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RESEARCH ARTICLE

Different roles of three emergent macrophytes in promoting sedimentation in Dongting Lake, China

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Abstract Aquatic macrophytes play an important role in promoting sediment deposition. However, compared to submerged macrophytes, the influence of emergent macrophytes on sedimentation dynamics have been studied less often. In this study, a field experiment was conducted to compare the influence of three typical emergent macrophytes (*Miscanthus sacchariflorus*, *Carex brevicuspis*, and *Phalaris arundinacea*) on sedimentation characteristics in Dongting Lake. In addition, the factors that determine sediment characteristics were also investigated. Both vegetation type and vegetation removal treatments had significant effects on sedimentation depth. Compared to the non-vegetated treatment, sedimentation depths were much greater in the vegetated treatments in all three communities. The order of sediment-trapping ability, from highest to lowest was *P. arundinacea* > *M. sacchariflorus* > *C. brevicuspis*; sedimentation rate was much higher in the *P. arundinacea* community than that in the other two communities, especially in the Tuanzhou and Chapanzhou lakeshores. In the vegetated treatment, clay and fine sand contents were significantly influenced by both vegetation type and vegetation removal treatment, whereas fine silt, coarse silt, and coarse sand contents were significantly affected only by vegetation type. Sand content was higher, but clay and silt contents were lower in the *M. sacchariflorus* community compared to the other two communities. Median particle size in the *M. sacchariflorus* community was much higher than that in the other two communities in both non-vegetated and vegetated treatments. Organic matter content, total N, and sediment pH were influenced by vegetation type alone. Sediment in the *M. sacchariflorus* community had a lower pH but higher organic matter and total N content compared to the other two communities. Multiple linear regression indicated that sediment characteristics were significantly correlated with vegetation characteristics (e.g. plant density, height, and biomass), elevation, and flooding time. The data indicate that the roles of these three emergent macrophytes in promoting sedimentation vary significantly, which is mainly due to their different structural properties and distribution patterns. Our results provide experimental information on the role of emergent macrophytes in promoting sedimentation and may assist in the effective management of Dongting Lake.

Keywords Sedimentation · Emergent macrophyte · Flooding time · Sediment characteristics

Introduction

Sedimentation occurs frequently in various wetlands such as reservoirs, rivers, catchments, estuarine deltas, and river-connected lakes (Madsen et al. 2001; Cotton et al. 2006; Wharton et al. 2006; Li and Xie 2009). Large amounts of sediment are transported into these wetlands during flooding, a primary process that regulates water physicochemical quality and biotic communities (Horppila and Nurminen 2001, 2005). Moreover, sedimentation characteristics (e.g.

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sedimentation rate and nutrient status) might change significantly with wetland types. Generally, compared to lentic wetlands, lotic wetlands have higher sedimentation due to their complex hydrological regime (Schulz et al. 2003; Li et al. 2008a, b; Heppell et al. 2009). Recently, in response to various natural and anthropogenic disturbances (e.g. deforestation and intensified land use), sediment yields have increased drastically in many wetlands, which significantly reduce wetland water capacity and biodiversity, and consequently, increases functional deterioration of wetland ecosystems (Horppila and Nurminen 2001; Kamp-Nielsen et al. 2002; Horppila and Nurminen 2005).

Aquatic macrophytes, a living link between water and sediment in wetlands, play an important role in structuring aquatic ecosystems through different ecosystem processes such as sedimentation, biomineralization, and nutrient cycling (Schulz et al. 2003; Cronin et al. 2006; Li and Xie 2009). Aquatic macrophytes and sediment dynamics are strongly interrelated in wetland systems; aquatic macrophytes not only reduce water current and shelter sediment from erosion and resuspension, but also promote sedimentation, serving as effective sediment traps by intercepting suspended sediment (James et al. 2004; Li et al. 2008a, b). In lakes with vegetated littoral regions, the sediment accretion rate is generally higher than in non-vegetated regions, and patterns of sediment composition, such as nutrient content and particle size distribution, also vary because of the influences of macrophytes on sedimentation dynamics (Anderson 1990; Madsen et al. 2001; Newbolt et al. 2008). Dense summer growth of macrophytes can increase the retention of organic matter and fine nutrient- rich particles in the stream sediments due to the hydraulic resistance of the plants (Sand-Jensen 1998). Until now, the influence of aquatic macrophytes on sedimentation dynamics has received the most attention (Vermaat et al. 2000; James et al. 2004; Li et al. 2008a, b); however, most of these studies focus on submerged macrophytes, and the intercepting effects of emergent macrophytes are rarely investigated (Horvath 2004; Horppila and Nurminen 2005).

Studies on the effect of aquatic macrophytes on sedimentation are usually associated with plant properties such as growth form and plant biomass (James et al. 2004; Horppila and Nurminen 2005; Li et al. 2008a, b). Different species have variable effects on hydrodynamics and sediment deposition because of substantial differences in the architecture and distribution of plant tissues among different species (Vermaat et al. 2000; Horppila and Nurminen 2005), which then play an important role in determining wetland development. For lake systems, Horppila and Nurminen (2005) confirmed that fully-submerged and emergent macrophytes usually have higher sedimentation efficiency than floating-leaved plants. Moreover, even for aquatic macrophytes with the same growth form, sedimentation effects also differed significantly according to the amount and spatial distribution of biomass, architecture of macrophytes, and physical properties of sediments, as well as the time that the plant is fully inundated by water (i.e. flooding time; Horvath 2004; Horppila and Nurminen 2005; Li et al. 2008a, b). For instance, *Callitriche cophocarpa* and *Elodea canadensis* had stronger sediment trapping abilities than *Sparganium emersum* due to different leaf structures (Sand-Jensen 1998). Further, the quantity and quality of sediment is not only controlled by vegetation, but also other factors, such as geomorphological and hydrological factors (Steiger et al. 2001). Plants distributed at lower elevations usually have higher sedimentation depth than those at higher elevations mainly due to longer flooding time (Cahoon and Reed 1995; Hensel et al. 1999). Walling and He (1997) confirmed that sedimentation rates were controlled by local hydrogeomorphological conditions, including channel geometry, overbank flow patterns, and floodplain morphology and microtopography in the floodplain of the River Cuhn, Devon, UK. Therefore, to fully understand the role of aquatic macrophytes on sediment interception, it is necessary to investigate the relationship between vegetation properties and sediment characteristics and the interrelationships with the hydrogeomorphological conditions.

In this study, we performed a field experiment to investigate the influence of three emergent macrophytes on sediment characteristics, including sedimentation depth, sedimentation rate, particle size distribution, median particle size, pH, organic matter content, and total N content. Three dominant emergent macrophyte communities with different shoot morphology and distribution patterns (low-elevation caulescent species *Phalaris arundinacea*, middle-elevation acaulescent species *Carex brevicuspis*, and high-elevation caulescent species *Miscanthus sacchariflorus*; Fig. 1) in Dongting Lake, China, were chosen. The relationship between sediment properties and vegetation characteristics, elevation, and flooding time were investigated to test the following hypotheses: (1) all three emergent macrophytes promote sediment deposition, and *P. arundinacea* might have a higher sediment-trapping ability than the other two species because of its low-elevation distribution and shoot morphology; and (2) sediment characteristics vary significantly among different communities and are linked to vegetation properties, elevation, and flooding time.

Materials and methods

Study site and plants

Dongting Lake (28°30′–30°20′N, 111°40′–113°10′E), located at the south bank of the middle reach of the

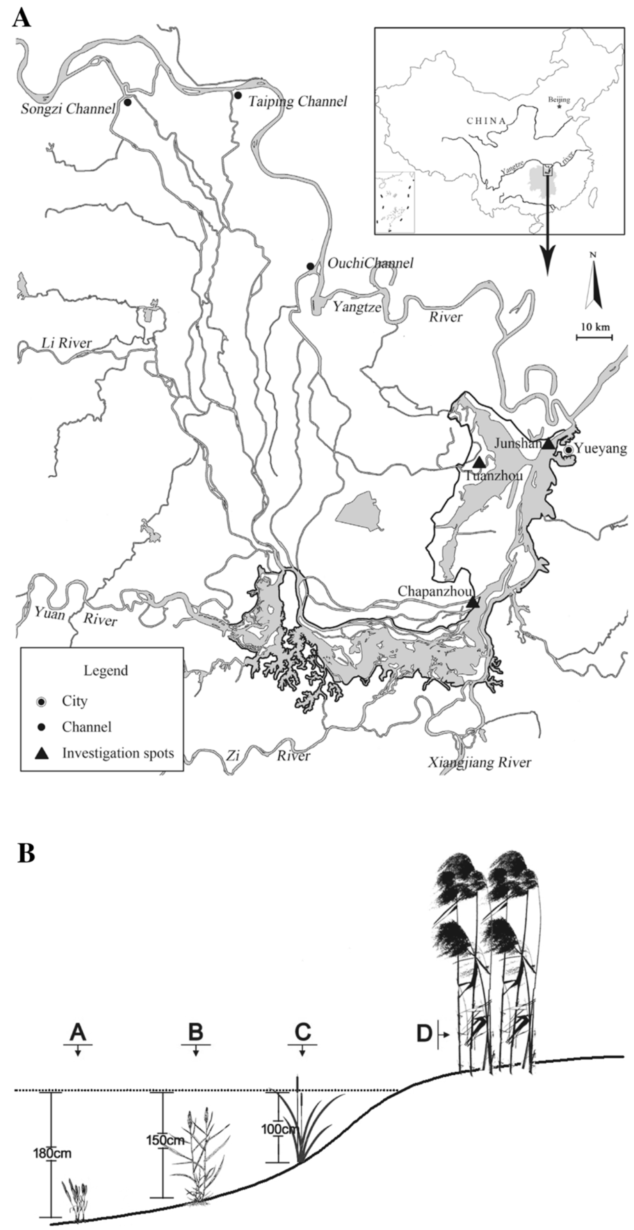

Fig. 1 **a** Dongting Lake, showing water system and location of sampling sites. The *shaded areas* show the wetlands. **b** Distribution patterns of common plants along a water level gradient in Dongting Lake *A* submerged macrophytes, *B Phalaris arundinacea*, *C Carex brevicuspis*, and *D Miscanthus sacchariflorus*

Yangtze River, is the second largest freshwater lake in China and has the largest water exchange capacity with the Yangtze River (Xie and Chen 2008). It receives inflow from four rivers (Xiang, Zi, Yuan, and Li) in the Hunan Province and from four channels (Songzikou, Taipingkou, Ouchikou, and Tiaoxiankou) connected to the Yangtze River (Fig. 1). The wetlands are characterized by large seasonal fluctuations in water level and are usually completely flooded from May to October and susceptible to drought from November to April. From 1951 to 2009, large amounts of sand and silt derived from upstream soil erosion and deforestation were transported into the lake and deposited at an average rate of 1.48×10^8 t year^{-1}. Due to the intensified amount of sedimentation, the lake basin is elevated by about 3–7 cm annually (Li et al. 2008a, b). The area of Dongting Lake has decreased from 6000 (1825 data) to 2625 km^2 from the Qing dynasty to now, and moreover, sedimentation is considered an important driving force regulating plant community succession in this lake (Li et al. 2008a, b; Xie and Chen 2008).

This study was conducted in three lakeshore areas of Dongting Lake: Chapanzhou (28°54′11.5″N, 112°48′34.6″E), Tuanzhou (29°20′27.5″N, 112°50′10.0″E), and Junshan (29°24′18.4″N, 113°04′35.7″E; Fig. 1). These three lakeshore areas are all active regions with heavy sedimentation (Shi and Xia 1999). Plant zonation along an elevation gradient is common (high-elevation species *M. sacchariflorus* and *Phragmites australis*, middle-elevation species *C. brevicuspis* and *Polygonum hydropiper*, and low-elevation species *P. arundinacea*). *P. arundinacea* is a perennial plant with a rugged stem, which can grow 60–150 cm tall and the width and length of leaves can be in the range of 5–15 mm and 8–15 cm, respectively. *C. brevicuspis* is a perennial acaulescent herb with a height of 40–110 cm. The leaves of *C. brevicuspis* can be 100 cm long and have a width of 5–7 mm. In Dongting Lake, this species usually displays a lodging pattern when it grows to a certain height. *M. sacchariflorus* is a perennial herb with an erect culm; it grows 4–5 m tall and has a diameter of 1.5–1.8 cm. The leaves of *M. sacchariflorus* have a length of 90–98 cm and a width of 1.5–4 cm.

Experimental design

In April 2010, sampling sites were established in the three plant community areas (*M. sacchariflorus*, *C. brevicuspis*, and *P. arundinacea*) at each lakeshore area, prior to flooding. In order to examine the influence of vegetation on sediment deposition, six circular plots containing two treatments (vegetated and non-vegetated) with three replicates were established in each community. The coordinates of each plot were recorded using a global positioning system (UniStrong, MG758E). For each vegetated and non-vegetated area, three sediment collection plates (20-cm diameter) were fixed using steel wire to prevent them from being dislodged by flooding, and the natural vegetation was maintained in the vegetated treatment. In each non-vegetated treatment, aboveground vegetation was removed by mowing, and an herbicide (glyphosate) was sprayed to prevent growth. Glyphosate is a commonly used herbicide, which is susceptible to tight absorption by soil colloids until degradation and is not easily leached by water flow.

The distance between vegetated and non-vegetated treatments was 10 m to avoid the influence of the herbicide on the vegetated treatment. The distance between each replicate was 50 m, and the diameter of each plot was 10 m, which was considered large enough to ensure unrestricted inflow of water into the non-vegetated treatment. In addition, a 1 × 1 m quadrat was established in each replicate for vegetation sampling. The presence of aboveground biomass (fresh weight), height, and diameter were recorded. Aboveground biomass was determined using an electronic scale with 0.01 kg precision. Plant height and diameter were measured using a 0.1-cm steel tape and a vernier caliper, respectively (Table 1). Additionally, the elevation of each plot was calculated using its coordinates and a digital elevation model (1:10,000) of Dongting Lake created in 1995 (Changjiang Water Resources Commission, Ministry of Water Resources, China) with an accuracy of 0.1 m. The flooding time of each plot was also calculated based on elevation and daily water level data (8:00 AM) from the Chenglingji hydrological gauging station during 2010 (Table 1).

In November 2010, we returned to each plot for sediment collection after flooding. First, the sedimentation depth at each sediment collection plate was measured with a 0.1-cm steel ruler. Sediments were then carefully brushed into plastic bags, placed in a cooler, and transported to the Key Laboratory of Agro-ecological Processes in the Subtropical Region, Chinese Academy of Sciences after collection, where the sediments were kept at 4 °C until analysis. Samples were processed within 20 days.

Sediment analysis

Sediment samples were air-dried and sieved to remove coarse fragments (<2 mm for all analyses; <0.5 mm for organic matter content and total N). Effective particle size was determined using a laser particle size analyser (Mastersizer 2000) and divided into clay (<0.002 mm), fine silt (0.002–0.02 mm), coarse silt (0.02–0.05 mm), fine sand (0.05–0.25 mm), and coarse sand (>0.25 mm) according to particle diameter (Zhu 1983). The classification of particle size was based on the classification system of the US Department of Agriculture (USDA), which is considered more suitable for soil classification in China than other systems (Lyu et al. 2015; Cotton et al. 2006). In addition, median particle size (d_{50}) was also calculated to further understand particle size characteristics among different treatments. pH was determined in the solution with a 1:2.5 ratio (w/v) of sediment to distilled water using a Mettler Toledo 320 pH meter (Mettler-Toledo Instruments Co., Ltd., China). Organic matter content was determined by the wet digestion method of potassium dichromate oxidation (Rayment and Higginson 1992), and total N was determined using the Kjeldahl method (Bremner and Mulvaney 1982).

Data analysis

Sedimentation due to vegetation (D_{net}) was calculated by the following formula:

$$D_{net} = D_v - D_n$$

Table 1 Vegetation characteristics and environmental factors of three dominant plant communities (*Phalaris arundinacea*, *Carex brevicuspis*, and *Miscanthus sacchariflorus*) in Dongting Lake

Vegetation location	Vegetation characteristic				Environmental factor	
	Density (plants m^{-2})	Height (cm)	Diameter (mm)	Biomass (kg)	Community distributing elevation (m)	Flooding time (days)
Junshan						
P. arundinacea	626.7 ± 104.1^{b}	51.7 ± 8.3^{b}	0.20 ± 0.00^{b}	$2.3 \pm 0.5^{a,b}$	21.7 ± 0.2^{f}	253.0 ± 9.1^{a}
C. brevicuspis	922.7 ± 69.3^{a}	55.0 ± 2.9^{b}	–	0.7 ± 0.2^{b}	22.7 ± 0.2^{e}	223.3 ± 2.6^{b}
M. sacchariflorus	145.3 ± 51.2^{c}	166.7 ± 14.2^{a}	0.77 ± 0.13^{a}	4.6 ± 1.0^{a}	28.8 ± 0.1^{a}	116.7 ± 3.5^{f}
Tuanzhou						
P. arundinacea	1066.7 ± 59.4^{a}	88.5 ± 1.8^{b}	0.27 ± 0.03^{b}	3.6 ± 0.4^{a}	25.0 ± 0.0^{c}	186.0 ± 0.0^{d}
C. brevicuspis	544.0 ± 108.6^{b}	40.0 ± 2.3^{c}	–	0.5 ± 0.1^{b}	26.7 ± 0.3^{b}	147.7 ± 5.3^{e}
M. sacchariflorus	$76.7.0 \pm 12.9^{c}$	133.8 ± 22.4^{a}	1.13 ± 0.43^{a}	3.3 ± 0.3^{a}	28.9 ± 0.0^{a}	107.7 ± 5.8^{f}
Chapanzhou						
P. arundinacea	500.0 ± 22.0^{b}	74.3 ± 3.7^{b}	0.32 ± 0.02^{b}	1.1 ± 0.0^{b}	24.2 ± 0.0^{d}	203.3 ± 0.3^{c}
C. brevicuspis	1226.7 ± 45.6^{a}	84.3 ± 2.8^{b}	–	1.8 ± 0.0^{b}	25.1 ± 0.0^{c}	186.0 ± 0.0^{d}
M. sacchariflorus	104.0 ± 6.9^{c}	124.0 ± 5.0^{a}	0.75 ± 0.03^{a}	3.2 ± 0.5^{a}	27.1 ± 0.0^{b}	142.0 ± 0.0^{e}

Different letters indicate significant differences between different communities at the 0.05 significance level where D_{net} is the sedimentation due to vegetation, D_v is the sedimentation depth of the vegetated treatment, and D_n is the sedimentation depth of the non-vegetated treatment. Sedimentation rate was calculated using sedimentation depth divided by flooding time. A general linear model (GLM), with vegetation community included as a fixed factor and sample site included as a random factor was used to analyse whether sedimentation due to vegetation differed significantly among the three communities. Significant differences in sedimentation characteristics were tested using nested models of ANOVAs with type Ⅲ sums of squares. We used vegetation type and vegetation removal treatment as fixed factors and the sample site as a random factor, with sedimentation depth, sedimentation rate, particle size distribution, median particle size, pH, and organic matter, and total N contents of sediments as response variables (McKone and Lively 1993; Biswas and Mallik 2010). Multiple comparisons of means were performed using Tukey's test, and a Bonferroni correction for multiple comparisons was applied when necessary. Data were $\log_{10}$-transformed, if necessary, to reduce heterogeneity of variances. Normality and homogeneity were tested using Liljefors' and Levene's tests, respectively. The relationships between sediment properties and vegetation characteristics, elevation, and flooding time were analysed using a stepwise multiple linear regression. To account for the multiple linear regressions, significance levels (P) were adjusted where needed using the Bonferroni method. All analyses were performed using the statistical software SPSS ver. 18.0 (SPSS Inc., USA).

Results

Sedimentation depth and sedimentation due to vegetation (D_{net})

Sedimentation depth was significantly affected by both vegetation type ($P < 0.05$; $F = 12.832$; df = 2; Fig. 2) and vegetation removal treatment ($P < 0.05$; $F = 6.844$; df = 1; Fig. 2). Sedimentation depth of *P. arundinacea* was much higher than that of the other two communities, especially in the Tuanzhou (1.1 to 11.2-fold higher) and Chapanzhou (1.7 to 5.9-fold higher) lakeshore areas. In the non-vegetated treatment, sedimentation depth displayed patterns similar to those in the vegetated treatment in the Tuanzhou and Chapanzhou areas. In the Junshan lakeshore area, the highest and lowest sediment depths occurred in the *C. brevicuspis* and *P. arundinacea* communities, respectively.

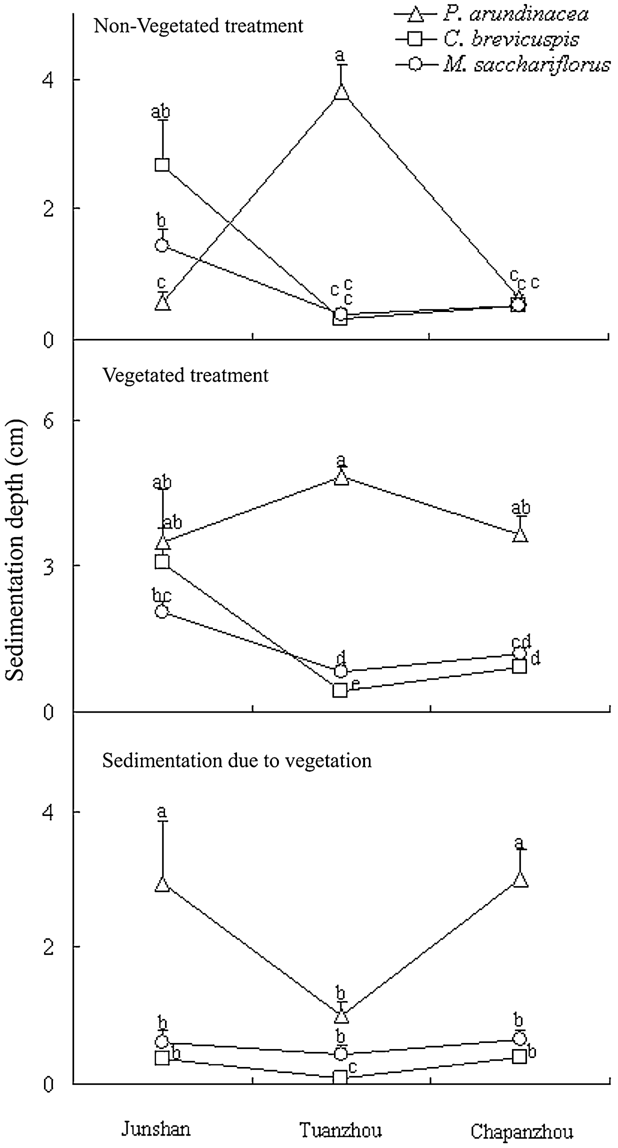

Fig. 2 Sedimentation depth of vegetated and non-vegetated treatments and sedimentation due to vegetation among three communities (*Phalaris arundinacea*, *Carex brevicuspis*, and *Miscanthus sacchariflorus*) at three experimental locations. *Different letters* indicate significant differences between treatments at the 0.05 significance level

Sedimentation due to vegetation differed significantly among the three vegetation communities ($P < 0.05$; $F = 32.712$; df = 2; Fig. 2). The highest and lowest D_{net} values occurred in the *P. arundinacea* community in the Chapanzhou lakeshore area (3.0 cm) and in the *C. brevicuspis* community in the Tuanzhou lakeshore area (0.1 cm), respectively. The order of D_{net} among the three communities was *P. arundinacea* (1.0–3.0 cm) > *M. sacchariflorus* (0.4–0.7 cm) > *C. brevicuspis* (0.1–0.4 cm), indicating that *P. arundinacea* had a higher sediment-trapping ability than the other two species.

Sedimentation rate

Both vegetation type ($P < 0.05$; $F = 6.214$; df = 2; Fig. 3) and vegetation removal treatment ($P < 0.05$; $F = 10.025$; df = 1; Fig. 3) had a significant influence on the sedimentation rate. In the non-vegetated treatment, both the highest and lowest sedimentation rates occurred in the *P. arundinacea* community in the Tuanzhou lakeshore and Junshan lakeshore, respectively, while in the vegetated treatment, sedimentation rate was much higher in the *P. arundinacea* community than that in the *C. brevicuspis* and *M. sacchariflorus* communities, especially in the Tuanzhou and Chapanzhou lakeshore areas.

Particle size distribution and median particle size

Clay and fine sand contents were significantly influenced by both vegetation type ($P < 0.05$; Table 2) and vegetation removal treatment ($P < 0.05$; Table 2), whereas fine silt, coarse silt, and coarse sand contents were significantly affected only by vegetation type ($P < 0.05$; Table 2). The *P. arundinacea* community had higher clay and fine silt contents than the other two communities (Table 2). Coarse silt content was lower in the *M. sacchariflorus* community than the other two communities in the vegetated treatment, while the *M. sacchariflorus* community had higher fine and coarse sand contents than the other two communities (Table 2).

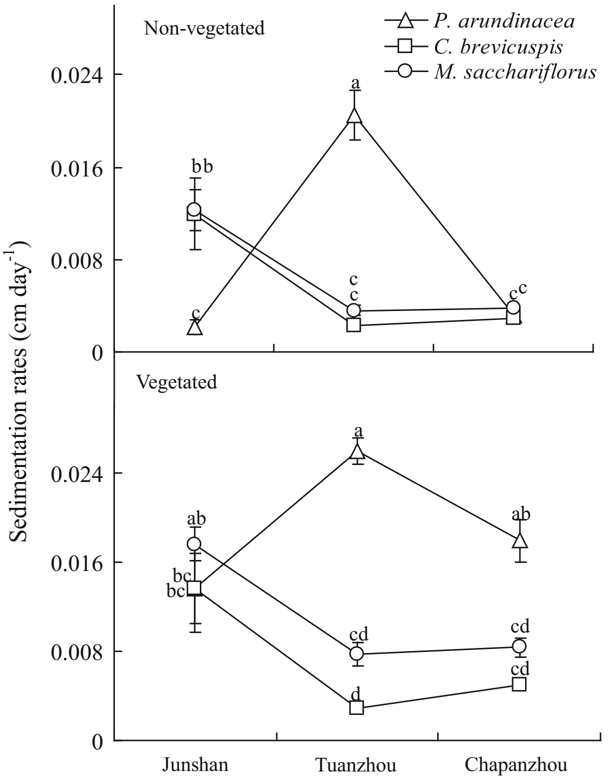

Fig. 3 Sedimentation rates of vegetated and non-vegetated treatments among three communities (*Phalaris arundinacea*, *Carex brevicuspis*, and *Miscanthus sacchariflorus*) in three experimental locations. *Different letters* indicate significant differences between treatments at the 0.05 significance level

Median particle size was much higher in the *M. sacchariflorus* community than that in the other two communities in both the non-vegetated and vegetated treatments, especially in the Junshan and Tuanzhou lakeshores ($P < 0.05$; $F = 14.608$; df = 2; Table 3), while there was no significant change between non-vegetated and vegetated treatments ($P > 0.05$; $F = 0.000$; df = 1; Table 3).

pH, organic matter content, and total N of sediment

Sediment pH was neutral to alkaline, and varied significantly among different vegetation types ($P < 0.05$; $F = 42.316$; df = 2; Table 4). Sediment pH was much lower in the *M. sacchariflorus* community than that in the other two communities (Table 4). In the vegetated treatment, sediment pH was 1.1 to 1.5 and 1.0 to 1.2-fold higher in the *P. arundinacea* and *C. brevicuspis* communities than in the *M. sacchariflorus* community, while in the non-vegetated treatment, it was 1.1 to 1.3 and 1.0 to 1.2-fold higher.

Organic matter content was only significantly influenced by vegetation type ($P < 0.05$; $F = 45.367$; df = 2; Table 4). In both the vegetated and non-vegetated treatments, the order of organic matter content was *M. sacchariflorus* > *C. brevicuspis* > *P. arundinacea*. In the Chapanzhou lakeshore area, in particular, the organic matter content of *M. sacchariflorus* was 1.51 to 1.54 and 2.80 to 4.32-fold higher than that of the *C. brevicuspis* and *P. arundinacea* communities, respectively.

Total N content was relatively high according to the Chinese Sediment Quality Guidelines, and was only significantly influenced by vegetation type ($P < 0.05$; $F = 52.751$; df = 2; Table 4). Total N was 2.1 to 3.5 and 1.3 to 3.6-fold higher in the *M. sacchariflorus* and *C. brevicuspis* communities, respectively, than that in the *P. arundinacea* community.

Factors influencing sediment characteristics

The factors that influenced sediment characteristics changed greatly with different sediment properties. Sedimentation depth of the vegetated treatment, median particle size, and fine silt content were positively affected by plant density (Table 5). Sedimentation due to vegetation and pH were positively influenced by flooding time (Table 5). Sedimentation rate was positively influenced by plant density and height (Table 5). Clay content was negatively related to plant biomass. Coarse silt content was positively

Table 2 Particle size distribution of sediments between non-vegetated and vegetated treatments in three communities (*Phalaris arundinacea*, *Carex brevicuspis*, and *Miscanthus sacchariflorus*) in three lakeshore areas

Vegetation location	Non-vegetated treatment (%)				Vegetated treatment (%)			
	Clay	Fine silt	Coarse silt	Fine sand	Coarse sand	Clay	Fine silt	Coarse silt	Fine sand	Coarse sand
Junshan										
P. arundinacea	2.5 ± 0.2^{a}	41.0 ± 1.2^{a}	48.0 ± 1.4^{a}	7.7 ± 0.9^{b}	0.8 ± 0.3^{b}	3.5 ± 0.1^{a}	45.8 ± 1.8^{a}	46.1 ± 1.4^{a}	3.9 ± 0.8^{c}	0.7 ± 0.6^{b}
C. brevicuspis	2.5 ± 0.2^{a}	39.2 ± 1.2^{a}	48.0 ± 1.4^{a}	9.5 ± 1.6^{b}	0.7 ± 0.4^{b}	2.8 ± 0.2^{b}	39.7 ± 0.4^{b}	46.8 ± 1.2^{a}	9.3 ± 0.9^{b}	1.4 ± 0.7^{b}
M. sacchariflorus	2.2 ± 0.1^{a}	26.0 ± 2.1^{b}	47.9 ± 1.9^{a}	18.9 ± 2.6^{a}	5.1 ± 1.4^{a}	2.1 ± 0.1^{c}	24.0 ± 1.1^{c}	41.9 ± 1.2^{b}	25.4 ± 1.0^{a}	6.6 ± 0.7^{a}
Tuanzhou										
P. arundinacea	2.6 ± 0.2^{a}	63.5 ± 1.9^{a}	29.4 ± 1.9^{a}	4.5 ± 0.2^{c}	0.0 ± 0.0^{c}	4.9 ± 0.1^{a}	64.4 ± 0.6^{a}	30.2 ± 0.7^{a}	0.5 ± 0.1^{c}	0.0 ± 0.0^{b}
C. brevicuspis	3.0 ± 0.3^{a}	47.5 ± 1.8^{b}	$26.5 \pm 0.5^{a,b}$	10.0 ± 1.3^{b}	13.0 ± 2.5^{b}	2.6 ± 0.2^{b}	49.0 ± 3.3^{b}	$27.5 \pm 1.4^{a,b}$	7.8 ± 1.5^{b}	13.1 ± 2.4^{a}
M. sacchariflorus	3.1 ± 0.2^{a}	33.5 ± 2.3^{c}	23.5 ± 1.0^{b}	20.6 ± 2.3^{a}	19.4 ± 1.7^{a}	2.9 ± 0.5^{b}	32.4 ± 3.2^{c}	24.9 ± 1.1^{b}	21.3 ± 1.7^{a}	19.5 ± 3.6^{a}
Chapanzhou										
P. arundinacea	5.4 ± 0.7^{a}	44.6 ± 3.6^{a}	33.6 ± 1.0^{a}	11.2 ± 2.2^{a}	5.2 ± 1.2^{a}	5.5 ± 0.4^{a}	53.7 ± 2.4^{a}	32.4 ± 1.6^{a}	4.8 ± 1.7^{b}	3.6 ± 2.3^{a}
C. brevicuspis	4.6 ± 0.0^{a}	47.1 ± 4.5^{a}	34.5 ± 2.2^{a}	11.0 ± 3.5^{a}	2.8 ± 1.2^{a}	5.0 ± 0.5^{a}	$52.1 \pm 2.3^{a,b}$	32.1 ± 2.8^{a}	$8.7 \pm 3.5^{a,b}$	2.1 ± 0.9^{a}
M. sacchariflorus	5.7 ± 0.2^{a}	48.4 ± 1.4^{a}	30.5 ± 0.8^{a}	12.2 ± 1.1^{a}	3.2 ± 0.9^{a}	4.8 ± 0.6^{a}	45.8 ± 1.5^{b}	28.7 ± 0.3^{a}	15.7 ± 1.1^{a}	5.0 ± 0.6^{a}

Sediment composition: clay (<0.002 mm), fine silt (0.002–0.02 mm), coarse silt (0.02–0.05 mm), fine sand (0.05–0.25 mm), and coarse sand (>0.25 mm). Different letters indicate significant differences between treatments at the 0.05 significance level

influenced by plant height and flooding time. Fine sand content was negatively affected by plant density and positively influenced by elevation. Coarse sand content was negatively affected by plant density and height but positively influenced by elevation. Both organic matter and total N contents were positively affected by elevation and were negatively influenced by plant density.

Discussion

Sediment dynamics in various types of wetlands have been widely studied, and factors that have been implicated in controlling sediment deposition rates include elevation (Hensel et al. 1999), flooding time (Cahoon and Reed 1995), floodwater velocity (Kozerski 2002), surficial floodwater suspended sediment load (Christie et al. 1999), and the presence of vegetation (Madsen et al. 2001; Darke and Megonigal 2003). Today, increasing attention is being paid to the role of vegetation on sedimentation. A previous study on a freshwater tidal flat in the St. Lawrence Estuary and a tidal freshwater marsh in the Pamunkey River, VA reported that the sediment deposition rate was highest in the presence of plants (Darke and Megonigal 2003). In our experiment, the vegetated treatment had a greater sedimentation depth and sedimentation rate in all three communities compared to the non-vegetated treatment, indicating that all three communities promote sediment deposition, which is in agreement with our first hypothesis. Our results also confirmed that *P. arundinacea* had a higher sedimentation capability than *M. sacchariflorus* and *C. brevicuspis* communities. Similar variation in sedimentation ability among different species has been reported in other studies (Horppila and Nurminen 2005; Li et al. 2008a, b). Different macrophyte species have variable influences on water hydrodynamics and sediment retention abilities, which could be attributed to the differences in their architecture and plant tissue distribution within the water column (Horppila and Nurminen 2005).

Sediment deposition rates are largely a function of flood duration. Sites that are flooded more frequently and for a longer time tend to exhibit higher deposition rates (Cahoon and Reed 1995; Leonard 1997; Neubauer et al. 2002). Flooding time varied spatially across the three macrophyte communities because of the differences in their elevation; in the *P. arundinacea* community, flooding time was 1.1 to 1.3 and 1.4 to 2.2-fold higher than the *M. sacchariflorus* and *C. brevicuspis* communities, respectively. The different flooding times can be used to explain the highest sedimentation depth in the *P. arundinacea* community, and the multiple linear regression confirmed that sedimentation depth was significantly linked to flooding time. The relationship between flooding time and sediment deposition

Table 3 Median particle size (D_{50}) of sediments between non-vegetated and vegetated treatments in three communities (*Phalaris arundinacea*, *Carex brevicuspis*, and *Miscanthus sacchariflorus*) in three lakeshore areas

Vegetation location	Non-vegetated treatment (mm)	Vegetated treatment (mm)
Junshan		
P. arundinacea	0.024 ± 0.001^{b}	0.021 ± 0.001^{c}
C. brevicuspis	0.025 ± 0.001^{b}	0.025 ± 0.001^{b}
M. sacchariflorus	0.034 ± 0.002^{a}	0.037 ± 0.001^{a}
Tuanzhou		
P. arundinacea	0.016 ± 0.000^{b}	0.015 ± 0.000^{b}
C. brevicuspis	0.021 ± 0.001^{b}	0.021 ± 0.002^{b}
M. sacchariflorus	0.040 ± 0.006^{a}	0.042 ± 0.008^{a}
Chapanzhou		
P. arundinacea	0.021 ± 0.003^{a}	0.017 ± 0.001^{b}
C. brevicuspis	0.020 ± 0.002^{a}	0.018 ± 0.001^{a,b}
M. sacchariflorus	0.019 ± 0.001^{a}	0.020 ± 0.001^{a}

Different letters indicate significant differences between treatments at the 0.05 significance level

Table 4 Sediment pH, organic matter content, and total N of vegetated and non-vegetated treatments in three communities (*Phalaris arundinacea*, *Carex brevicuspis*, and *Miscanthus sacchariflorus*) in three experimental locations

Vegetation location	Non-vegetated treatment			Vegetated treatment		
	pH	Organic matter content (%)	Total N (mg g^{-1})	pH	Organic matter content (%)	Total N (mg g^{-1})
Junshan						
P. arundinacea	8.1 ± 0.03^{a}	4.3 ± 0.57^{b}	2.4 ± 0.10^{c}	8.1 ± 0.09^{a}	4.4 ± 0.32^{b}	2.4 ± 0.10^{c}
C. brevicuspis	8.0 ± 0.06^{a}	5.5 ± 0.25^{b}	3.2 ± 0.12^{b}	8.0 ± 0.05^{a}	5.6 ± 0.36^{b}	3.1 ± 0.09^{b}
M. sacchariflorus	7.7 ± 0.01^{b}	7.7 ± 0.64^{a}	5.6 ± 0.15^{a}	7.6 ± 0.05^{b}	9.6 ± 1.18^{a}	5.8 ± 0.09^{a}
Tuanzhou						
P. arundinacea	8.2 ± 0.02^{a}	2.3 ± 0.21^{b}	2.2 ± 0.01^{b}	8.0 ± 0.08^{a}	2.5 ± 0.32^{b}	2.2 ± 0.01^{b}
C. brevicuspis	7.7 ± 0.30^{a}	11.4 ± 1.04^{a}	7.9 ± 0.52^{a}	7.2 ± 0.09^{b}	11.5 ± 0.77^{a}	7.6 ± 0.26^{a}
M. sacchariflorus	6.3 ± 0.44^{b}	11.1 ± 0.91^{a}	7.7 ± 0.55^{a}	5.3 ± 0.17^{c}	10.6 ± 1.36^{a}	7.1 ± 0.96^{a}
Chapanzhou						
P. arundinacea	8.2 ± 0.02^{a}	1.7 ± 0.85^{c}	2.3 ± 0.10^{c}	8.1 ± 0.05^{a}	2.5 ± 0.08^{c}	2.1 ± 0.04^{c}
C. brevicuspis	8.1 ± 0.05^{a}	4.8 ± 0.24^{b}	3.4 ± 0.12^{b}	8.1 ± 0.04^{a}	4.7 ± 0.52^{b}	3.5 ± 0.19^{b}
M. sacchariflorus	7.0 ± 0.13^{b}	7.3 ± 0.62^{a}	4.7 ± 0.17^{a}	6.8 ± 0.39^{b}	7.1 ± 0.32^{a}	4.6 ± 0.10^{a}

Different letters indicate significant differences between treatments at the 0.05 significance level

rates has also been confirmed in other studies (Leonard 1997; Neubauer et al. 2002; Darke and Megonigal 2003).

Besides flooding time, plant characteristics also play an important role in determining the amount of vegetation–induced sediment deposition (Vermaat et al. 2000; Li et al. 2008a, b). Trapping of suspended matter is achieved through a combination of processes. James et al. (2004) confirmed that a much higher shear stress was required to resuspend sediments when high biomass sheltered the sediment surface from wave action. *Potamogeton maackianus* had a greater capacity to prevent sediment resuspension than *Vallisneria spinulosa* because of its higher shear stress and higher biomass accumulation (Li et al. 2008a, b). Darke and Megonigal (2003) proved that plant density and height were highly correlated with sediment deposition rate at a downstream site in the Mattaponi River. However, studies conducted by Pearce et al. (1998) confirmed that sediment yields from plots under two montane riparian grass and sedge communities subjected to three height treatments did not vary with vegetation height. Our study also confirmed that plant density is significantly correlated with sedimentation depth in the vegetated treatment. In addition, the lower sedimentation capability of *C. brevicuspis* might be due to its different shoot morphology, which is typically characterized by a false stem composed of a series of overlapping leaf sheaths (Bernard

Table 5 Standardized coefficients (β values) of the multiple linear regressions between sediment properties and vegetation characteristics, elevation, and flooding time

Sedimentation characteristic	β values						Adjusted r^2
	Density (plants m^{-2})	Height (cm)	Diameter (mm)	Biomass (kg)	Elevation (m)	Flooding time (days)	
Sedimentation depth of vegetation treatment	0.909*	–	–	–	–	–	0.816
Sedimentation due to vegetation	–	–	–	–	–	0.800*	0.618
Sedimentation rate	1.163	0.575	–	–	–	–	0.781
Clay	–	–	–	–0.502*	–	–	0.205
Fine silt	0.787*	–	–	–	–	–	0.595
Coarse silt	–	1.361*	–	–	–	1.689*	0.560
Fine sand	–0.506*	–	–	–	0.523*	–	0.866
Coarse sand	–0.488*	–1.312*			1.458*	–	0.754
Median particle size	0.646	–	–	–	–	–	0.381
pH	–	–	–	–	–	0.689*	0.442
Organic matter content	–0.432*	–	–	–	0.491*	–	0.670
Total N	–0.369*	–	–	–	0.603*	–	0.767

*$P < 0.016$ after Bonferroni correction

1990). During flooding, the *C. brevicuspis* plant community without vertical stems compressed more easily than the other two plant communities, which significantly reduced the interception area between the plant and the water column and, consequently, lead to the lowest sedimentation capability.

Our study found that other sediment characteristics such as particle size distribution, median particle size, and organic matter content did not show statistically significant differences between the vegetated and non-vegetated areas, except for clay and fine sand contents, which is inconsistent with other studies. For instance, Kenworthy et al. (1982) and Madsen et al. (2001) found that organic matter content accumulated more in submerged macrophyte beds than in adjacent unvegetated areas. Sand-Jensen (1998) also confirmed that in dense patches of *C. cophocarpa* and *E. canadensis*, the sediment surface was markedly raised and enriched with fine particles. However, our result is consistent with Mellors et al. (2002), which confirmed that particle size distribution and nutrient status were not significantly different between vegetated and non-vegetated habitats. Our study also demonstrated that these sediment characteristics vary greatly among different plant community types and are significantly correlated with different vegetation characteristics, elevation, and flooding time, which is in agreement with our second hypothesis. Lower plant density might account for higher sand and lower clay and silt contents in the *M. sacchariflorus* community. Newbolt et al. (2008) confirmed that sediments from sparsely vegetated communities had more sand and less clay than sediments from densely vegetated milfoil communities. Higher pH in the *P. arundinacea* community might be caused by longer flooding time, as confirmed by the multiple linear regression analysis, mainly because of the denitrification of soil nitrate to nitrogen gas under anaerobic conditions (Moraghan and Patrick Jr 1974). In contrast, the low organic matter and total N contents in the *P. arundinacea* community might be caused by higher intensity of flood erosion due to its low elevation distribution.

In conclusion, our study demonstrated that the presence of three macrophytes could promote sedimentation and that the order of sedimentation ability was *P. arundinacea* > *M. sacchariflorus* > *C. brevicuspis*. We also found that sediment characteristics varied greatly among these three communities and were significantly linked to vegetation characteristics (e.g. plant density and height), and elevation, as well as flooding time. Due to high sediment deposition due to farmland expansion, the area and water storage capability of Dongting Lake decreased drastically, resulting in an increase in the frequency of flood disasters after the 1980s (Zhao et al. 2005; Yu et al. 2009). Our results provide experimental information on the role of macrophytes in promoting sedimentation, facilitating better understanding of the interactions between macrophytes and changing lake area, and may assist in the conservation and management of Dongting Lake. In addition, accumulation of fine sediment was accompanied by the deposition of plentiful seeds and other plant propagules. Sediment retention caused by these three emergent macrophytes could accelerate landform accretion, which might benefit plant establishment and vegetation regeneration, especially in some marginal areas (Gurnell et al. 2007; Liffen et al. 2011; Osei et al. 2015). However, these results were obtained from a 1-year experiment, and sedimentation characteristics may change significantly among different years because of the large-scale fluctuations in water level. Therefore, long-term observations are needed to fully understand the sediment characteristics of this lake.

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