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Biogenic silica in intertidal marsh plants and associated sediments of the Yangtze Estuary

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Abstract

Biogenic silica (BSi) contents in the marsh plants (*Phragmites australis*, *Scirpus mariqueter* and *Spartina alterniflora*) and associated sediments in Chongming Island eastern intertidal flat of the Yangtze Estuary were determined. The BSi contents in *P. australis*, *S. mariqueter* and *S. alterniflora* varied from 25.78–42.74 mg/g, 5.71–19.53 mg/g and 6.71–8.92 mg/g, respectively. Over the entire growth season, *P. australis* and *S. mariqueter* were characterized by linear accumulation patterns of BSi. The aboveground biomass (leaves and culms) of the marsh plants generally contained more BSi than underground biomass (roots). BSi contents were relatively higher in dead plant tissues than in live tissues which was probably due to the decomposition and the leaching of labile components of plant tissues such as organic carbon and nitrogen. Comparing with the habitats of *S. mariqueter* and *S. alterniflora*, the highest BSi content was recorded in sediments inhabited by *P. australis*, with an annual average of 15.69 mg/g. Overall, the intertidal marshes in the Yangtze Estuary may act as a net sink of BSi via plant uptake and sedimentary burial.

Key words: biogenic silica; marsh plants; intertidal flat; the Yangtze Estuary

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Introduction

Silicate is one of the major nutrients for estuarine and coastal ecosystems, which can significantly affect planktonic microbial communities (e.g., diatoms, radiolaria and silicoflagellate) (Srithongouthai et al., 2003; Wu and Chou, 2003; Natori et al., 2006). Comparing with silicate, large amounts of anthropogenic nitrogen and phosphorus have been transported into the estuarine and coastal areas over the past several decades (Boesch, 2002; Smith, 2006), and thus largely alter nutrient compositions in receiving waters, which is related closely to the occurrence of eutrophication problems (Braga et al., 2000; Havens et al., 2001; Dai et al., 2007). Therefore, it is of eco-environmental significance to study the biological silica (BSi) cycling in estuarine and coastal ecosystems. So far, numerous studies have focused on the production, accumulation and dissolution of BSi in those environmental systems (Banahan and Goering, 1986; Natori et al., 2006; Luo et al., 2008). In general, the tidal marshes constitute major portions of meso- and macrotidal estuaries across the world. Although the importance of the tidal marshes to the estuarine BSi cycling has been recently recognized (Norris and Hackney, 1999; Struyf et al., 2005), the study is by far limited compared with nitrogen and phosphorus cycles. Also, the roles of the tidal marshes in the estuarine BSi cycling still need to be defined in detail (Conley, 1997; Struyf et al., 2006).

The Yangtze River is the largest river in Euro-Asian continent, and is ranked third in length, fifth in freshwater discharge and fourth in sediment discharge in the world (Tian et al., 1993; Liu et al., 2003). The Yangtze River plays a significant role in the global biogeochemical cycles. Numerous reports have studied the distributions and variations of nitrogen and phosphorus in the Yangtze estuarine waters (Edmond et al., 1985; Yu et al., 1990; Hou et al., 2002) and in coastal sediments (Ou et al., 2002; Zhang et al., 2002; Hou et al., 2009), also nutrient fluxes across the intertidal sediment-water interface (Hou et al., 2006), and adsorption of ammonium and phosphate on sediments in the Yangtze Estuary (Liu et al., 2002; Hou et al., 2003). However, to our knowledge, few studies have dealt with biogenic silica cycling in the estuarine system (Hou et al., 2008).

The objectives of the present study are (1) to investigate the contents of BSi in plants and associated sediments in the intertidal marshes; (2) to compare the difference in BSi contents between the tissues of marsh plants; (3) to explore the accumulation patterns of BSi in plants; and (4) to elucidate the role of the intertidal marshes in the estuarine system.

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1 Materials and methods

1.1 Study area

The Yangtze Estuary is situated on the center of east coast of China and covers from 31°45′N to 30°50′N and 121°50′E to 122°30′E. Due to the substantial transportation of suspended sediment by the Yangtze River, the extensive tidal flats develop along the Yangtze estuarine and coastal zone, which can be divided into the high, middle and low tidal flats. The high tidal flats are generally characterized by clayey sediments, the middle tidal flats by silts mixed with clays, and the low tidal flats by silts with fine sands (Hou et al., 2007). The study site is located in the eastern intertidal marsh of Chongming Island where the marsh vegetation is dominated by *Phragmites australis*, *Scirpus mariqueter* and *Spartina alterniflora* (Fig. 1). The study area is a representative intertidal flat of the Yangtze Estuary, with an area of approximately 4688 ha (Huang et al., 2007). It is roughly estimated that *P. australis*, *S. mariqueter* and *S. alterniflora* occupy about 452, 2953 and 1283 ha, respectively.

1.2 Sample collection and pretreatment

Live plant samples of *P. australis*, *S. mariqueter* and S. *alterniflora* were collected in April, June, August and October 2007, while dead plants were sampled in February 2008. At each sampling, 8–10 plots (50 cm × 50 cm) were randomly chosen in the same area (ca., 6 m^2) for collecting each vegetation sample by a steel shovel. Sampling depth of individual vegetation depended completely on the distribution of the major root-rhizome system. In addition, triplicate sediments cores (7.5 cm i.d., 30 cm in length) were also taken from each vegetation habitat using PVC tubes. After collection, all samples were immediately transported to the laboratory. Upon arrival at the laboratory, plant samples were rinsed with deionized water and separated into roots, culms and (or) leaves. After they were dried at 70–80°C, the same plant tissues were mixed, ground and sieved through a 300-µm mesh for BSi analysis. Core sediments were sliced at the intervals of 0–1, 1–10, 10–20 and 20–30 cm, and subsequently ground and sieved through a 300-µm mesh after frozen-drying.

1.3 Analysis

To extract plant silica, sieved plant samples were soaked in 50% bleach solutions for 1 hr (Norris and Hackney, 1999), and then incubated in 1% Na_2CO_3 for 4 hr (DeMaster, 1981). Sedimentary BSi was extracted for 7 hr with 1% Na_2CO_3 at 85°C, and subsamples were serially taken at 1 hr interval. The extracted silica was plotted versus time, and the extrapolated concentration (Y intercept) was used to estimate the silica content of the sediment samples (DeMaster, 1981). Dissolved silica in the extractions was measured by the molybdate blue spectrophotometric method (Mortlock and Froelich, 1989). All plant silica and sedimentary BSi are reported as mg SiO_2 /g dry weight. The contents of organic carbon (OC) and organic nitrogen (ON) in plants and sediments were determined using a CHN elementary analyzer (VVAIRO EL3, Elemetar, Germany) (Liu et al., 2006; Yu et al., 2008). Sediment grain size was analyzed using a Laser grain sizer (LS 13320, Beckman Coulter, USA).

2 Results and discussion

2.1 Characteristics of marsh habitats

Sediments in the habitats of *P. australis*, *S. mariqueter* and *S. alterniflora* were composed mainly of silty clay and clayey silt (Table 1), as observed in many salt marshes of the Yangtze Estuary (Liu et al., 2006). In general, fine fractions in the marsh habitats accounted for more than 92% of sediments. The highest content of sedimentary organic carbon was found in the habitat of *P. australis* (8.16–13.02 mg/g), followed by *S. alterniflora* (8.05–11.36 mg/g) and *S. mariqueter* (4.66–8.31 mg/g). Similar to sedimentary organic carbon, the maximum and minimum contents of sedimentary organic nitrogen were recorded in the habitats of *P. australis* (0.92–1.32 mg/g) and *S. mariqueter* (0.53–0.92 mg/g).

Organic carbon and nitrogen in the tissues of the marsh

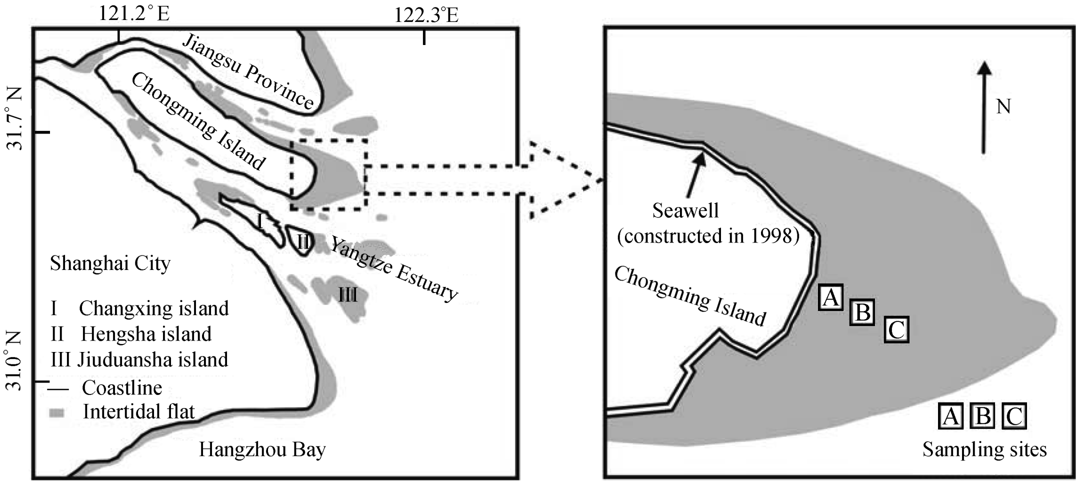

Fig. 1 Location of Yangtze Estuary and the sampling sites. A, B and C represent the sampling sites of *Phragmites australis*, *Spartina alterniflora* and *Scirpus mariqueter*, respectively.

Table 1 Physico-chemical parameters of sediments in the marsh habitats of *P. australis*, *S. mariqueter* and *S. alterniflora*

	P. australis			*S. mariquete*			*S. alterniflora*		
	Clay-silt (%)	OC (mg/g)	ON (mg/g)	Clay-silt(%)	OC (mg/g)	ON (mg/g)	Clay-silt (%)	OC (mg/g)	ON (mg/g)
Apr	95.9	10.14	0.95	93.2	4.66	0.53	98.5	8.05	0.93
Jun	99.1	8.16	1.01	99.3	8.23	0.92	98.6	8.52	0.92
Aug	96.4	8.32	0.92	97.2	8.31	0.86	95.6	8.43	0.97
Oct	97.1	9.14	1.07	96.9	6.52	0.82	99.2	9.86	1.05
Feb	95.7	13.02	1.32	92.1	6.38	0.83	94.8	11.36	1.24

OC: organic carbon, ON: organic nitrogen.

plants are shown in Fig. 2. In general, *P. australis* had the highest content of organic carbon, followed by *S. alterniflora* and *S. mariqueter*. In contrast, the maximum content of organic nitrogen was observed in *S. mariqueter*, while the minimum appeared in *S. alterniflora*. Organic carbon and organic nitrogen showed significant differences between the different tissues of the marsh plants (one-way ANOVA, $p < 0.05$). Plant culms and leaves generally contained more organic carbon and organic nitrogen than roots. Seasonal changes of organic carbon in the marsh plants were not significant (one-way ANOVA, $p > 0.05$). However, organic nitrogen in plants showed significant seasonal differences (one-way ANOVA, $p < 0.05$). With plant growth, the contents of organic nitrogen gradually decreased. Compared with live plants, organic carbon and organic nitrogen in dead plants were relatively low, which may be mainly due to the microbial decomposition of organic matter (Wilson et al., 1986; Torreta and Takeda, 1999; Davis III et al., 2003). In addition, Fig. 3 gives the change characteristics of biomass and height of the marsh plants during the growth season, showing that they almost reached mature stages in August.

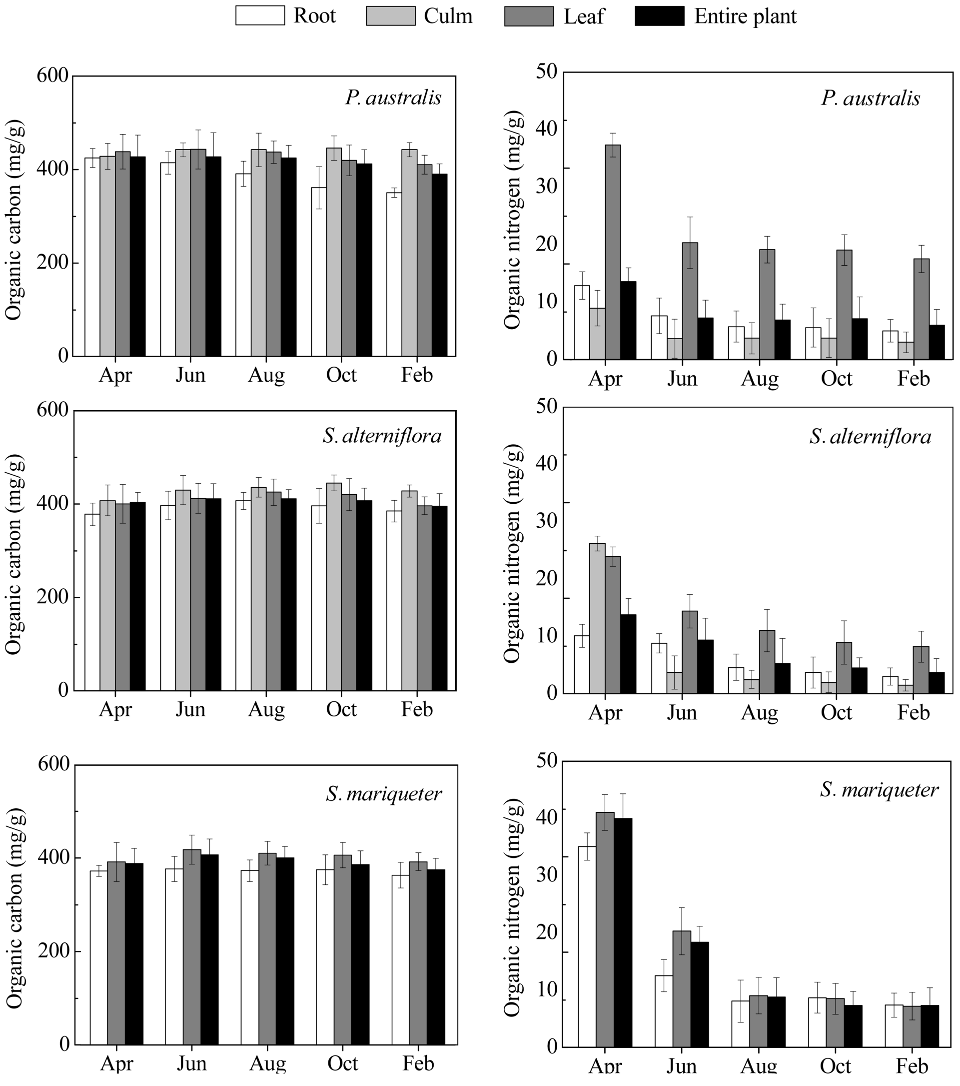

Fig. 2 Organic carbon and organic nitrogen in the tissues of *P. australis*, *S. mariqueter* and *S. alterniflora* over the sampling season. Vertical bars represent standard deviation.

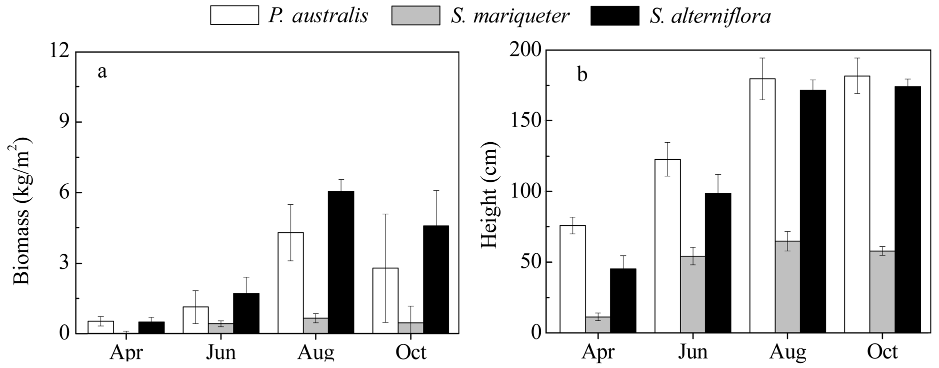

Fig. 3 Biomass (a) and height (b) of *P. australis*, *S. mariqueter* and *S. alterniflora* over growth seasons. Vertical bars represent standard deviation.

2.2 Biogenic silica in marsh plants

As shown in Fig. 4, the contents of BSi in *P. australis* was the most, followed by *S. mariqueter* and *S. alterniflora*. Throughout the growth season (April to October), BSi contents in *P. australis*, *S. mariqueter* and *S. alterniflora* were in the range of 25.78–40.92, 5.71–18.12 and 6.71–7.97 mg/g, respectively. In general, wetland plants are known as silicon accumulators, which can assimilate dissolved silicate faster than that expected from nonselective uptake of dissolved silicate during plant growth (Raven, 2003; Struyf et al., 2005). Ma et al. (2001) reported that silicon accumulators are enriched in BSi (> 10 mg/g) relative to their dry weight, whereas nonaccumulators of silicon contain low amounts of BSi (< 5 mg/g). This reflects that *P. australis* and *S. mariqueter* are silicon accumulators at the study area, and *S. alterniflora* should belong to an intermediate category between accumulators and nonaccumulators of silicon. Differential biological strategies of assimilating dissolved silicate are hypothesized to be the reason for different BSi content in *P. australis*, *S. mariqueter* and *S. alterniflora*. Comparing with *S. alterniflora*, *P. australis* and *S. mariqueter* may be more active in taking up dissolved silicate by their roots.

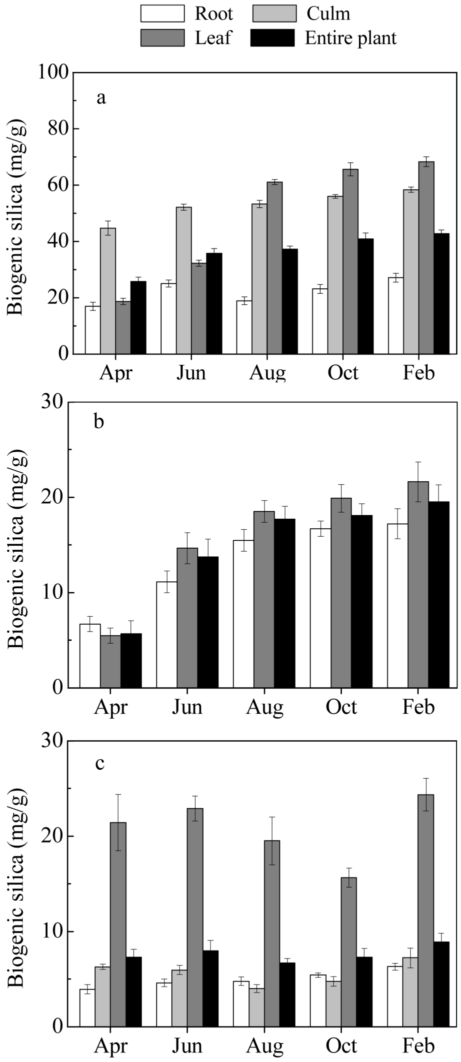

Fig. 4 Biogenic silica in the tissues of *P. australis* (a), *S. mariqueter* (b) and *S. alterniflora* (c) over sampling seasons. Vertical bars represent standard deviation.

Significant differences in BSi contents were found between the three tissues (Fig. 4). Generally, the live aboveground tissues contained more BSi. This may be related to the relatively higher transpiration in the aboveground tissues of the marsh plants. BSi in plants has been found to be mainly deposited at sites with the highest transpiration (e.g., plant leaves), where transported water is saturated with dissolved silicate, resulting in its deposition (Handreck and Jones, 1968; Jones and Handreck, 1969; Struyf et al., 2005). In contrast, lower BSi contents appeared in the live underground tissues (roots), with the values of 16.95–23.12, 6.72–16.71 and 3.93–5.44 mg/g for *P. australis*, *S. mariqueter* and *S. alterniflora*, respectively. This is mainly attributed to the transfer of dissolved silicate from roots to leaves with water transport (Jones and Handreck, 1969; Epstein, 1994).

Comparing with living marsh plants, dead plants had relatively higher BSi contents, with the values of 42.74, 19.53 and 8.92 mg/g for *P. australis*, *S. mariqueter* and *S. alterniflora*, respectively (Fig. 4). Enrichment of BSi in dead marsh plants is probably due to the decomposition and leaching of more labile components of plant tissues such as organic carbon and organic nitrogen (Gallagher et al., 1976; Benner et al., 1987; Eleuterius and Lanning, 1987; Currin et al., 1995). As the labile components were leached from the tissues of marsh plants, the BSi contents in dead plants gradually increased. This hypothesis is also supported by the increased OC:BSi and ON:BSi ratios in decayed plants collected in February.

In this work, significant linear correlations between BSi contents and culm heights were observed for *P. australis* ($R = 0.87$, $p = 0.0002$) and *S. mariqueter* ($R = 0.89$, $p = 0.0001$). Assuming that the height of plant culm can be used as a plant age indicator (Norris and Hackney, 1999), it can reflect that there was linear accumulation of BSi in *P. australis* and *S. mariqueter* throughout their growth seasons. However, the linear accumulation pattern was not found for *S. alterniflora*. It is supported by no significant seasonality of BSi contents in *S. alterniflora* (one-way ANOVA, $p > 0.05$).

2.3 Biogenic silica in marsh sediments

The contents of BSi in sediments from the habitats of *P. australis*, *S. mariqueter* and *S. alterniflora* are shown in Fig. 5. The highest BSi content was recorded in sediments inhabited by *P. australis* (10.84–22.49 mg/g), followed by *S. alterniflora* (9.01–15.43 mg/g), and *S. mariqueter* (8.56–14.25 mg/g). Significant seasonal change of sedimentary BSi contents was found in each vegetation habitat (one-way ANOVA, $p < 0.05$). The lowest contents of BSi appeared in June and August (summer). This is partly attributed to relatively rapid dissolution of sedimentary amorphous silica induced by a higher temperature in the warm season (House et al., 2000; Boswell et al., 2002). Also, fast uptake by the marsh plants may make significant contribution to sedimentary BSi loss in this season (Raven, 2003). In contrast, the maximum contents of BSi were observed in February sediments. It is hypothesized that higher BSi contents in February are likely related to the burial of the plant phytoliths in the marsh sediments. In addition, there was a pronounced depth difference in sedimentary BSi contents in each vegetation habitat (one-way ANOVA, $p < 0.05$). The highest BSi contents were appeared in the upper sediment layers, gradually decreasing in the deeper sediments layers (Fig. 5). The depth gradient may be resulted from BSi loss via early diagenetic reaction over its burial (Struyf et al., 2005).

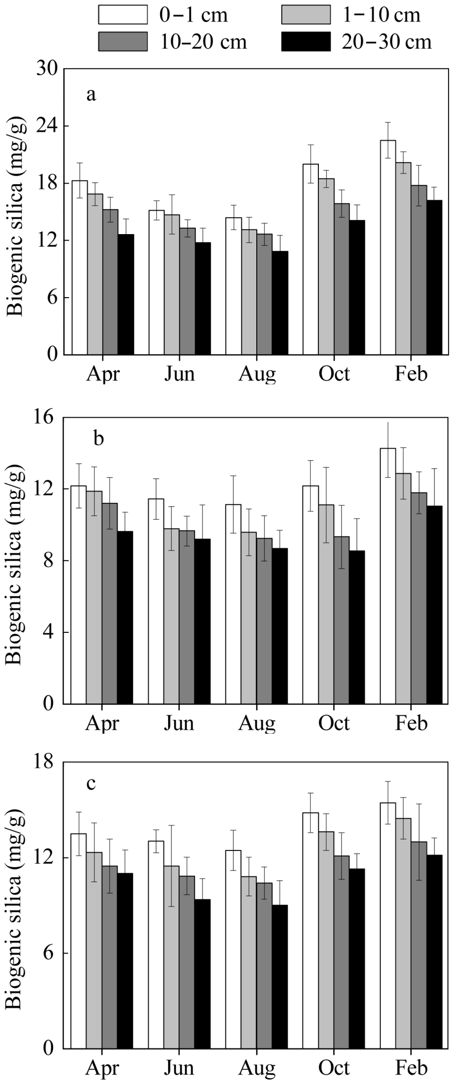

Fig. 5 Biogenic silica in different sediment layers from the mash habitats of *P. australis* (a), *S. mariqueter* (b) and *S. alterniflora* (c) over the sampling seasons. Vertical bars represent standard deviation.

2.4 Roles of the intertidal marshes

In the present work, we also attempted to clarify the roles of the intertidal marshes in the whole estuarine BSi cycling. According to the maximum biomass and BSi contents in marsh plants, the annual stocks of BSi in *P. australis*, *S. mariqueter* and *S. alterniflora* were roughly estimated to be 1.75×10^5, 1.18×10^4, 4.81×10^4 mg/m^2, respectively. The burial flux (BF, mg/(m^2·yr)) of BSi in each vegetation habitat can be calculated using the following Eq. (1) (Hou et al., 2009):

$$\mathrm{BF} = C_{\mathrm{BSi}} \times \rho_{\mathrm{S}} \times R_{\mathrm{S}} \times 10^4 \quad (1)$$

where, C_{BSi} (mg/g) is the annual average content of BSi in sediments, ρ_{S} (g/cm^3) is the sediment density, R_{S} (cm/yr) is the sedimentation rate, 10^4 is the conversion factor from cm^2 to m^2. At the study area, the sediment density is about 2.68 g/cm^3 (Hou et al., 2003), and the sedimentation rates are approximately 6.1, 2.5 and 5.5 cm/yr in the *P. australis*, *S. mariqueter* and *S. alterniflora* habitats, respectively. Therefore, the BF of BSi can be estimated to be 2.95×10^6 mg/(m^2·yr) in the *P. australis* habitat, 8.21×10^5 mg/(m^2·yr) in the *S. mariqueter* habitat and 2.04×10^6 mg/(m^2·yr) in the *S. alterniflora* habitat. In addition, the vertical distribution characteristics of sedimentary BSi shows that the deeper sediment has lost a substantial part of BSi through dissolution (Fig. 5). Based on the changes in sedimentary BSi over burial, the average dissolution flux (DF, mg/(m^2·yr)) of BSi in the sediment profile (0–20 cm) was estimated by the following Eq. (2):

$$\mathrm{DF} = \Delta C_{\mathrm{BSi}} \times \rho_{\mathrm{S}} \times R_{\mathrm{S}} \times 10^4 \quad (2)$$

where, ΔBSi (mg/g) is the difference in BSi contents between the surface and bottom sediments. The calculated DF of BSi in the sediment profiles were 8.12×10^5, 1.88×10^5 and 4.83×10^5 mg/(m^2·yr) in the *P. australis*, *S. mariqueter* and *S. alterniflora* habitats, respectively. If these calculated results are extrapolated to the whole Estuary, the accumulation and dissolution amounts of BSi in the entire intertidal marshes can be obtained on an annual scale (Table 2). It is shown that the sediments are the major sink of BSi in the intertidal marshes of

Table 2 Annual accumulation and dissolution amounts of BSi in entire intertidal marshes of the Yangtze estuary

Marsh habitat	Habitat area (ha)	Vegetative BSi (tons)	Buried BSi (tons)	Dissolved BSi (tons)	Net BSi (tons)
P. australis	1.10×10^4	1.93×10^4	3.25×10^5	-8.94×10^4	2.55×10^5
S. mariqueter	5.70×10^3	6.73×10^2	4.68×10^4	-1.07×10^4	3.68×10^4
S. alterniflora	4.55×10^3	2.19×10^3	9.29×10^4	-2.20×10^4	7.31×10^4

Negative value means the loss of BSi from marsh sediments.

the Yangtze Estuary compared with the marsh plants. However, the marsh sediment also is an important source of dissolved silicate for the estuarine ecosystem, which can annually release 8.94×10^4, 1.07×10^5 and 2.20×10^4 tons of BSi from the *P. australis*, *S. mariqueter* and *S. alterniflora* marsh sediments, respectively. The dissolved silica may be discharged from the intertidal marshes by flooding water, and supplied to the estuarine ecosystem. Overall, the intertidal marshes act as a net sink of BSi in the estuarine ecosystem, which can annually trap 2.55×10^5, 3.68×10^4 and 7.31×10^4 tons of BSi in the *P. australis*, *S. mariqueter* and *S. alterniflora* habitats, respectively.

3 Conclusions

Over growth seasons, the contents of BSi in the marsh plants ranged from 25.78–40.92, 5.71–18.12 and 6.71–7.97 mg/g for *P. australis*, *S. mariqueter* and *S. alterniflora*, respectively. According to the difference in plant silica contents, *P. australis* and *S. mariqueter* were found to be silicon accumulators at the study area, while *S. alterniflora* belonged to an intermediate category between accumulators and nonaccumulators of silicon. There were linear accumulation patterns of BSi in *P. australis* and *S. mariqueter* throughout their growth seasons. In general, leaves accumulated more BSi than other tissues, because BSi in plants is mainly deposited at sites with the highest transpiration. In contrast to live marsh plants, dead plants had relatively higher BSi contents. It is primarily due to the decomposition and leaching of more labile components of plant tissues such as organic carbon and organic nitrogen. BSi contents in the marsh sediments showed significant seasonal changes. The lowest contents of BSi generally appeared in June and August (summer), while the highest contents of BSi were observed in February sediments. The seasonality of sedimentary BSi is related closely to BSi dissolution and plant uptake. In addition, an apparent depth gradient was observed at the study area, with highest BSi contents in the upper sediment layers. Comparing with plants, sediments are the major sink of BSi in the intertidal marshes of the Yangtze Estuary. Due to BSi dissolution over burial, the marsh sediments also act as a potential source of dissolved silicate for the estuarine system. Altogether, the intertidal marshes, however, plays an important role in BSi retention in the Yangtze estuarine ecosystem.

Acknowledgments

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