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Effect of an Alien Species *Spartina alterniflora* Loisel on Biogeochemical Processes of Intertidal Ecosystem in the Jiangsu Coastal Region, China*[1]

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ABSTRACT

Spartina alterniflora Loisel, a species vegetating in intertidal flats along the eastern coast of the United States, was introduced in China almost 30 years ago and has become an urgent topic due to its invasiveness in the coastal zone of China. The impacts of this alien species *S. alterniflora* on intertidal ecosystem processes in the Jiangsu coastland were investigated by comparing the sediment nutrient availability and trace element concentration characteristics in a mudflat and those of a four-year old *Spartina* salt marsh that had earlier been a mudflat. At each study site, fifteen plots were sampled in different seasons to determine the sediment characteristics along the tidal flats. The results suggested that *Spartina* salt marsh sediments had significantly higher total N, available P, and water content, but lower pH and bulk density than mudflat sediments. Sediment salinity, water content, total N, organic C, and available P decreased along a seaward gradient in the *Spartina* salt marsh and increased with vegetation biomass. Furthermore, the concentrations of trace elements and some metal elements in the sediment were higher under *Spartina* although these increases were not significant. Also, in the *Spartina* marsh, some heavy metals were concentrated in the surface layer of the sediment. The *Spartina* salt marsh in this study was only four years old; therefore, it is suggested that further study of this alien species on a longer time frame in the Jiangsu coastland should be carried out.

Key Words: alien species, biogeochemical processes, intertidal ecosystem, salt marsh, *Spartina alterniflora* Loisel

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Salt marshes are generally considered among the most productive ecosystems in the world, with important ecological and social functions (Costanza *et al.*, 1997; Mitsch and Gosselink, 2000). The ecosystem is characterized by inundated and saline soil conditions, few associated vegetation types, and the inability to resist disturbance. Considering its positive effects of slowing water flow (Knuston *et al.*, 1982) and accelerating sediment deposition (Stumpf, 1983), *Spartina alterniflora* Loisel, a species vegetating in intertidal flats along the eastern coast of the United States, was introduced into China in 1979 to promote the seaward expansion of land. Now, the coastline of north Jiangsu Province, China, protected by *S. alterniflora*, is about 410 km long (Shen *et al.*, 2002). This exotic species has colonized the front line of salt marshes in the form of pure stands in the coastal region of north Jiangsu.

The reported studies of *S. alterniflora* have focused on its growth characteristics (Gallagher *et al.*, 1980; Fang *et al.*, 2004), invasive mechanism (Davis *et al.*, 2004), ecological effects such as the impact on the carbon cycle of salt marshes (Gallagher *et al.*, 1976; Gallagher and Plumley, 1979; Valery *et al.*, 2004), application in restoring the polluted or destroyed salt marsh (Gallagher *et al.*, 1979; Lin *et al.*, 2002; Craft *et al.*, 2003; Weis and Weis, 2004), and amelioration of the negative impacts on the salt marsh due to the rise in the sea level (Mendelssohn and Kuhn, 2003). Although *S. alterniflora* is

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useful in coastal wetland conservation and restoration, the species has become an urgent topic among scientists due to its invasion of local ecosystems in the coastal zone of China. We previously examined the dynamics of nutrients and mineral elements in the *Spartina* salt marsh (Qin *et al.*, 1992a, 1992b, 1992c, 1985; Zhou *et al.*, 1985), but the variability in nutrient availability caused by the presence of *S. alterniflora* has not received sufficient attention in China. In recent years, Chinese scholars have studied the effect in accelerating sedimentation and the economic exploitation and ecological engineering application of this species (Chen, 1990; Qin *et al.*, 1998; Ma *et al.*, 2001, 2002; Shen *et al.*, 2003), as well as the expansion and distribution of *Spartina* in Jiangsu (Shen *et al.*, 2002). Moreover, Chen *et al.* (2004) reported local competitive effects on *Scirpus mariqueter* by *Spartina* at Chongming Island in the Yangtze River estuary. But up to the present, the study in China of the effect of *Spartina* on the intertidal ecosystem processes and functions is deficient.

In this study, the impacts of *S. alterniflora* on the physiochemical properties of intertidal sediments in the Jiangsu coastland were compared to similar properties in barren tidal flats, used as a control. The objectives were 1) to analyze the effect of *S. alterniflora* on biogeochemical processes of the intertidal ecosystem in the Jiangsu coastland and 2) to provide the primary foundation for evaluating the ecological, social, and economic effects of *S. alterniflora* in the inshore areas of China.

MATERIALS AND METHODS

The Jiangsu coastland has a northern sub-tropical monsoon climate (Ren, 1985), with a mean annual precipitation ranging from 850 to 1 000 mm and a mean air temperature ranging from −1.5 to 2.5 °C in the winter and 26.5 to 27.5 °C in the summer. For this study, the sampling site for the *Spartina* salt marsh was located at the Dafeng coastland and the sampling site for the mudflat was located at the Rudong coastland.

The coastline of Dafeng County is 112 km long and has the most developed *Spartina* salt marsh and the highest sediment accretion rate. The *Spartina* salt marsh in the Wanggang estuary (33° 17′ N, 120° 45′ E) of Dafeng County was selected for our study. *S. alterniflora* was planted in 1989 in this area, but the present *Spartina* salt marsh was considered to be four years old as a result of the seaward expansion of land due to *Spartina* and the continuous human activity of marsh reclamation. The intertidal mudflat (32° 36′ N, 120° 59′ E) without vegetation, the only remaining mudflat in the Jiangsu coastal area, was located in the Xiaoyangkou estuary in Rudong County, whose coastline is 103 km long. The distance between the two sampling sites is about 79 km. The two sites were selected because the salt marsh sampling site in Dafeng County is representative of the Jiangsu coastland that is good for the development of *Spartina* vegetation and the rapid sedimentation and progradation of the seashore, and the sampling site in Rudong County is the only existing mudflat in Jiangsu coastland that has environmental properties, such as accretion surface dynamics, soil type, accretion material sources, tidal inundation, and climate, similar to the Dafeng site. Considering the time and space replacement theory in ecological study, the mudflat in Rudong County can be seen as the natural or primary state of the coast prior to the invasion of *Spartina* in Jiangsu Province.

At both study sites, different tidal levels (high tide, mid-tide and low tide) were established from the upper edge of the marsh or its equivalent of the mudflat to the lower non-vegetated flat of the marsh or its equivalent of the mudflat in a seaward direction (Fig. 1). There were 15 plots (1 m × 1 m) at each sampling site, with a 500 to 1 000 m interval between neighboring plots (Fig. 1). Sampling was conducted in October and December of 2002 and in April and July of 2003. These sampling times selected all fall within the ebb tide hours of the spring tidal period, and the quadrats were set at the same tidal levels at the two sites in order to obtain comparable experimental data.

Surface-layer samples (0–20 cm) were taken from each plot for analyses of physical and chemical characteristics of the sediments according to the methods in Liu *et al.* (1996). Soil water content was determined as water loss after drying the sediments for 12 h at 105 °C (GB 7833-87). Soil bulk density was determined by drying the sediments at 70 °C for 24 h. Sediment cores from each plot were collected, air-dried, and sieved through a 2-mm mesh sieve. Sediment salinities were determined by measuring conductivity in a distilled water solution (sediment:water ratio = 1:5) (GB 7871-87). Soil pH was measured by an acidimeter (sediment:water ratio = 1:5) (GB 7859-87). Soil NH_4-N content was measured by the colorimetric methods (Liu *et al.*, 1996). Total soil N availability was measured by the semi-micro Kjeldahl method (GB 7113-87). The total P (GB 7852-87) and available P (GB 7853-87) in the soil were analyzed using the colorimetric methods (Liu *et al.*, 1996). Organic matter was measured using the potassium dichromate digestion method (GB 7857-87). Trace elements were determined by inductively coupled plasma-atomic emission spectrometer (ICP-AES) (J-A1100, USA) analysis.

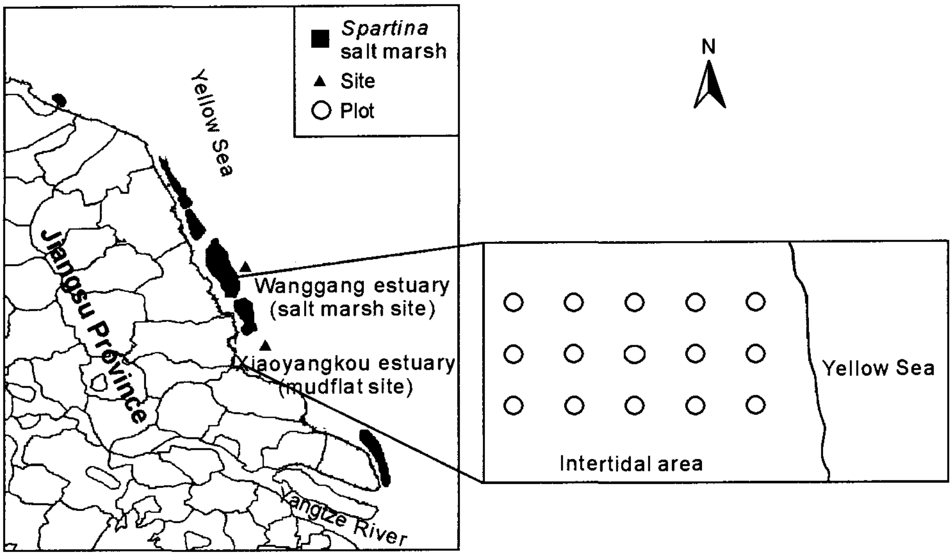

Fig. 1 Location of the *Spartina* salt marsh and mudflat sampling sites in the Jiangsu coastland, China, and the sampling scheme along the intertidal areas of the two sites.

Average height and stem density of *S. alterniflora* were recorded for each replicate sample. Above-ground plant material was harvested in a randomly chosen 10 cm × 10 cm quadrat for each replicate sample. Corresponding below-ground plant material was collected by digging 30 cm into the sediment and washing all soils away. Live and dead biomass was not separated. To estimate biomass, above- and below-ground plant materials were dried to constant weight at 70 °C.

Statistical comparisons of environmental variables among sites (*Spartina* salt marsh and mudflat), dates (October and December 2002 and April and July 2003), and vegetation characteristics were made using the Student's t test to determine if there were differences ($P < 0.05$). All hypotheses were tested at the 0.05 probability level unless otherwise indicated.

RESULTS

Physical and chemical properties of the sediments at the study sites

The physical and chemical properties of the sediments at the study sites are shown in Table I. Sediments from the *Spartina* marsh had higher total N, total P, organic C, NH_4-N, available P, salinity, and water content, but lower pH and bulk density values than the mudflat without vegetation. Sediment salinities increased with the distance from the sea at both study sites, but in the *Spartina* salt marsh the situation was more complex. No statistically significant differences in salinity were observed between the two sites (Table II). Furthermore, both in the mudflat and the *Spartina* salt marsh, sediment salinities were clearly lower in the April and July samples than in the October and December samples due to greater precipitation in the Jiangsu coastland during spring and summer.

TABLE I

Physiochemical characteristics of the sediments from the *Spartina* salt marsh and mudflat sites during different sampling times (means±standard deviations)

Site	Item	Oct. 2002	Dec. 2002	Apr. 2003	Jul. 2003
Spartina salt marsh	Salinity (g kg^{-1})	11.67±3.33	10.51±1.23	3.55±0.53	4.16±0.74
	pH	8.36±0.03	8.36±0.02	8.38±0.04	8.13±0.04
	Water content (g kg^{-1})	359.74±70.40	395.83±52.84	339.66±53.75	444.04±55.86
	Bulk density (g cm^{-3})	1.26±0.19	2.08±0.13	1.49±0.21	1.23±0.04
	Total N (g kg^{-1})	0.40±0.13	0.42±0.08	0.28±0.13	0.28±0.10
	NH_4-N (mg kg^{-1})	3.69±0.60	2.51±0.28	1.97±0.62	2.37±0.98
	Total P (P_2O_5) (g kg^{-1})	1.00±0.04	1.09±0.06	1.73±0.16	1.42±0.04
	Available P (mg kg^{-1})	6.85±1.97	6.70±1.02	3.32±0.62	3.30±0.74
	Organic C (g kg^{-1})	4.11±1.23	4.70±0.74	3.75±1.01	3.35±0.67
	C/N	10.31±0.36	11.15±0.61	16.32±7.80	12.80±3.33
Mudflat	Salinity (g kg^{-1})	10.61±1.77	11.07±3.91	2.95±0.42	3.06±1.01
	pH	8.50±0.05	8.45±0.06	8.42±0.02	8.32±0.13
	Water content (g kg^{-1})	306.83±18.44	306.00±44.37	281.29±17.00	295.73±28.95
	Bulk density (g cm^{-3})	1.60±0.17	2.29±0.12	1.76±0.12	1.33±0.17
	Total N (g kg^{-1})	0.20±0.02	0.18±0.01	0.16±0.02	0.14±0.01
	NH_4-N (mg kg^{-1})	1.92±0.33	2.22±0.35	1.06±0.09	0.92±0.34
	Total P (P_2O_5) (g kg^{-1})	0.94±0.04	1.00±0.06	1.37±0.09	1.27±0.04
	Available P (mg kg^{-1})	2.68±0.38	3.25±0.18	2.23±0.31	1.68±0.28
	Organic C (g kg^{-1})	2.33±0.26	2.47±0.38	2.02±0.26	1.63±0.65
	C/N	11.66±0.38	13.34±1.77	12.45±2.80	11.37±4.51

TABLE II

Statistical differences in the physiochemical characteristics of the sediments between the *Spartina* salt marsh and the mudflat during different sampling times

Item	Oct. 2002	Dec. 2002	Apr. 2003	Jul. 2003
Salinity	NS[a)]	NS	NS	NS
pH	***	*	**	**
Water content	NS	*	*	**
Bulk density	*	*	*	NS
Total N	*	**	NS	*
NH_4-N	**	NS	**	*
Total P	*	*	**	***
Available P	**	***	**	**
Organic C	*	**	*	**
C/N	**	NS	NS	NS

*, **, ***Significant at the 0.05, 0.01 and 0.001 levels of probability, respectively.
[a)]Not significant.

In the *Spartina* salt marsh, total N and organic C contents were lower during the growing season (April and July) and the value of the C/N ratio was lowest in October. The mudflat had the lowest values of organic C content and C/N in July and the highest values in December, but no difference in total N content was detected among seasons. The other sediment physical and chemical properties, such as bulk density, total P, and available P, behaved in a similar fashion seasonally in both the *Spartina* salt marsh and mudflat. In addition, the values of sediment salinity, water content, total N, organic C, and available P decreased along seaward gradients in the *Spartina* salt marsh but not in the mudflat (data not shown).

Characteristics of Spartina vegetation

Spartina growing at the seaward edge was lower in height and sparser than those at the intermediate position in the salt marsh. During the autumn (October 2002), the vegetation reached its greatest height and biomass. No differences in stem density were detected between autumn and winter (December 2002) (Table III). In the spring (April 2003), stem density increased due to the sprouting of new shoots. The above- and below-ground biomass did not vary significantly among tidal levels, except at the lowest edge where the values decreased (data not shown).

TABLE III

Spartina vegetation characteristics during different sampling times (means±standard deviations)

Sampling time	Stem density	Average height	Above-ground biomass	Below-ground biomass
	individuals m^{-2}	cm	$g\ m^{-2}$	
Oct. 2002	60.80±13.57	160.57±5.02	605.29±142.00	454.88±160.27
Dec. 2002	61.47±5.13	141.53±18.62	466.71±82.07	266.46±55.93
Apr. 2003	76.13±17.75	45.64±5.15	70.89±34.62	83.39±19.39
Jul. 2003	109.47±58.29	100.12±13.36	246.68±93.23	231.89±81.98

Trace elements and major metal elements in the sediments and tidal creek water

The concentrations of trace elements and some major metal elements in the sediments and tidal creek water are shown in Table IV. At the study sites, the element concentrations in the intertidal sediments were higher than those in the water from the tidal creek. In *Spartina* salt marsh, concentrations of the major metal elements, Al, Fe, and Mg, and the trace elements, B, Cr, and Se, in the creek water were higher than those of the mudflat. There was a decreasing trend of the trace element concentrations in the April sediment of the *Spartina* salt marsh, in contrast to the mudflat sediment. Furthermore, the major metal concentrations in the sediments, such as Fe, Mg, and Al, had the same trend as the trace elements shown above. Trace elements of the samples collected in July were not measured. The differences of all the element concentrations between the *Spartina* salt marsh and the mudflat were not obvious (Table IV).

TABLE IV

Concentrations of trace elements and some metal elements of sediments and tidal creek water at the study sites during different sampling times (means±standard deviations)

Element	Sediment						Water (Apr. 2002)		Sediment/ water (Apr. 2003)	
	Spartina salt marsh (SSM)			Mudflat			SSM	Mud-flat	SSM	Mud-flat
	Oct. 2002	Dec. 2002	Apr. 2003	Oct. 2002	Dec. 2002	Apr. 2003				
	$mg\ kg^{-1}$									
B	17.1±2.0	11.6±1.8	7.6±0.7	14.9±0.8	9.6±1.8	4.8±1.0	3.1±0.1	2.1±0.8	2.5	2.2
Cr	62.6±6.1	66.7±5.3	59.9±6.1	52.8±1.8	49.2±1.5	60.7±1.7	0.2±0.02	0.1±0.1	327	638
Pb	37.8±4.2	36.8±1.7	31.1±5.9	26.7±1.8	27.4±2.7	34.0±3.2	0.1±0.03	0.4±0.1	241	96.8
Se	60.3±18.5	55.7±15.6	47.6±10.5	42.3±6.2	40.8±11.1	50.0±12.0	3.2±0.4	2.5±0.9	14.7	19.7
Zn	71.9±11.1	71.3±7.0	63.9±13.1	55.4±15.8	52.6±8.3	67.2±18.9	0.05±0.01	0.1±0.04	1232	657
Al	62924±4866	64962±2630	59159±4446	54228±1647	52601±2084	63091±1487	1.7±0.3	1.2±0.5	33898	50790
Fe	28888±3585	29995±2136	26568±3683	22174±814	21282±698	25732±339	1.3±0.4	0.6±0.2	20613	43592
Mg	13969±1876	14681±939	12324±1489	12018±322	11716±277	13759±355	945±46	693±305	13.0	9.9

DISCUSSION

Effect of Spartina on intertidal sediment physical and chemical characteristics

Sediment subsidies induced by *S. alterniflora* had an ameliorating effect on sea level rise-induced impacts on salt marsh vigor. Sediment subsidies increased soil mineral matter and, in turn, soil fertility and marsh elevation, thereby reducing nutrient deficiency, flooding, and interstitial sulfide stresses.

Thus, sediment subsidies generated a favorable environment for plant growth and potential marsh sustainability (Mendelssohn and Kuhn, 2003; Huckle *et al.*, 2000).

The introduction of an exotic invasive species has the potential to change many components of the C, N, water, and other cycles of an ecosystem (Ehrenfeld, 2003). Gribsholt *et al.* (2003) found that roots of *S. alterniflora* have a greater impact on sediment biogeochemistry than on the macrobenthos. It has been reported that organic matter has important impacts on the interception of N in flooded wetland soils (Zhai *et al.*, 2003). In our study, the higher above- and below-ground biomass of *S. alterniflora* resulted in higher organic C in the sediments; *i.e.*, *Spartina* increased the C fixation capacity of the intertidal ecosystem. Simultaneously, there was a marked increase of total N and NH_4-N in the *Spartina* salt marsh sediment, but a lower C/N ratio compared with the mudflat. Craft *et al.* (2003) compared attributes related to biological productivity and soil development among different constructed *Spartina* marshes and natural reference marshes. Their results showed that sediment deposition, organic C, and N were higher in the recently (1 to 3 years old) constructed marshes, whereas after 28 years, soil organic C and N pools were significantly lower in the constructed marshes. In addition, sediment of the *Spartina* marsh had a higher water content than that of the mudflat due to dense plant cover that reduced water evaporation from the sediment, especially during winter and spring. To some degree, the presence of *Spartina* vegetation reduced the sediment pH and bulk density in the intertidal habitat, which would influence the biogeochemical processes of other elements in the sediment.

The *Spartina* salt marsh and mudflat were located in an intertidal area, as both habitats experienced similar tidal actions and high sediment salinity which was expected, although salinity was slightly higher in *Spartina* salt marsh sediment. *S. alterniflora* excretes salt from its leaves, so the salt is returned to the intertidal ecosystem when the plant is dormant. Plants in the upper levels of the *Spartina* marsh were greater in height than those growing at the lower edge of the marsh, so the impacts of *Spartina* on sediment elements and salinity were not so strong in the latter, which resulted in the decreasing pattern of sediment water content, salinity, N, organic C, and available P along the seaward gradient.

Effect of Spartina on intertidal sediment trace elements and major metal elements

The trace metal elements entering the marsh on the incoming tides are absorbed effectively in the salt marsh sediments (Nixon, 1980) and their concentrations in sediments may reflect the potential element supplementation by the vegetation. In our research, the concentrations of trace elements and some major metal elements such as Al, Fe, and Mg in the sediments were higher than those in the tidal creek water at both sites. Sediment trace elements can be absorbed by *S. alterniflora* and transferred into above-ground tissues (Gallagher and Kibby, 1980; Sanders and Osman, 1985; Kraus, 1988; Peverly *et al.*, 1995; Ye *et al.*, 1997). When the plant withers, the elements return to the environment and enter the food web of the salt marsh. So the salt marsh vegetation can be looked at as a source of as well as a storage for metal pollution (Weis and Weis, 2004).

Due to absorption and transfer of trace and metallic elements from and to the sediments by the plant, the concentrations of these elements were higher in the *Spartina* salt marsh than in the reference mudflat. Furthermore, the effect of *Spartina* on trace elements mainly appeared at the rhizosphere with higher root biomass, and changed with the various growing stages of the plant (Lacerda *et al.*, 1997). In our research, the *Spartina* salt marsh sediment had lower trace element concentrations correlated with lower below-ground biomass and also with lower plant growth in April, but differences between the *Spartina* salt marsh and the mudflat were not detected. Tidal creek water was sampled in April; at that time the *Spartina* salt marsh exhibited relatively higher trace and major metal element concentrations in the water than in the mudflat, except for Pb and Zn. Such results might be due to the transfer of heavy metals absorbed in the surface sediment by the root activity of *S. alterniflora*. In addition, the physical and chemical processes of the elements may have been affected by the relatively acidic environment in the *Spartina* salt marsh.

Many plant species have been applied in wetland rehabilitation and restoration because of their effects on absorption, transfer, and release of sediment metal elements (Weis and Weis, 2004). *Spartina* was found to accumulate metals from marsh sediment and release them into the environment through the excretion of metal-containing salts produced by leaf glands (Burke *et al.*, 2000). *Spartina* was also found to accumulate and release larger quantities of metals, such as Cr, Pb, and Zn, into the marsh environment than *Phragmites australis* through both excretion and leaf deposition (Burke *et al.*, 2000; Windham *et al.*, 2001, 2004).

Compared with mudflat sediments, *Spartina* salt marsh sediments had higher trace and metal element concentrations because of the amelioration effect of the plants on metal concentrations in the intertidal areas, but the increase was not statistically significant in our study. The vegetation in the *Spartina* salt marsh in this study was relatively young (only 4 years old) as a result of continuous inning activity in the Jiangsu coastland. Its long-term effect on the coastal ecosystem processes is not clear at present, therefore the long-term effect of this alien species on biogeochemical processes of the intertidal ecosystem of the Jiangsu coastal region should continue to be studied in the future.

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