the

redox conditions and oxygen availability were fit for the rhizomes' growth due to the intense exchange of the aerobic and anaerobic status. Therefore, the belowground biomass of reed was highest in the ecotone zones.

2.1.3 Effects of nutrient loadings in the lake on reed growth

As shown in **Table 2**, the average nutrient concentrations of surface water and sediment in the submerged zone of Site A were 1–3 times higher than those in Site B, and the statistical differences between the two sites were significant ($p < 0.05$). Thus, the two study sites were characterized by significantly different nutrient loadings, and the surface water quality in Site A was worse than in Site B.

Although nutrient loadings in the two study sites were significantly different, the reed growth seemed to be comparable. As shown in **Table S1**, the average stem length and stem diameter in Sites A and B were nearly the same. The average aboveground biomass and belowground biomass in Site B were 12.7% and 41.0% higher than in Site A, respectively, and there were almost no significant differences for the growth parameters between the two study sites. In lakes, the question as to whether nutrient loadings or water depth has a stronger effect on reed growth has frequently arisen. In Baiyangdian Lake, the elevated nutrient contents in the water and sediment were high enough for reed growth, so nutrient loadings in the environment were not the primary factors that influenced reed growth. Similar results were also reported by Clevring (1998). However, Haslam (1970) reported that reed growth was limited more by nutrient status than by water depth at its wetter limit, which was probably due to the fact

Table 2 Comparison of the average nutrient concentrations of submerged zones in sites A and B

	Surface water (mg/L)			Sediment (mg/kg)		
	Site A	Site B	<i>p</i>	Site A	Site B	<i>p</i>
TN	7.88 ± 2.87	4.24 ± 2.37	0.038*	4403.44 ± 909.49	2370.46 ± 1535.75	0.012*
NH ₄ ⁺ -N	1.98 ± 1.74	1.23 ± 1.05	0.390	62.86 ± 57.55	35.41 ± 23.12	0.171
NO ₃ ⁻ -N	0.77 ± 0.61	0.18 ± 0.08	0.106	2.73 ± 2.94	1.92 ± 0.88	0.264
NO ₂ ⁻ -N	0.23 ± 0.26	0.03 ± 0.05	0.107	–	–	–
TP	0.60 ± 0.30	0.14 ± 0.09	0.005**	631.43 ± 334.25	276.42 ± 89.91	0.044*
PO ₄ ³⁻ -P	0.09 ± 0.05	0.03 ± 0.01	0.039*	23.41 ± 18.39	18.08 ± 11.63	0.481

** $p < 0.01$; * $p < 0.05$.

that the studied lake was in an oligotrophic state.

2.2 Effects of water level variation and nutrient loadings in the lake on reed nutrient accumulation

2.2.1 Seasonal variation of nutrient concentrations in reeds

As shown in **Fig. 3**, the seasonal variations of both TN and TP concentrations in aboveground reed tissues were similar, and they gradually decreased from July to December. The pattern of change in the nutrient concentration in reed tissues generally reflects the mobility of the nutrient in the internal translocation system. In the early stage of reed growth in Baiyangdian Lake, higher

nutrient concentrations existed in the newly emerging stems and leaves. Then, the nutrient concentrations in the aboveground tissues decreased gradually as a result of the “dilution effect” caused by the growth of aboveground biomass. At the end of the growing season, the nutrients in the aboveground tissues were lowest due to their slow transfer to the belowground tissues. In addition, the decline in nutrient concentrations in the aboveground tissues was related with senescence of the stems in winter because of low air temperatures (Ruiz and Velasco, 2010).

However, the nutrient concentrations in the belowground tissues of reeds presented the opposite temporal variation to that in aboveground tissues (**Fig. S1**). They

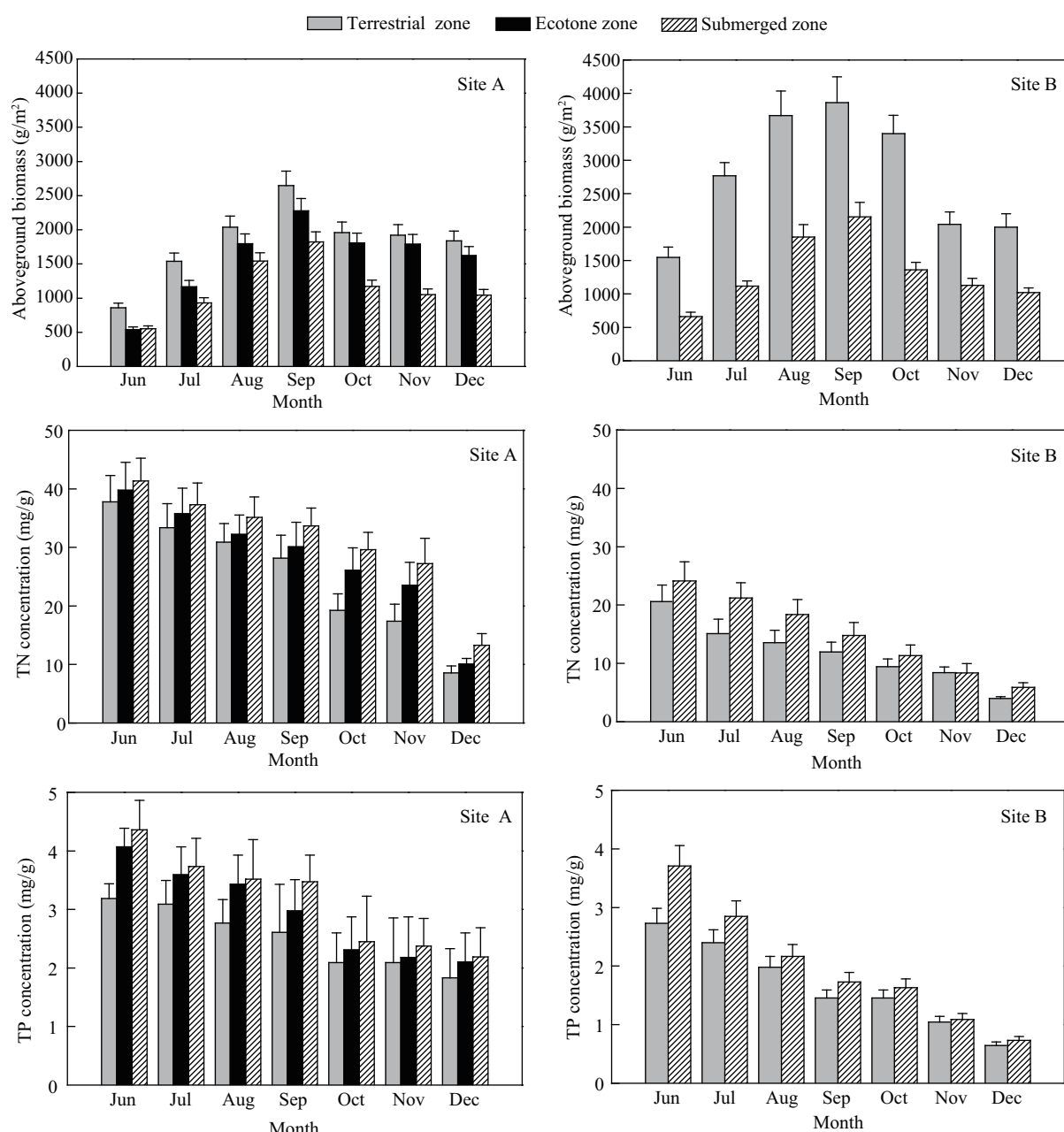


Fig. 3 Aboveground biomass and nutrient concentrations in aboveground reeds during the growing season in different zones of sites A and B.

were increasing from July to December with the maximum in December, when the rhizomes had senesced. It was observed that the main nitrogen-rich compound was the dominant amino acid in reed rhizomes, especially in autumn and winter (Hocking and Steer, 1989). The higher nutrient concentrations in belowground reeds provide essential amounts of nutrients to be used for the growth of young stems in the following year. The nutrient translocation capacity from some organs to others enables plants to face nutrient fluctuations and therefore be highly adaptive in habitats with fluctuating resources.

It was found that the P dynamics was a little different from that of N. The results showed that the mean TN concentrations were 2.0%–45.4% higher in aboveground tissues than in belowground tissues during the growing season of reeds. However, the average TP concentrations were 13.7%–23.0% higher in belowground tissues than in aboveground tissues (Table 3). Ruiz and Velasco (2010) also indicated that the phosphate was downward translocated and easily concentrated in the belowground tissues of reeds.

Table 3 Comparison of average reed nutrient concentrations for submerged zones of two sites with different nutrient loadings

	Site A	Site B	<i>p</i>
Aboveground TN (mg/g)	31.08 ± 9.14	14.87 ± 6.74	0.001**
Belowground TN (mg/g)	23.67 ± 8.45	14.59 ± 5.50	0.035*
Aboveground TP (mg/g)	3.16 ± 0.82	1.99 ± 1.03	0.036*
Belowground TP (mg/g)	3.76 ± 1.24	2.50 ± 0.76	0.040*

***p* < 0.01; **p* < 0.05.

2.2.2 Effects of water level variation on nutrient accumulation of reeds

In terms of water level variation, TN and TP concentrations in aboveground tissues of the two study sites varied in the following order: the submerged zone > the ecotone zone > the terrestrial zone (Fig. 3). The reason that the lowest nutrient concentrations occurred in the terrestrial zones was mainly due to the stronger “dilution effect” of the larger aboveground biomass in this zone. As for the nutrient concentrations in belowground tissues of the two study sites, they followed the same order as aboveground tissues (Fig. S1). This reason was mainly related to the decomposition rates of organic matter and inorganic elements in belowground tissues by microorganisms. Generally, the decomposition rates of nutrients are higher under aerobic conditions, which leads to a relatively lower accumulation of nutrients in belowground tissues (Larmola et al., 2006). In the terrestrial zones of our study, the oxygen concentration of the rhizosphere was higher. Therefore, the decomposition rates of nutrients by microorganisms were also higher under aerobic environments, and the nutrient concentrations in belowground tissues were lower. By contrast, in the submerged zones, the nutrient concentrations were higher in belowground tissues due to the existence

of anaerobic conditions and lower decomposition rates of nutrients.

However, there were no significant differences in nutrient concentrations in reed tissues between the two compared zones with different water levels (Table S2). Thus, the nutrient concentrations in both aboveground and belowground tissues were less influenced by water level variation.

2.2.3 Effects of nutrient loadings in lake on nutrient accumulation of reeds

The comparisons were conducted between Site A and Site B, where the nutrient concentrations of surface water and sediments in the submerged zones of Site A were significantly higher than in Site B (Table 2). The results showed that the TN and TP concentrations of reeds in the submerged zone of Site A were significantly higher than in Site B (*p* < 0.05), both for the aboveground and the belowground tissues of the reeds (Table 3). The higher nutrient loadings in Site A increased the average reed nutrient concentrations during the growth period by 44.5%–52.1% for TN and 37.0%–37.8% for TP.

The reason was that the higher nutrient concentrations in the water and sediment of the submerged zone could facilitate the nutrient assimilations of reeds in the environment that is well-adapted for reed growth. Koerselman and Meuleman (1996) reported that the N:P ratio of the vegetation directly indicated which of the two nutrients was limiting. An N:P ratio greater than 16 on a weight basis may indicate P limitation on a community level, whereas an N:P ratio less than 14 should be indicative of N limitation. It was reported that the N: P ratio was an effective indicator to estimate nutrient limitation and was applied in many studies (Romero et al., 1999; Tessier and Raynal, 2003; Mou et al., 2011). However, this relationship is only valid when either N or P could control plant growth. Duarte (1992) compiled data on nutrient concentrations in a wide range of aquatic macrophytes and found that N and P tended always to be present in the plant tissue at a N:P ratio of 12 on a weight basis.

In the submerged zone of Site A, the N:P ratios in aboveground and belowground tissues varied in the range of 6.1–12.1 and 5.9–6.8 for the growth period of the reeds, respectively. In the submerged zone of Site B, the corresponding values were 7.0–8.5 and 4.6–6.6, respectively. Meanwhile, the N:P ratios in the two studied sites presented no significant seasonal variation. In addition, the N:P ratio in aboveground reeds was generally once to twice that in belowground reeds, which was mainly due to the higher P concentrations existing in belowground reeds that was referred to above. According to the above relationship, the reed growth for the two sites would be indicative of N limitation. Thus, the N concentrations in the reed tissues of Site A were increased by its higher TN concentrations in surface water and sediment. The N:P weight ratios in aboveground reed tissues were higher in Site A and tended

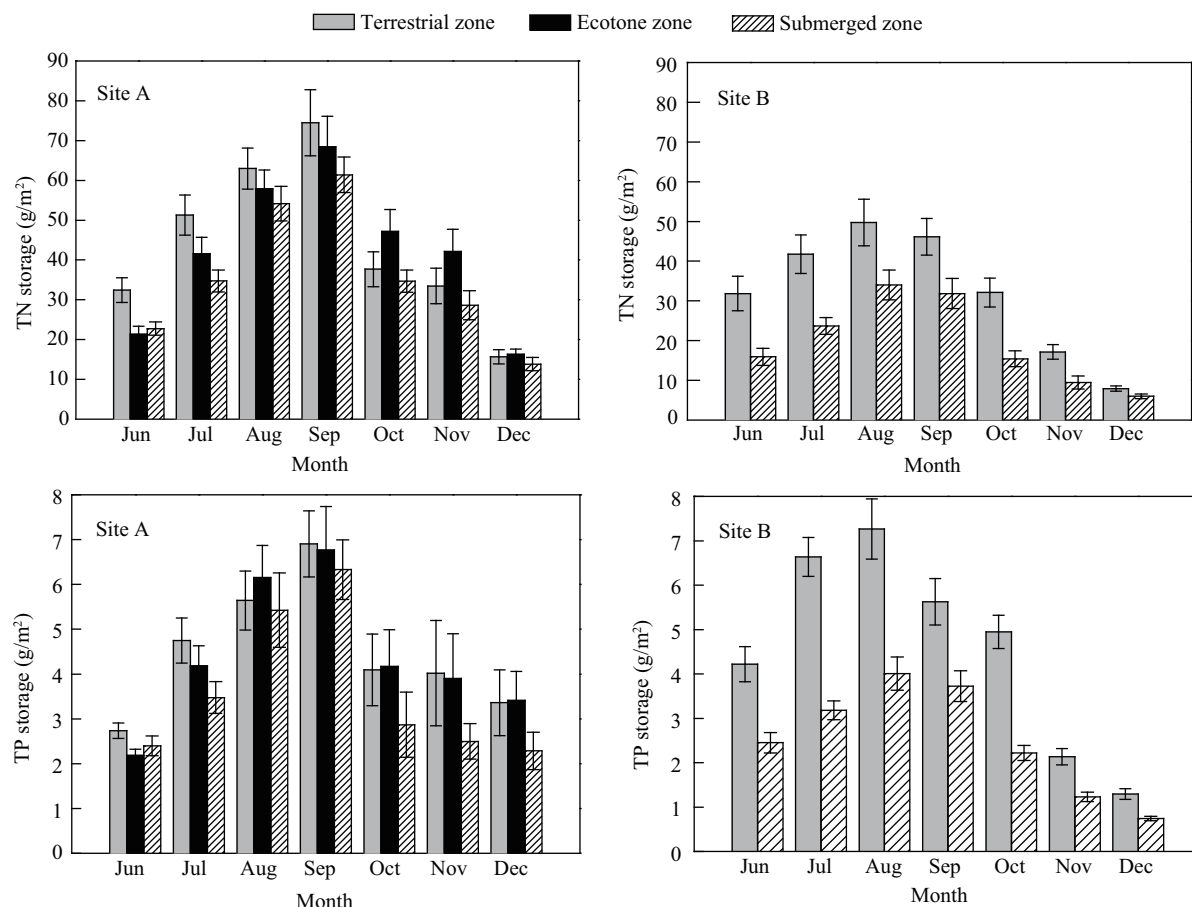


Fig. 4 TN and TP storage of aboveground reeds in different zones of sites A and B.

to be 12, which suggested that the nutrient loadings in Site A were favorable for reed nutrient assimilations. Romero et al. (1999) also proved that the N and P concentration in reed tissues increased with the nutrient level in the root solution, by a hydroponic culture experiment in the laboratory. In addition, the results of this study showed that the average TN concentrations in the surface water and sediment of Site A were about twice those in Site B. Similarly, the TN concentrations in aboveground and belowground reeds in Site A were also twice those in the corresponding parts of reeds in Site B. However, we did not find the corresponding relationships between TP concentrations in reeds and in the environment (including surface water and sediment).

2.3 Nutrient storage of reeds in Baiyangdian Lake

The aboveground nutrient storage was calculated by multiplying the N or P concentration in the aboveground tissues of reed and the aboveground biomass. As shown in Fig. 4, the highest nutrient storages in aboveground tissues occurred in August or September, with the highest values of 34.0–74.5 g/m² for TN and 4.0–7.3 g/m² for TP. The belowground nutrient storage was calculated by multiplying the N or P concentration in the belowground tissues of reed and the belowground biomass. The results

demonstrated that the belowground nutrient storages increased during the growing season, with highest values of 13.2–36.1 g/m² for TN and 3.0–6.7 g/m² for TP (Fig. S2). As only the aboveground tissues of reeds were harvested, the optimum time for reed harvesting should be in late August and early September, when the nutrient storages of aboveground tissues were largest.

In addition, the results also showed that the nutrient storages were generally higher in Site A than in Site B, and in each site they were the highest in the terrestrial zones and the lowest in the submerged zones. When comparing the maxima in September of Site A and in August in Site B, we further found that although aboveground TN storage was the lowest in the submerged zone of Site A, it was still 8.2%–42.7% larger than the highest aboveground TN storage in the terrestrial zone of Site B. Therefore, higher nutrient loadings in the surface water and sediment was a stronger factor influencing the reed nutrient storages, and reed seemed to be well-adapted to the higher nutrient loading status.

3 Conclusions

In this study, the effects of water level variation and nutrient loadings in the environment on reed growth and

nutrient accumulation of reeds were investigated based on field samplings in Baiyangdian Lake. It was found that water level variation had clear effects on reed growth. The results showed that reed stem lengths and above-ground biomass in the terrestrial zones were significantly higher compared to the submerged zones in both study sites ($p < 0.05$). However, the belowground biomass of reeds in ecotone zones was significantly higher than in submerged zones ($p < 0.05$) and terrestrial zones ($p < 0.01$), respectively. In addition, the nutrient accumulations and storages of reeds were more limited by the nutrient loadings in the lake rather than by water level variation. It was observed that the higher nutrient loadings in Site A significantly increased the TN and TP concentrations in reed tissues by 44.5%–52.1% and 37%–38%, respectively ($p < 0.05$). For the maximum nutrient storages in two sites, although aboveground TN storage was the lowest in the submerged zone of Site A with higher nutrient loadings, it was still larger than the highest aboveground TN storage in the terrestrial zone of Site B with lower nutrient loadings. Therefore, a higher nutrient loading in the surface water and sediment was a stronger factor that influenced the reed nutrient storages, and reed seemed to be well-adapted to the higher nutrient loading status. To summarize, when using reeds as remediation plants for controlling lake eutrophication, it is suggested that both water level variation and nutrient loadings in the environment should be considered.

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Supporting materials

Supplementary data associated with this article can be found in the online version.

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