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ORIGINAL ARTICLE

Spatial and seasonal variation of salt ions under the influence of halophytes, in a coastal flat in eastern China

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Abstract The high salinity of coastal saline field is a key factor limiting the reclamation. Halophytes have been utilized in the reclamation of saline land. The study area is in Yancheng, China. An analysis of the concentrations of Rb, Cs, Sr, and Ba, the ratio of Rb/Cs, and Sr/Ba in soils in autumn shows that the soil of this study area has great homogeneity. *Artemisia halodendron*, *Gossypium hirsutum*, and *Sesbania cannabina* were selected as the reclamation plants in the present study. In order to know the spatial-temporal distribution of soil salinity, the influence of plant-specific vegetation, and the difference of desalination among these halophytes in coastal flat, the authors analyze the soil-layers and seasonal variation in salt ions. Sodium chloride was accumulated in 0–5 cm topsoil with no vegetation during the winter and spring. The effect of desalinization of halophytes is significant. Of the three plant species, *Sesbania cannabina* has the greatest desalinization. The difference of ions composition of soils covered with various plant species is significant. It can be concluded that halophytes have better amelioration of coastal soil salinity. Special attention should be paid to the selection of plant species and measures to plant and cultivate crops in the reclamation of saline land.

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Introduction

Rapid industrialization and urbanization have resulted in the loss of great amount of agricultural land. To alleviate the severe conflict between the ever-growing population and the limited agricultural land resources, there is an urgent demand for the reclamation of coastal tidelands. A total of 1,190,000 ha tidelands have been reclaimed for agricultural use along the coastal line in China under a series of reclamation programs since 1950s (Qin et al. 2004). However, the salinity content of newly reclaimed tide flats was high due to the salination, which was the consequence of a long-time tidal influence. The mitigation and control of soil salinity was recognized as one of the main challenges in the agriculture of the twenty-first century (Amezketa 2006). The high salinity in coastal saline field is a key factor limiting the reclamation.

Previously, rainwater or fresh water was used to desalinize the coastal saline field, which consumed much time, money, and fresh water. Presently, halophytes are applied to the reclamation of saline land (e.g. Zedler et al. 2003; Ravindran et al. 2007). Because of their diversity, halophytes have been regarded as a rich source of potential crops. They have been tested as vegetable, forage, and oilseed crops in agronomic field trials (Chen et al. 1999; Glenn et al. 1999). The selection of plant species is one of the most important considerations in reclamation of saline land. The understanding of the relationship between halophytes and soil salt ionic composition is key to the reclamation of saline land. Reclamation is based on the knowledge of soil salinity's spatial distribution and its evolution with time.

Several studies have focused on the effect of ionic composition of soil in saline field on the zonation, physiological, morphological, and biochemical variation of halophytes (Snow and Vince 1984; McKee, 1993; Krüger and Peinemann 1996; Álvarez-Rogel et al. 2001; Gleason et al. 2003; Marchand et al. 2004). However, the effect of the growth of halophytes on the ionic composition of soil in saline field has not been well understood yet. *Sesbania cannabina*, *Artemisia halodendron*, and *Gossypium hirsutum*, three species of halophytes of high economic and ecological value, are widely used in the reclamation of saline land (Brugnoli and Lauteri 1991; Pan et al. 1998; Chen et al. 1999; Xin et al. 2007). The difference of desalination among these halophytes was unclear. Therefore, the objectives of the present study are to investigate the temporal and spatial variation of ion compositions in a coastal soil, the influence of plant-specific vegetation, and the desalination among these halophytes. The results would provide some technical parameters for the selection of plant species and the measures to plant and cultivate crops in the reclamation of saline land.

Materials and methods

Study site and plant species

The study area lies in the east-northeast region of Yangcheng city (33°45′00″–33°57′00″ N, 120°15′00″–120°25′00″ E), Jiangsu Province, China, by the western coastline of Yellow Sea (Fig. 1). It belongs to the transitional zone from the north subtropical one to the warm temperate one. The summer is warmer than the winter (the average temperature in July is 26.4 and in January is 2.3°C). The annual average temperature is 13.9°C. The annual average precipitation is 1,035 mm. There are two main seasons: (1) the wet season (May–August) with an average rainfall of 745 mm and (2) the dry season (September–April) with an average rainfall of 290 mm. The average elevation of the area is approximately 1.0 m. The soils were formed by the modern marine and alluvial deposit matters. Soil textures are light loam, with a high concentration of Na-salt. The groundwater level ranges from 50 to 70 cm. Over the past 35 years, many coastal tideland areas have been successively reclaimed for agricultural uses. The study was conducted in a field of about 3 ha, which was reclaimed in 1993. The plant species selected for coastal salt flat restoration are *Sesbania cannabina* (SC), *Artemisia halodendron* (AH), and *Gossypium hirsutum* (GH). The plants were sowed and cultured under no tillage.

Fig. 1 Map of the study area

Soil sampling and analysis

Four types of plots were selected for this study, and the sampling sites are shown in Fig. 2. Each type of plot had the same topographic and hydrological conditions. The first one was covered with no plants (NP), the second one with only *Sesbania cannabina* (SC), the third one with only *Artemisia halodendron* (AH), and the fourth one with only *Gossypium hirsutum* (GH). In each plot, five similar soil cores were selected randomly and soil samples were taken from 0–5, 5–10, 10–15, 15–20, and 20–25 cm depths, respectively, on 10 March (spring), 21 July (summer), 23 October (autumn) 2003, and 15 January 2004. Plant debris and roots were removed from each sample. Each soil sample was sieved (<2 mm) and stored, respectively, in different plastic bags at 4°C until soil analyses were performed. Subsamples of the soil were taken, air-dried, ground, and analyzed for chemical compositions.

All analyses were performed at Institute of Geochemistry, Chinese Academy of Sciences. Rb, Cs, Sr, and Ba

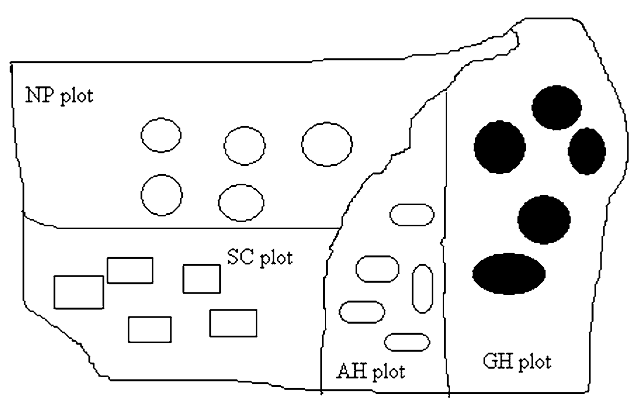

Fig. 2 The sampling sites in the study area

concentrations in soils in autumn were determined with inductivity coupled plasma-mass spectrophotometry (ICP-MS) after the samples were digested by mixed acid (nitric acid, hydrofluoric acid, perchloric acid) (Wu et al. 1996). The routine soil chemical parameters were analyzed using the methods suggested by Li (1983). The $pH_{(1/2.5)}$ of soil in suspension with distilled water (1/2.5, w/v) was measured with pH-meter. Exchangeable cations (K, Mg, Ca, Na) extracted with 1N ammonium acetate were determined with atomic absorption spectrophotometry (Ca, Mg) and atomic emission spectroscopy (AES) (Na, K) (Zas and Serrada 2003). Soluble chloride and sulfate extracted with distilled water (soil/water:1/5, w/v) were determined by ion chromatography(Fu et al. 2004). All determinations were performed in triplicate and the results are expressed on the basis of the oven-dry weight of soil.

Statistical analysis

The mean and standard errors were calculated for each treatment. One-sample *t* test, one-way ANOVA, pairwise comparison tests (Tukey) and bivariate correlations were conducted for the study.

Results

The homogeneity of the soils in the study area

Table 1 shows the statistical results of the concentrations of Rb, Cs, Sr, and Ba, the ratio of Rb/Cs, and Sr/Ba in soils of autumn. The average concentrations of Rb, Cs, Sr, and Ba among all soil samples in autumn are 89.039, 5.430, 209.860, and 405.988, respectively, the average ratios of Rb/Cs and Sr/Ba, 16.434 and 0.517, respectively. The *P* values are all close to 1.000. It indicates no significant difference among soil-layers and plots. Rb, Cs, Sr, and Ba are in low concentrations in plants and not available to plants. Rb, Cs, Sr, and Ba contents in soil do not depend on the growth of plants on the soil. Therefore, all soil samples could be regarded as one, and the soils in all soil-layers and plots are homogeneous.

Table 1 Descriptive statistics (one-sample *t* test) for the concentrations of Rb, Cs, Sr, and Ba, the ratio of Rb/Cs and Sr/Ba in soils of autumn ($n = 20$)

	Mean (*t* test) value ($\mu g\ kg^{-1}$)	Standard error mean	*P* value
Rb	89.039	0.937	1.000
Cs	5.430	0.090	1.000
Sr	209.860	1.949	1.000
Ba	405.988	3.254	1.000
Rb/Cs	16.434	0.124	1.000
Sr/Ba	0.517	0.002	1.000

The relationship among exchangeable cations, soluble chloride and sulfate, and the ratios

The correlations among exchangeable cations, soluble chloride and sulfate, and the ratios in the four types of plots are presented in Table 2. It can be seen that there are significant positive correlations between exchangeable Na and soluble chloride, soluble chloride and sulfate, exchangeable Na and the ratio of exchangeable K/Na, exchangeable Ca and the ratio of exchangeable Ca/Mg, and soluble chloride and the ratio of exchangeable K/Na in the four types of plots. Except in GH plot, soluble sulfate has a significant positive correlation with exchangeable Na, and the ratio of exchangeable Ca/Mg has a significant positive correlation with the ratio of exchangeable K/Na. Except in AH plot, the ratio of soluble Cl/SO_4 has a significant negative correlation with the ratio of exchangeable K/Na, and a positive correlation with soluble chloride. Except in SC plot, exchangeable Ca has a significant positive correlation with exchangeable Mg, and the ratio of exchangeable K/Na, a negative correlation with pH; soluble sulfate has also a negative correlation with the ratio of exchangeable K/Na.

In NP and GH Plots, exchangeable K is related to exchangeable Na, Ca, and Mg. In NP and SC Plots, exchangeable Na is related to the ratio of soluble Cl/SO_4. In NP and AH Plots, the ratio of exchangeable Ca/Mg has a significant negative correlation with soluble chloride and sulfate. In SC and GH plots, exchangeable Ca has a significant negative correlation with the ratio of soluble Cl/SO_4. In AH and GH plots, pH is significantly correlated with exchangeable Mg.

Additionally, exchangeable K has a significant positive correlation with soluble chloride in NP plot, and with soluble sulfate in SC plot. Exchangeable Ca has a significant negative correlation with soluble chloride, sulfate, and exchangeable Na in AH plot. The correlations between exchangeable K and the ratio of exchangeable K/Na, between the ratio of soluble Cl/SO_4 and that of exchangeable Ca/Mg, and between pH and the ratio of soluble Cl/SO_4 are present in GH plot.

The spatial and seasonal variation of soil parameters

Figure 3 shows the spatial and seasonal variation of exchangeable K. The average content of exchangeable K in SC plot is lower than that in the other plots. In spring, the content of exchangeable K in 0–5 cm depth topsoil in NP plot is the highest. The content of exchangeable K in SC plot is lower than that of other soil-layers in other plots in

Table 2 Correlation coefficient (Pearson) of exchangeable cations, soluble chloride and sulfate, and the ratios in the four types of plots ($n = 20$)

	Variables	K	Na	Ca	Mg	K/Na	Ca/Mg	$pH_{(1/2.5)}$	Cl^-	SO_4^{2-}
NP	Na	0.72**								
	Ca	0.47*	−0.11							
	Mg	0.64**	0.38	0.63**						
	K/Na	−0.37	−0.87**	0.49*	−0.08					
	Ca/Mg	0.12	−0.41	0.75**	−0.01	0.67**				
	$pH_{(1/2.5)}$	−0.04	0.34	−0.56*	−0.37	−0.44	−0.42			
	Cl^-	0.60**	0.94**	−0.25	0.38	−0.89**	−0.58**	0.31		
	SO_4^{2-}	0.48*	0.71**	−0.20	0.41	−0.67**	−0.52*	0.08	0.88**	
	Cl/SO_4	0.56*	0.77**	−0.16	0.13	−0.74**	−0.33	0.47*	0.63**	0.22
SC	Na	0.49*								
	Ca	0.57**	−0.24							
	Mg	0.62**	0.30	0.43						
	K/Na	0.16	−0.66**	0.58**	0.33					
	Ca/Mg	0.38	−0.33	0.91**	0.04	0.45*				
	$pH_{(1/2.5)}$	0.10	0.55*	−0.29	−0.19	−0.54*	−0.21			
	Cl^-	0.37	0.94**	−0.29	0.35	−0.61**	−0.38	0.39		
	SO_4^{2-}	0.66**	0.77**	0.10	0.52*	−0.30	−0.06	0.15	0.82**	
	Cl/SO_4	−0.41	0.43	−0.64**	−0.38	−0.78**	−0.47*	0.39	0.51*	0.00
AH	Na	−0.17								
	Ca	0.13	−0.76**							
	Mg	−0.04	−0.54*	0.55*						
	K/Na	0.39	−0.85**	0.74**	0.30					
	Ca/Mg	0.12	−0.67**	0.98**	0.40	0.70**				
	$pH_{(1/2.5)}$	−0.05	0.37	−0.57**	−0.65**	−0.19	−0.51*			
	Cl^-	0.14	0.76**	−0.79**	−0.20	−0.74**	−0.81**	0.24		
	SO_4^{2-}	0.06	0.74**	−0.59**	−0.05	−0.68**	−0.58**	0.03	0.83**	
	Cl/SO_4	0.03	0.22	−0.41	−0.24	−0.40	−0.44	0.27	0.44	−0.09
GH	Na	−0.32								
	Ca	0.16	−0.51*							
	Mg	0.18	−0.51*	0.79**						
	K/Na	0.76**	−0.78**	0.36	0.44					
	Ca/Mg	0.17	−0.40	0.91**	0.48*	0.26				
	$pH_{(1/2.5)}$	0.00	0.48*	−0.58**	−0.60**	−0.24	−0.45*			
	Cl^-	0.48*	0.84**	−0.17	−0.13	−0.82**	−0.19	0.23		
	SO_4^{2-}	−0.21	0.32	0.38	0.19	−0.47*	0.43	−0.41	0.58**	
	Cl/SO_4	−0.47*	0.81**	−0.58**	−0.44	−0.72**	−0.59**	0.62**	0.78**	−0.04

*Correlation is significant at the 0.05 level (two tailed). K, Na, Ca, and Mg represent exchangeable K, Na, Ca, and Mg, respectively. Cl^- and SO_4^{2-} represent soluble chloride and sulfate, respectively. K/Na and Ca/Mg represent the ratios of exchangeable K and Na, Ca, and Mg, respectively. Cl/SO_4 represents the ratio of soluble chloride and sulfate

**Correlation is significant at the 0.01 level (two tailed)

the season. In autumn and winter, the content of exchangeable K in 10–15 cm depth subsoil is significantly higher than those in other plots in the same season. The difference of exchangeable K in AH and GH plots is not significant.

Figure 4 shows the spatial and seasonal variation of exchangeable Na. The average content of exchangeable Na in SC plot is lower than those in the other plots. The content of exchangeable Na in 0–5 cm depth topsoil in NP plot is higher than those of other soil-layers in the other plots in the same season. The difference of exchangeable Na in AH and GH plots is not significant, either. The highest value of exchangeable Na occurred in 0–5 cm depth topsoil in NP and SC plots. Figure 5 shows the spatial and seasonal variation of the ratio of exchangeable K/Na. The ratio of exchangeable K/Na in 0–5 cm depth

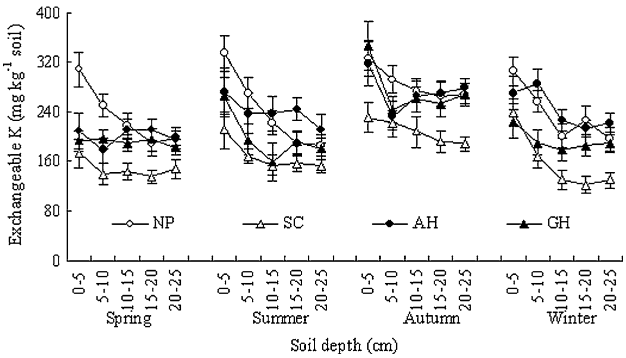

Fig. 3 Exchangeable K contents of soil samples under different vegetation ($n = 5$; SE, standard error of the means). NP, plot without plants; SC, *Sesbania cannabina* plot; AH, *Artemisia halodendron* plot; GH, *Gossypium hirsutum* plot

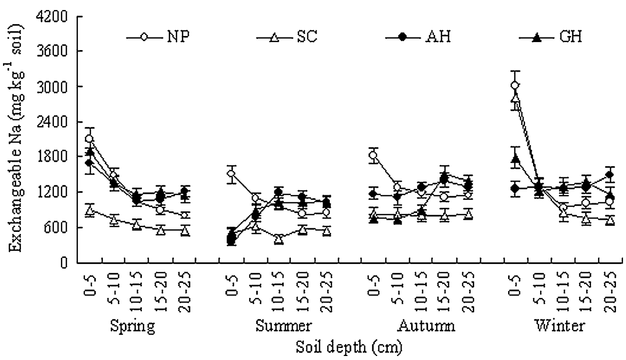

Fig. 4 Exchangeable Na contents of soil samples under different vegetation ($n = 5$; SE, standard error of the means). NP, plot without plants; SC, *Sesbania cannabina* plot; AH, *Artemisia halodendron* plot; GH, *Gossypium hirsutum* plot

topsoil in AH and GH plots in summer is significantly higher than those in other soil-layers in the same plot and season. The ratio of exchangeable K/Na in 0–5 cm depth topsoil in AH plot in autumn is the highest of all the soil-layers and plots.

Figures 6, 7, and 8 show the spatial and seasonal variation of exchangeable Ca, Mg, and the ratio of exchangeable Ca/Mg, respectively. The characteristic variation is that exchangeable Ca, and the ratio of exchangeable Ca/Mg in 0–10 cm depth soil in AH plot and summer is significantly higher than those in other soil-layer soils. Figure 9 shows the spatial and seasonal variation of pH. The characteristic variation is that pH in 5–20 cm depth soils in NP plot is higher than those in other plots in the same soil-layer soil and season except in winter.

Figures 10, 11, and 12 show the spatial and seasonal variation of soluble chloride, sulfate, and the ratio of soluble Cl/SO_4, respectively. The characteristic variation is that the content of soluble chloride in 0–5 cm topsoil in NP plot is the highest among all the soil-layer soils and plots in spring, and that of 0–5 cm topsoil with vegetations in

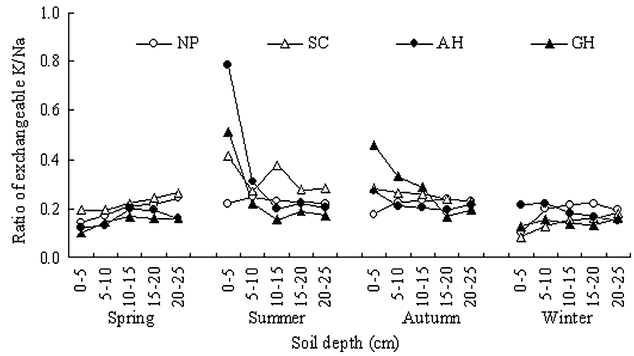

Fig. 5 The ratio of soil exchangeable K/Na under different vegetation. NP, plot without plants; SC, *Sesbania cannabina* plot; AH, *Artemisia halodendron* plot; GH, *Gossypium hirsutum* plot

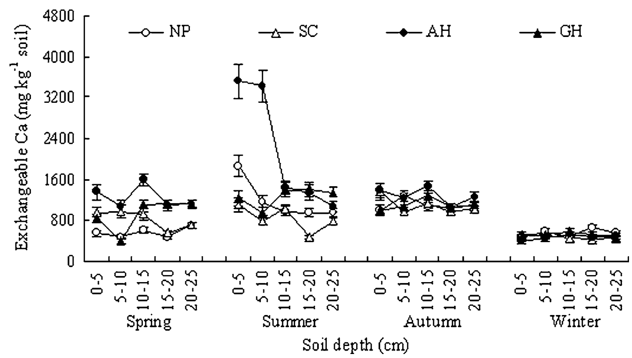

Fig. 6 Exchangeable Ca contents of soil samples under different vegetation ($n = 5$; SE, standard error of the means). NP, plot without plants; SC, *Sesbania cannabina* plot; AH, *Artemisia halodendron* plot; GH, *Gossypium hirsutum* plot

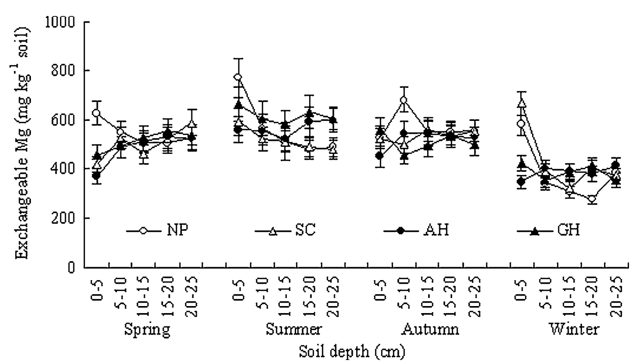

Fig. 7 Exchangeable Mg contents of soil samples under different vegetation ($n = 5$; SE, standard error of the means). NP, plot without plants; SC, *Sesbania cannabina* plot; AH, *Artemisia halodendron* plot; GH, *Gossypium hirsutum* plot

summer is significantly lower than that in 0–5 cm topsoil in NP plot in the same season. In winter, the content of soluble chloride in 0–5 cm topsoil in NP/SC plots is significantly higher than those of other soil-layer soils and plots in the same season. The characteristic variation of soluble sulfate is similar to that of soluble chloride. The

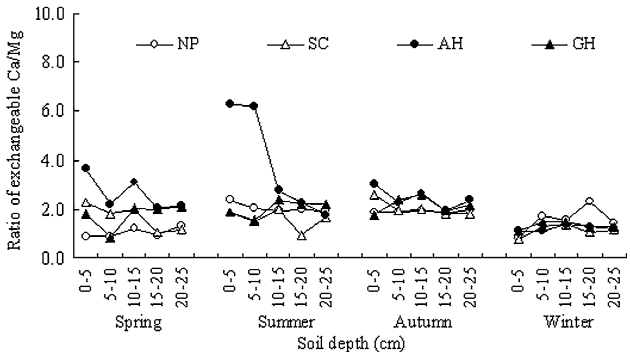

Fig. 8 The ratio of soil exchangeable Ca/Mg under different vegetation. NP, plot without plants; SC, *Sesbania cannabina* plot; AH, *Artemisia halodendron* plot; GH, *Gossypium hirsutum* plot

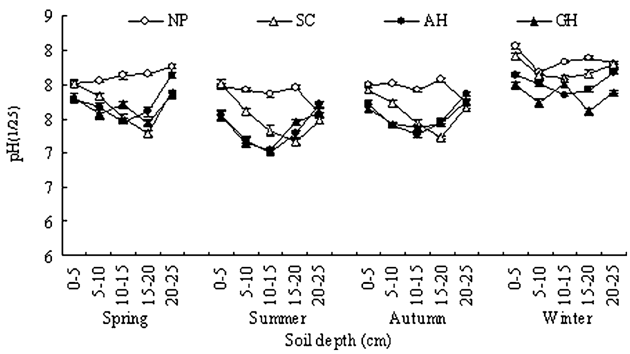

Fig. 9 The soil pH under different vegetation ($n = 5$; SE, standard error of the means). NP, plot without plants; SC, *Sesbania cannabina* plot; AH, *Artemisia halodendron* plot; GH, *Gossypium hirsutum* plot

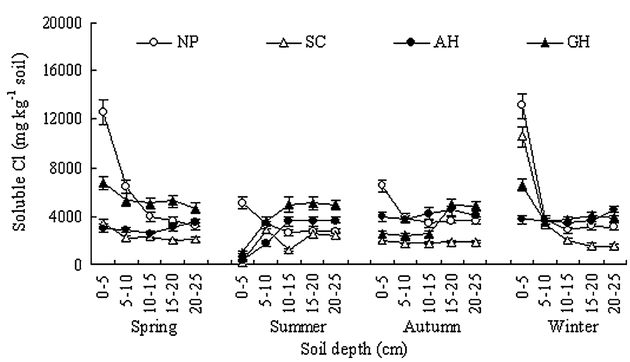

Fig. 10 Soluble chloride contents of soil samples under different vegetation ($n = 5$; SE, standard error of the means). NP, plot without plants; SC, *Sesbania cannabina* plot; AH, *Artemisia halodendron* plot; GH, *Gossypium hirsutum* plot

average value of the ratio of soluble Cl/SO_4 in GH plot is the highest of all the plots.

Discussion

Plant zonation and species distribution in coastal flats are influenced by the edaphic properties and the ionic

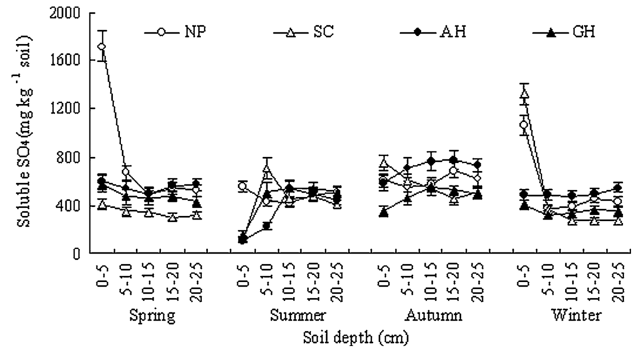

Fig. 11 Soluble sulfate contents of soil samples under different vegetation ($n = 5$; SE, standard error of the means). NP, plot without plants; SC, *Sesbania cannabina* plot; AH, *Artemisia halodendron* plot; GH, *Gossypium hirsutum* plot

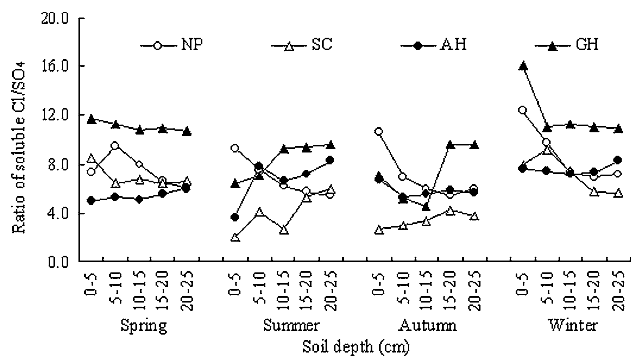

Fig. 12 The ratio of soil soluble chloride and sulfate under different vegetation. NP, plot without plants; SC, *Sesbania cannabina* plot; AH, *Artemisia halodendron* plot; GH, *Gossypium hirsutum* plot

composition in saline soils (Ukpong 1997; Álvarez-Rogel et al. 2001; Hoyer et al. 2004; Deegan et al. 2005). Biotic factors such as nutrient availability, competition, and facilitation also participate in controlling the distributional patterns of species (Silander and Antonovics 1982; Pennings and Callaway 1992; Bertness and Shumway 1993; Tessier et al. 2003). However, edaphic characterization, spatial, and seasonal variation in soil ionic composition in a coastal flat is affected by climate, groundwater levels, and microtopography, which, in turn, affect the distribution of coastal flat vegetation (Danin 1981; Snow and Vince 1984; Krüger and Peinemann 1996; Cemek et al. 2007). Human activities impact the soils and vegetation in coastal salt marsh (Álvarez-Rogel et al. 2007). Adaptation to saline soils can be mostly due to specific biophysical, physiological, morphological, and biochemical variation in plants (Brugnoli and Lauteri 1991; Aragüés et al. 2005; Maricle et al. 2007). Plants can simultaneously ameliorate soils and decrease salinity in soils when they adapt themselves to high salinity.

A number of studies have demonstrated that the soil in coastal flats is heterogeneous, and there is spatial-temporal variation among soil sections owing to climate, groundwater levels, and microtopography (Webster 1985; Silvestri et al. 2005; Shi et al. 2005). However, the data obtained from the present study indicate that the soil in all soil-layers and plots are homogeneous (Table 1). It suggests that the environmental factors such as groundwater levels, microtopography, and human activity in the sampling plots were identical. It can be inferred that the distribution difference of soil ionic composition is the consequence of the corporate impact of climate and vegetation. Without respect to vegetation, seasonal salt ionic concentration of 0–5 cm topsoil varies in NP plot. Sodium chloride is the dominating salinity of the study area according to the data obtained from the present study. Soil salinity in some coast flats is regulated by seasonal rainfall patterns (de Leeuw et al. 1991; Silvestri et al. 2005; Tho et al. 2008), which is proven by the present study. The distribution characteristic of sodium chloride is that higher concentration occurs in spring and winter and lower concentration in summer and autumn. The solubility of sodium chloride is small compared with potassium sulfate. Sodium chloride is prone to be accumulated in 0–5 cm topsoil during the winter and spring, due to small rainfall and low temperature. The lower concentration of salinity in 0–5 cm topsoil in summer and autumn resulted from the increase in rainfall and the dilution of salinity.

Halophytes tend to reduce the soil salinity in coastal flats. The results from the present study show that the distinct decrease of soil salinity occurred in 0–5 cm depth topsoil with vegetation in summer. The salinity of 0–5 cm depth topsoil under no vegetation in spring is obviously higher than that with vegetation in the same season, and the salinity of 0–5 cm depth topsoil in NP/SC plots in winter is obviously higher than those of other soil-layer and plots. The root system distribution may account for the higher salinity of 0–5 cm depth topsoil in NP/SC plots in winter. Compared with *Artemisia halodendron* and *Gossypium hirsutum*, the root system of *Sesbania cannabina* was mostly distributed in 20–40 cm depth soil-layer, while those of *Artemisia halodendron* and *Gossypium hirsutum* were mostly distributed in 5–30, and 0–40 cm depth soil-layer, respectively (Zhao 1994; Wang et al. 1999; Yan et al. 2001). The root system of *Sesbania cannabina* is weak in the absorption of ions in winter, and the root system is far from the 0–5 cm topsoil. Therefore, the salinity of 0–5 cm depth topsoil in winter and in SC plot was not influenced by root system. No evident salinity difference between AH and GH plots was observed. The *Sesbania cannabina*'s ability to decrease the salinity of soil is the greatest of the three species because the lowest average value in exchangeable Na and soluble chloride can be found in Figs. 4 and 10. In practice, the good effect of desalinization can be obtained by planting *Sesbania cannabina* (Wang et al. 1999).

Halophytes also have facility to decrease the soil pH in coastal flats. The distinct decrease of soil pH occurred in 5–20 cm depth soil with vegetation. The physical, chemical, and biological properties of soil in coastal areas may be improved by a decrease in pH.

The relationship between ions varied with the plant species covering the soil. From Table 2, the pattern of relationship between ions in the soil was unique in each plot. Exchangeable K had no significant correlation with any other ions in AH plot. The significant correlation between exchangeable Ca and soluble chloride or sulfate occurred only in AH Plot. The significant correlation between exchangeable K and the ratio of exchangeable K/Na also occurred only in GH plot. Exchangeable K had a significant correlation with the ratio of exchangeable K/Na only in the GH plot. Among the plots with vegetation, exchangeable K was related to soluble sulfate only in SC plot. The difference in patterns of relationship resulted from the plant-specific variation in uptake, translocation, accumulation, and use of mineral elements required for plant growth (Clark 1983).

Conclusion

The soil samples in the present study were homogeneous, and the spatial and seasonal distribution of salt ions in a coastal flat varies with the plant species and seasons. Halophytes had a strong desalinization. The difference of desalinization among halophytes is significant. Similarity, halophytes may decrease the pH in 5–20 cm soil-layer soil. Desalinization of *Sesbania cannabina* is greater than that of other plant species. The ions composition of soil varied with the plant species covering the soil. Halophytes have a possible amelioration of the salinity of coastal soil. The selection of plant species and measures to plant and cultivate crops should be taken into consideration while solving the environmental problems of the coastal soil salinity.

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