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Spatial and seasonal variations of soil salinity following vegetation restoration in coastal saline land in eastern China

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ABSTRACT

Ecological restoration by plants on coastal saline lands affects salt accumulation, distribution patterns and related mechanisms. In Chongmind Island, eastern China, we explored the way vegetation restoration affected the profile distributions of soil moisture and salinity in various seasons in naturally salt-affected coastal saline land. In four types of vegetation, five soil cores were acquired in the ~80 cm depth range and the sampling depths of the five cores were respectively 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm. Soil moisture firstly decreased and then increased with the depth in woodland and shrubland, while soil moisture consistently increased in grassland and control plots. Salt profiles showed the higher values in surface soil in control plots, whereas the pattern of soil salinity showed the reverse trend under vegetation. The effect of vegetation restoration on the profile distributions of salt is significant. In control plots, soil moisture and salinity showed a clear seasonal trend. Soil moisture values were the highest in spring and the lowest in autumn, when values of soil salinity were the highest in summer and the lowest in winter. Relative to control plots, the seasonal trend of soil moisture and salinity under vegetation appeared to be complex for no clear trend was observed. It can be concluded that plant communities significantly affect the spatial–temporal distribution of soil salinity. The selection of plant species is important in the reclamation of costal saline land.

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1. Introduction

The analysis of vegetation–environment relationships has always been a study hotspot in ecology (Antoine and Niklaus, 2000). Soil heterogeneity is very important for plant growth in stressed environments (Chapin et al., 1994). For example, the heterogeneous distribution of water and nutrient promotes the formation and maintenance of resources underneath the plant canopy in coastal saline land (Reynolds et al., 1999). Meanwhile, individual plants and plant community composition affect the distribution of soil nutrients at various spatial scales (Hook et al., 1991; Jackson and Caldwell, 1993). Vegetation is so closely related to soil that it is difficult to identify the causal relationships, but the analysis of soil heterogeneity in different plant community compositions can provide a deeper understanding of the ecological relationship between vegetation and soil.

In the eastern China, it is urgent to implement the reclamation of coastal tidelands because of the severe conflict between rapid urbanization and limited land resources. However, owing to the high soil salinity, the high water levels, the heavy clay texture, the poor permeable performance of ventilation, and the deficiency of fresh water resources, the development and utilization of newly reclaimed tide flats were largely restricted. The mitigation and control of soil salinity were recognized as two of the main challenges in the development of coastal tidal flats. Water conservancy engineering, physical and chemical measures were used to desalinize the coastal saline land. These measures consumed much time and money, and were even harmful to environment through changing natural and geographical environments in a larger scale. Re-vegetating or reintegrating halophytes (Marcar et al., 1995) in saline lands has been regarded as one effective solution to improve the physical and chemical properties of soil (Garg, 1998). Reclamation is based on the knowledge of the spatial distribution and temporal variation of soil salinity. Therefore, it is important to explore the relationship between vegetation and soil following vegetation restoration of saline field.

The effect of soil salinity in saline land on the zonation, physiological, morphological, and biochemical variation of halophytes was extensively studied (Gleason et al., 2003; Marchand et al., 2004; Snow and Vince, 1984). However, the effect of the growth of halophytes on the salt distribution in saline lands is seldom reported. Due to the close relationships among salts, dynamics and water transport, plants affect the moisture and salinity dynamics across the ecosystem–vadose zone–aquifer

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continuum (Marcelo et al., 2007). Having contrasted the capacity of utilizing soil moisture and nutrient, different vegetation have different effects on evapotranspiration, run-off, deep drainage patterns and redistribute salts through plant–soil feed-backs, as well as the spatial pattern and variability of soil resources (Lane and BassiriRad, 2005). In recent years, with amelioration of coastal saline soil and utilization of salt tolerant plants, the intrinsic relationships between vegetation types and soil salinization have attracted more and more attention. How different vegetation affects soil moisture and salinity in restoration process is an important issue to address due to the importance of soil moisture and salinity in influencing plant survival and restoration success. Yet, little is known about how the spatial and temporal distributions of soil moisture and salinity may develop following vegetation restoration in coastal saline field.

The paper aims to explore the relationship between vegetation restoration and the spatial and temporal variations of soil moisture and salinity in coastal saline lands. It is assumed that the spatial and temporal variations of soil moisture and salinity vary with vegetation restoration of coastal saline land. We modeled the vertical distribution patterns of soil moisture and salinity under different types of vegetation, and explored seasonal and spatial variations of soil moisture and salinity following vegetation restoration in coastal saline lands.

2. Materials and methods

2.1. Site descriptions

The study area is in the eastern end of Chongming Island (31°27′00″–31°51′15″N, 121°09′30″– 121°54′00″E), in Shanghai, China (Fig. 1). It is the biggest and most perfect development river and tidal mudflat wetland in Yangtze estuary. The area is characterized by the oceanic and monsoonal climate, and an annual average precipitation of 1100 mm, and 71% of precipitation is concentrated in the period from April to September. The annual average open pan evaporation is about 718 mm, while the annual mean temperature is around 15.3 °C. The lowest monthly average temperature is 2.8 °C in January and the highest monthly average temperature is 27.5 °C in July. The area has distinct four seasons, the prevailing southeast wind in the hot and rain-rich summers, and the prevailing north wind in the windy and dry winters. Soils are light loam and composed of the modern marine and alluvial deposit matters, with the average salinity between 0.2% and 0.6%. Over the past 30 years, many coastal tideland areas have been successively reclaimed for agricultural usages. The study was conducted in the field of about 300 ha, which was reclaimed in 2000. After 10 years of ecological restoration, it has become the ecological demonstration area of wetland protection and rational utilization. Many plant species were introduced and planted for coastal salt flat restoration, including grasses (e.g., *Cynodon dactylon (L.) Pers.*, *Lolium perenne L.*, *Hemerocallis fulva (L.) L.*), shrubs (e.g., *Nerium indicum Mill.*, *Amorpha fruticosa L.*, *Jasminum mesnyi Hance.*), arbors (e.g., *Taxodium mucronatum Ten.*, *Sapium sebiferum (L.) Roxb.*, *Sapindus mukorossi Gaertn.*).

2.2. Experimental design

According to the representative and the distribution area of artificial vegetation, four types of plots were selected and each plot was about 50 × 100 m. Except for the first plots without vegetation cover (Control), the dominant species in other three plots were respectively *Taxodium mucronatum Ten.* (Woodland), *Nerium indicum Mill.* (Shrubland) and *Cynodon dactylon (L.) Pers.* (Grassland). Each type of plot had the same micro-topography situations, as confirmed by detailed topographic map and direct observations in the field. The small differences (<0.5 m) in topography are very important because groundwater depth plays a dominant role in the development of these soils (Toth et al., 1991). Moreover, the source data confirmed that the initial edaphic variations between each plot were negligible. These conditions provided support to warrant careful comparisons.

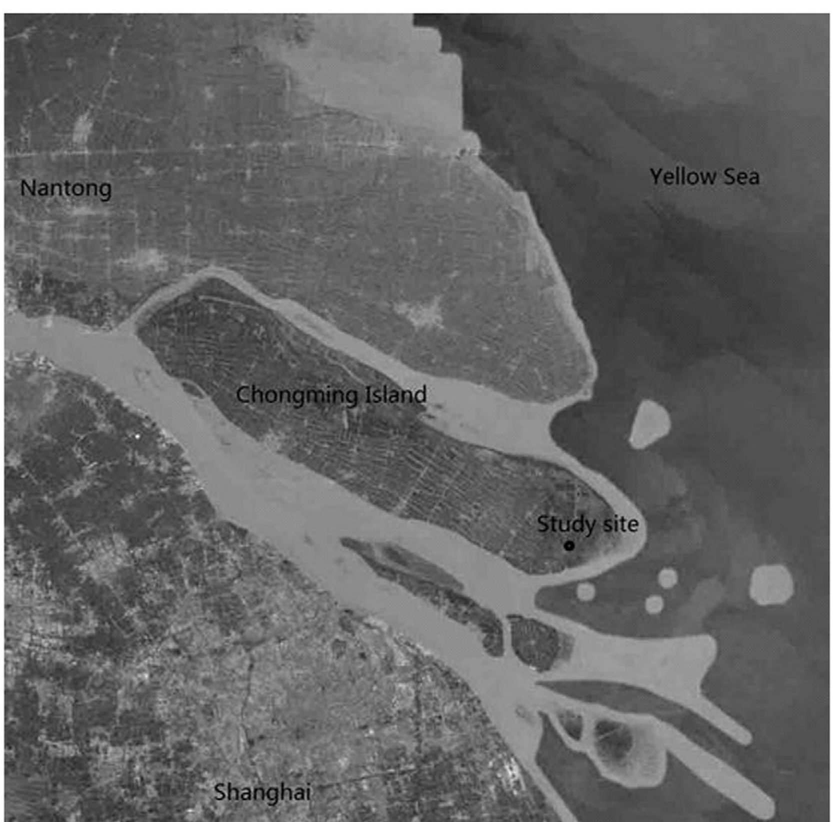

Fig. 1. Map of the study area.

In each plot, five replicate soil cores were selected randomly and soil samples were respectively obtained in various depths of 0–10, 10–20, 20–40, 40–60, and 60–80 cm with a 5 cm diameter soil auger, in the middle of each month from June 2012 to May 2013. Soil sampling cores in each plot were separated by less than 10 m. Currently, research interest is growing in soil electrical conductivity (EC) as a surrogate for soil salinity (McCutcheon et al., 2006; Zheng et al., 2009), and many findings have demonstrated that diverse types of spatial and temporal information can be derived from EC survey data (Lesch et al., 2005; Li et al., 2007). At each sampling point, surface litter was firstly cleared by hand, and then, soil samples were collected. Soil electrical conductivity (EC) measurements were conducted in situ with a portable and corrected sensor probe (Spectrum Technologies Inc., USA). Within the same core, when the soil samples were taken out with an auger, the sensor probes were inserted into the soil to measure the electrical conductivity and temperature, and each layer was measured for three times. The average value was calculated as the representative value of the EC for the layer. Then, after the removal of some obvious plant root segments and other impurities in each soil layer, soil samples were mixed evenly, loaded in 3 aluminum boxes, and timely carried to the lab for the determination of moisture contents. Soil moisture content was measured with the oven-drying method (105 °C, 6 h). The average of three measurements was used as the soil moisture content of each layer. For avoiding the disturbance of hydrology, we sampled 2 m departure from the previous points in the next month.

We collected 240 data points across 4 plots to analyze soil moisture and salinity across temporal and spatial scales. We firstly modeled the annual profile distribution of soil moisture and salinity among different plots. Then, we analyzed seasonal variations of soil moisture and salinity in different depths among various plots. Finally, we examined the relationships among soil EC, soil moisture and temperature.

2.3. Statistical analysis

Differences of soil moisture and salinity in profile distribution and seasonal variation between different vegetation were compared using the one-way analysis of variance (ANOVA) procedures and Tukey's multiple range test. Pearson correlation analysis was performed to determine the relationships among soil EC, moisture and temperature. Statistical analyses were performed with SAS 9.0 software package (SAS Institute, Cary, NC) and differences were considered to be significant if $P < 0.05$.

3. Results

3.1. Profile distributions of soil moisture and salinity

According to profile distributions of soil moisture (Fig. 2), the contents of soil moisture increased exponentially with the depth in grassland and control plots. However, the soil moisture contents were decreased firstly and then increased in woodland and shrubland, and the minimum moisture content was respectively obtained in the 40–60 cm and 10–20 cm depth. As shown in Table 1, the average content of soil moisture in grassland was higher than that in other plots except the depth of 0–10 cm; and significant differences were observed in the deeper soil ($P < 0.05$). The soil moisture content in control plots was lower than that in other plots.

Due to the movement of the underground water, soil salts were redistributed and resulted in salt accumulation. Soil salinity showed different profile distribution patterns in the four types of vegetation (Fig. 3). The higher EC was observed at the shallower soil layers and largely varied in control plots, indicating the surface accumulation phenomenon. This is the typical distribution pattern of salty soil in natural conditions. However, the pattern of soil EC was reversed at deeper layers in other plots, and showed the smaller variation. As shown in Table 2, the average content of soil EC in control plots was significantly higher than that in other plots ($P < 0.05$) except that in the depth of 60–80 cm.

3.2. Seasonal variation of soil moisture and salinity

Soil moisture showed strong seasonal variability (Fig. 4). In control plots, the average content of soil moisture was the highest in spring, reached the lowest in autumn, and increased in winter. Moreover, significant differences were observed between spring and autumn ($P < 0.05$). In woodland, the soil moisture content showed a clear seasonal trend, the values were the highest in winter (26.32–30.38%) and the lowest in summer (21.68–23.01%). Profile soils showed significant differences except for the depth of 10–20 cm ($P < 0.05$). In the shrubland, the average content of soil moisture in the top 20-cm soils in winter was higher than that in other seasons, while the content in the deeper soils (20–80 cm) was higher in spring. Minimal values occurred in autumn in profile soils except the depth of 0–10 cm. With the exception of the depth of 20–40 cm, no significant differences were detected ($P < 0.05$). In the grassland, the average content of soil moisture in the top 40-cm soils in summer was lower than that in other seasons and the contents in the deeper soils (40–80 cm) were lower in autumn. Different seasons showed no significant difference in profile soils except the depth of 0–10 cm ($P < 0.05$).

Fig. 5 showed a clear seasonal variation pattern of soil salinity, which varied with vegetation type and soil depth. These results suggested that the variation pattern of soil EC with depth tended to shift from season to season and in different ways in different plots. In control plots, the average content of soil EC was maximal in summer and decreased in autumn and winter. Except the 20–40 cm deep layer, the variation of EC in each layer in various seasons was not significant ($P < 0.05$). In woodland, except the top 10-cm soil, the average value of soil EC in winter was the highest throughout the year, while the lower values were detected in summer and sometimes detected in autumn (Fig. 5b). Significant

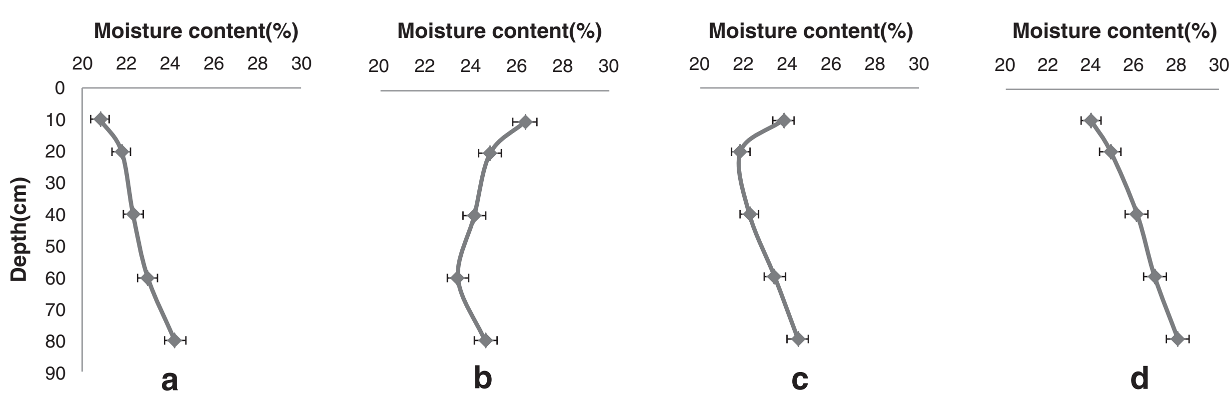

Fig. 2. Distributions profiles of soil moisture under different vegetation. a. Control, b. woodland, c. shrubland, and d. grassland.

Table 1
Vertical changes of soil moisture (mean ± SD) in the four types of plots ($n = 60$).

Plots	Soil depth (cm)				
	0–10	10–20	20–40	40–60	60–80
Woodland	26.32 ± 4.94a	24.81 ± 3.44a	24.11 ± 2.54b	23.4 ± 2.19b	24.58 ± 2.06b
Shrubland	23.8 ± 3.32a	21.84 ± 1.69b	22.31 ± 0.86c	23.4 ± 17b	24.47 ± 1.08b
Grassland	24.01 ± 2.71a	24.92 ± 2.02a	26.15 ± 1.66a	26.97 ± 1.39a	28.06 ± .99a
Control	20.85 ± 1.65b	21.81 ± .53b	22.24 ± 3c	23.01 ± 2.73b	24.25 ± 2.56b

The letters behind average represent multiple comparison results and the same letter indicates the insignificant difference ($P < 0.05$).

differences were detected except the 60–80 cm deep layer ($P < 0.05$). In shrubland, the average value of soil EC in the first 2 layers in spring was lower than that in other seasons, while the values in the 20–80 cm depth were lower in summer. The difference of EC in soil profiles was significant ($P < 0.05$). Under the grassland, there was an increasing trend of EC in various seasons except autumn, while no significant differences were observed throughout the soil profile. Additionally, minimal values were only detected in spring and significant difference in EC variation was found in the first 40 cm deep soil ($P < 0.05$).

3.3. Relationships among soil EC, soil moisture and temperature

The relationships among EC, soil moisture and temperature beneath plots are provided in Table 3. It can be seen that there are positive correlations between soil EC and soil moisture. However, significant positive correlation between EC and soil moisture was only observed under the grassland ($P < 0.01$). The correlation between EC and soil temperature was inconsistent. A negative correlation between EC and soil temperature was found except control plots. Significant correlation between EC and soil temperature was not found only under the grassland ($P < 0.01$). Negative correlation between soil moisture and temperature was found and no significant correlation was observed in control plots ($P < 0.01$).

4. Discussion

4.1. Impact of vegetation restoration on the vertical distribution of soil properties

Plant-induced heterogeneity in soil properties has been recognized in many ecosystems (Boettcher and Kalisz, 1990; Schlesinger and Pilmanis, 1998). The establishment of vegetation on bare land in coastal saline lands has not only profoundly changed the regional hydrology, but also substantially changed water dynamics at different scales, salt accumulation and distribution patterns along the ecosystem–vadose zone–aquifer continuum. Our study indicated that vegetation development resulted in different vertical distribution patterns of soil moisture. The moisture contents gradually increased with depth in control plots and grassland, while the moisture content firstly decreased and then increased in woodland and shrubland (Fig. 2). Owing to the impact of hydraulic lifting and water utilization by plants, the soil moisture in deeper layers is absorbed by deep-rooted plants and then released into the drier and shallower zones for utilization by shallow-rooted plants (Dawson, 1993; Fu, 2003).

The spatial distribution characteristics of soil salinity is the integrated result of various factors, such as land use (vegetation), weather (rain), topography, soil, human activities and so on (Chen et al., 2003). In bare land, surface soil shows the significant salt accumulation phenomenon (Fig. 3a). The high soil evapotranspiration induced an upward soil water flow and transported a large quantity of salt to the surface soil. In plant communities, plants significantly affect the contents and distribution of soil nutrients by altering the physical, chemical, and biological properties of the soil and concentrating biomass and organic matters (Cao et al., 2011; Dong et al., 2009), resulting in the shallower vertical variation of nutrient distributions (Bai et al., 2012). The salt profile reversed following vegetation restoration (Fig. 3b, c, d). It can be interpreted in three aspects. First, plants can improve land coverage, reduce wind speed, adjust microclimate, reduce the quantity of ground evaporation from groundwater and avoid the salt accumulation in the surface soil. Second, plants can re-establish the discharge regime by their greater rooting depth and trigger groundwater utilization through the greater evapotranspiration capacity (Heuperman, 1999; Jobbágy and Jackson, 2004), and lower the groundwater level. Third, the improved soil physical conditions formed by plants (Devitt and Smith, 2002) can decrease runoff, increase infiltration, and promote salt leaching from the upper soil layers (Eldridge and Freudenberger, 2005; Mishra and Sharma, 2003).

The land use changes, particularly re-vegetation on bare land, affect the ecosystem water balances and soluble salt fluxes (Jobbágy and Jackson, 2004). Vegetation development may lower the groundwater table and decrease the soil moisture content because the increased leaf area, canopy roughness and root systems of plants (Canadell et al., 1996; Kelliher et al., 1993; Schenk and Jackson, 2002) often result in more evaporation water loss (Kelliher et al., 1993). However, our results showed that soil moisture content (0–80 cm) increased with the vegetation restoration (Table 1). The discrepancy may be interpreted as

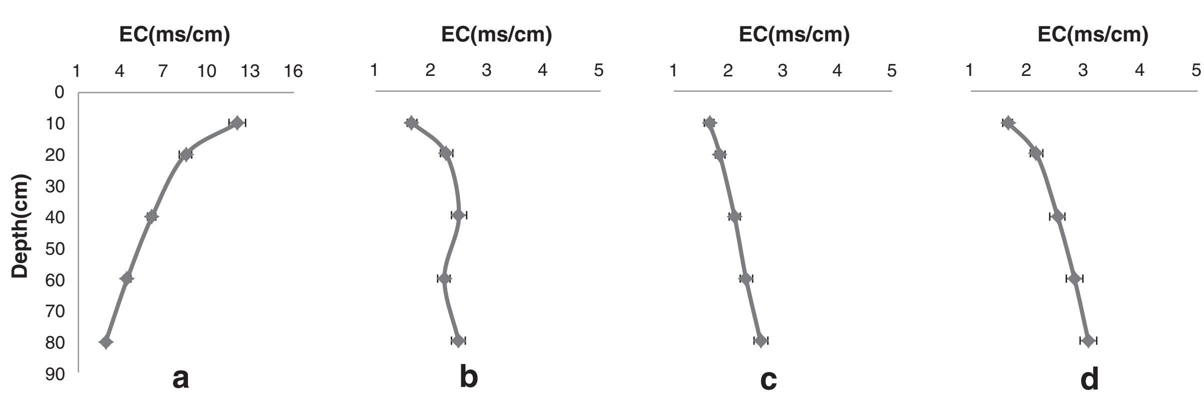

Fig. 3. Distribution profiles of soil EC under different vegetation. a. Control, b. woodland, c. shrubland, and d. grassland.

Table 2
Vertical changes of soil EC (mean ± SD) in the four types of plots ($n = 60$).

Plots	Soil depth (cm)				
	0–10	10–20	20–40	40–60	60–80
Woodland	1.64 ± 0.46b	2.25 ± 0.42b	2.49 ± 0.55b	2.22 ± 0.35b	2.47 ± 0.4a
Shrubland	1.64 ± 0.79b	1.83 ± 0.58b	2.1 ± 0.52b	2.31 ± 0.4b	2.58 ± 0.35a
Grassland	1.66 ± 0.78b	2.16 ± 0.59b	2.54 ± 0.511b	2.84 ± 0.44ab	3.08 ± 0.46a
Control	12.04 ± 1.63a	8.45 ± 1.38a	6.11 ± 1.36a	4.39 ± 1.17a	2.91 ± 0.63a

The letters behind average represent multiple comparison results and the same letter indicates the insignificant difference ($P < 0.05$).

follows: the soil moisture contents came from the whole year while it mostly came from summer.

Moreover, plants are conducive to reducing soil salinity in saline lands. The results from the present study showed that soil salinity decreased with the vegetation restoration (Table 2), indicating the roles of plants in reducing soil salinity. The presence of plants in bare land creates benign microclimatic conditions (Holmgren and Scheffer, 2001; Li et al., 2002; Su et al., 2005) and significantly improves the physical and chemical properties of soils (Mun and Whitford, 1998), thus reducing groundwater recharge (Le Maitre et al., 1999) and soil salt contents.

4.2. Seasonal variation of salinity in soil profile

A number of studies have demonstrated that the spatial and temporal variations of soil salinity among soil sections are the consequences of the combined actions of climate, ground-water levels, and vegetation. According to the data obtained from the present study, the distribution of soil salinity in control plots is characterized by the higher concentration in summer and the lower concentration in winter. This is closely related to seasonal temperature and rainfall patterns (Silvestri et al., 2005; Tho et al., 2008). The results from the present study showed that the salinity in surface soils with vegetation was higher in autumn, while the salinity in deeper soil was lower in summer. This may be the comprehensive consequence of plant cycling and climate. The clear seasonal variation of climate leads to distinct phenological patterns in plant growth, while nutrient dynamics are also strongly affected by this seasonal variation through microbial activity or hydrological processes in the canopy, litter, and soil layers (Anaya et al., 2007; Yamashita et al., 2011). It is well known that plants assimilate a lot of nutrients from soils for their growth and partial nutrients adsorbed by plants are transported aboveground in summer, resulting in lower salt contents in deeper soil. Additionally, the lower salt contents in the deeper soil in summer were also closely related to the increased soil macroporosity and more rainfall. However, the inputs and decomposition of plant litters in autumn contributed to salinity accumulation in surface soils. The seasonal variation pattern of soil salinity in profile varies with vegetation. Compared with grasses, woody plants

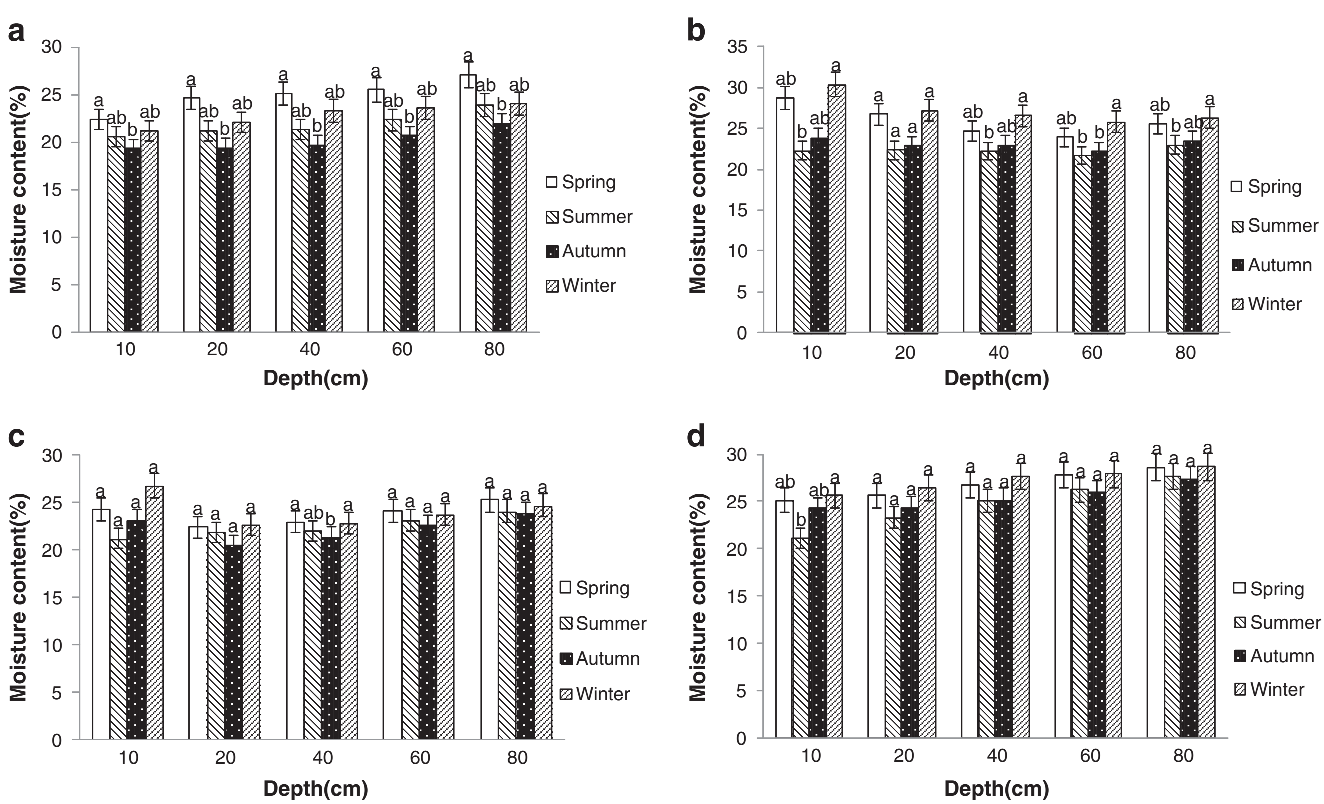

Fig. 4. Seasonal variation of soil moisture across profile under different vegetation. Different letters above bars show significant difference at the 5% level. a. Control, b. woodland, c. shrubland, and d. grassland.

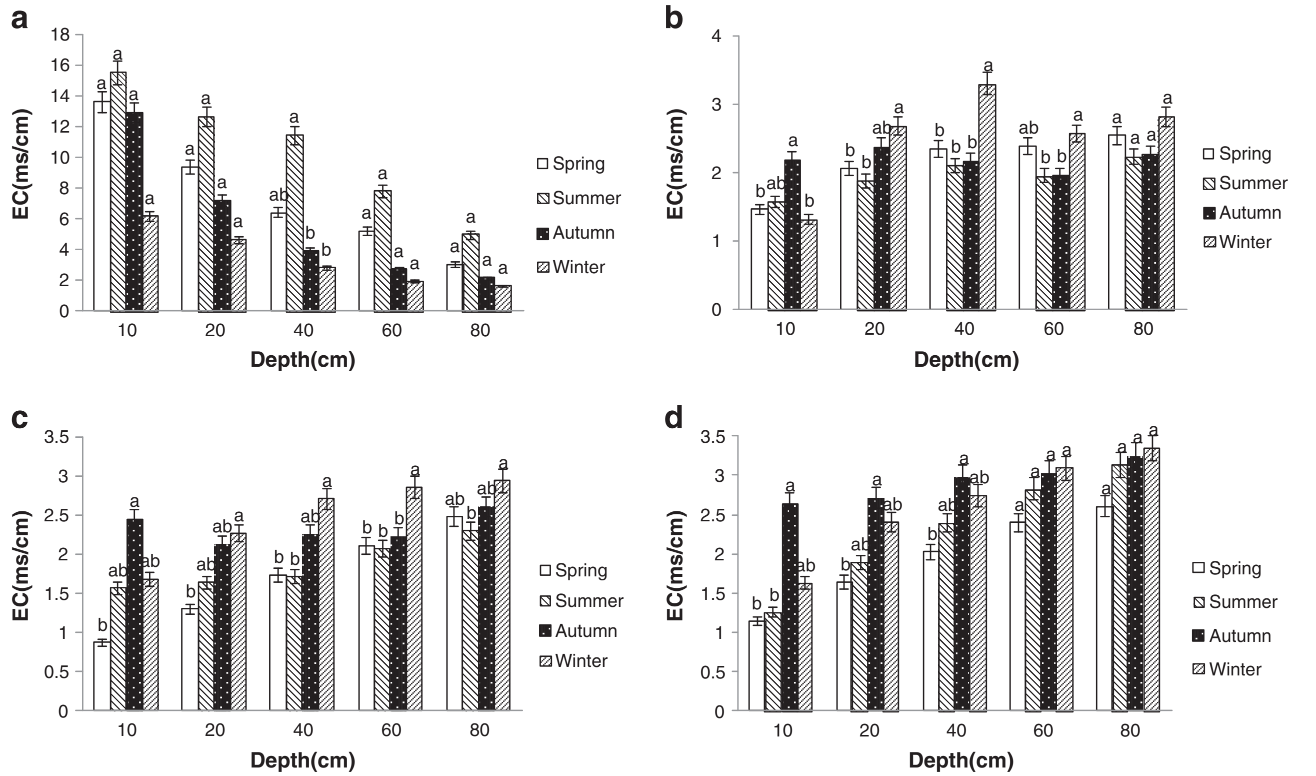

Fig. 5. Seasonal variation of soil EC across profile under different vegetation. Different letters above bars show significant difference at the 5% level. a. Control, b. woodland, c. shrubland, and d. grassland.

often present the higher evaporation capacity, dictated by greater aerodynamic conductance and deeper root systems (Canadell et al., 1996; Kelliher et al., 1993). Moreover, with the higher root density and larger litter amount, compared with grasses, woody plants often exhibit better soil physical properties for water and salt movement (Devitt and Smith, 2002; Dunkerly, 2000).

4.3. Hypothetical mechanisms of salinization patterns

Although the ecological rehabilitation on saline soil by plants has significantly promoted salt removal in surface soil, the opposite case can be observed in the deeper depth and salts are accumulated in the vadose zone and aquifer (Marcelo et al., 2007). This can be explained by the hypothetical mechanisms. Before vegetation establishment, the water level in the coastal region was shallow and the surface soil results from seasonal salt accumulation due to the soil evaporation and poor physical conditions of soils. When the water evaporation quantity by capillarity was balanced by the water input quantity of precipitation, salt contents in the soil profile reached a steady state. After vegetation establishment, improved soil condition increased downward water percolation and as a result, salts in the upper soil layers were flushed into deeper soil. In addition, plant roots lowered the water table through groundwater absorption in the greater depth, thus increasing the hydraulic gradient and leading to Darcian flows from surrounding soil. An evaporation groundwater discharge regime was developed and a new salt accumulation process was initiated in the vegetation, whose transpiration was the most important component compared to soil evaporation. Therefore, one consequence of rehabilitation on saline soil by plants could be a gradual accumulation of salt in the vadose zone and aquifer. Therefore, the whole ecosystem–vadose zone–aquifer continuum is critical for understanding salinization processes at different temporal and spatial scales.

Table 3
Correlation coefficient (Pearson) of soil EC, soil moisture, and soil temperature in the four types of plots ($n = 60$).

Plots	Variables	EC	Moisture content	Temperature
Woodland	EC	1		
	Moisture content	0.204	1	
	Temperature	−0.429**	−0.655**	1
Shrubland	EC	1		
	Moisture content	0.213	1	
	Temperature	−0.388**	−0.313**	1
Grassland	EC	1		
	Moisture content	0.463**	1	
	Temperature	−0.136	−0.563**	1
Control	EC	1		
	Moisture content	0.126	1	
	Temperature	0.5**	−0.004	1

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

5. Conclusions

Our study indicates that vegetation establishment on naturally salt-affected soils has strong effects on soil moisture with cascading consequences on salt accumulation and distribution, and the spatial and seasonal distribution of water and salt in a coastal saline field varied with the plant communities and seasons. Soil moisture content is firstly decreased and then increased with soil depth in woodland and shrubland, while soil moisture is consistently increased in grassland and control plots. Salt profiles showed the higher values in surface soil in control plots, whereas the pattern of soil salinity showed the reverse trend under vegetation. No clear seasonal trend of soil moisture or salinity is observed in re-vegetated plots compared with the control plots. In the study of spatial and seasonal variations of salt ions under the influence of halophytes (Wu et al., 2009), it is concluded that plant communities promote the desalinization in the first 80 cm deep soil. However, large-scale afforestation may trigger a rapid secondary salinization of vadose zones and aquifers compromising the sustainability of forestry in the long term. Moreover, motivated by the soil degradation (salinization, desertification, etc.) and eventual carbon sequestration market (Wright et al., 2000), human-induced afforestation in saline land is increased around the world. In the future, in order to solve the problems of ecological restoration in coastal saline land, the selection of salt-tolerant plant species and the construction of plant community should be thoroughly considered. Meanwhile, the whole and explicit vegetation–soil–groundwater perspective needed to be considered at different temporal and spatial scales in the ecological restoration on saline land.

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