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Bo Guan[1,2]
Junbao Yu[1,2]
Di Cao[3]
Yunzhao Li[1,2]
Guangxuan Han[1,2]
Peili Mao[1,2]

[1]Key Laboratory of Coastal Zone Environmental Processes and Ecological Remediation, Yantai Institute of Coastal Zone Research (YIC), Chinese Academy of Sciences (CAS), Yantai Shandong, P. R. China
[2]Shandong Provincial Key Laboratory of Coastal Zone Environmental Processes, YICCAS, Yantai Shandong, P. R. China
[3]College of Life Science and Technology, Heilongjiang Bayi Agricultural University, Daqing Heilongjiang, P. R. China

Research Article

The Ecological Restoration of Heavily Degraded Saline Wetland in the Yellow River Delta

As a result of discontinuous water flow, agriculture, and increasing urban use of fresh water affecting the natural wetlands of the Yellow River Delta, these areas have experienced significant degradation in the past two decades, ultimately diminishing the overall natural wetland land area in the region. This study aimed to address the issue of decreasing fresh water in the Yellow River Delta by studying the effects of three different approaches to restoration on long-term wetland recovery. The results of the study demonstrated that soil salt and available Na contents significantly decreased in response to all three restoration treatments. Impacts of the restoration treatments were more significant in 2009 than in 2010, as shown by the high rate of activity in the reed debris group. The highest phosphatase activity of the experimental period was also observed in the reed debris group. Meanwhile, a marked variation in soil nutrient elements (total carbon (TC), total nitrogen (TN), available phosphorus, and available potassium) was observed in the restoration treatment plots throughout the experimental period. TC and TN contents were generally higher in the restoration treatment groups than in the control group. Moreover, urease and phosphatase activity levels were highly correlated with one another, as well as with soil nutrient elements. In 2009, the yield of the *Suaeda salsa* plant was highest in the reed debris treatment group and lowest in the ploughing treatment group. The *S. salsa* plant did show a positive response to all of the different restoration treatments. Taken together, these results suggest that restoration approaches that implement ploughing techniques aided in the restoration of degraded saline wetlands.

Keywords: Reed debris; Enzyme activity; Plant growth; Wetland degradation

Received: October 22, 2012; *revised:* November 25, 2012; *accepted:* December 4, 2012

DOI: 10.1002/clen.201200569

1 Introduction

Wetland loss is a global problem, and it has been estimated that over half of the world's original wetlands have been lost as a result of destructive human activities [1]. Wetland loss disproportionately affects heavily populated or developed regions, such as coastal areas. In response to the growing threat to ecosystems worldwide, studies of wetland restoration, reconstruction, and protection have been increasingly implemented [1, 2].

Coastal wetlands in China cover approximately 5.94×10^4 hm^2, a figure that amounts to only about 70% of the total coastal wetland areas that existed in this area 50 years ago [3]. As economic growth accelerates and is encouraged in coastal areas, wetland security is concurrently threatened, making the negative impact of human activity on wetlands increasingly evident. The conflict between protection and use or exploitation of wetlands grows tense, and serving the interests of competing groups is extremely difficult. The above developments have made coastal wetland restoration studies a research hotspot in recent decades [4–7]. The first coastal wetland restoration project in China began in the 1970s. In 1979, *Spartina alterniflora* Loisel was introduced into certain areas in China in an effort to accelerate sedimentation and land formation [4, 8]. Researchers introduced *Suaeda salsa* (L.) into certain areas to investigate its remediation capacity in oil-polluted coastal zones [9]. Many coastal wetland natural reserves were constructed during this time to prevent greater loss of vegetation and wildlife biodiversity.

The Yellow River Delta is the fastest growing delta in the world, as the Yellow River carries tons of sediment into the estuary, making this delta one of the world's most emblematic river wetland ecosystems. However, in the last two decades, the discontinuous flow of the Yellow River, seawater erosion, and intense anthropogenic activity have significantly contributed to the degradation and diminishment of these natural wetlands [10, 11]. Furthermore, most of the salt marshes have become dry lands and saline wetlands. In some highly degraded saline areas of the Yellow River Delta, no vegetation can grow, including the most salt tolerant plant, *S. salsa*.

The addition of freshwater has proven to be an effective method to aid in reconstruction of estuary wetlands that have been subjected to drainage and seawater intrusion [6, 7, 12]. A series of restoration

Correspondence: Dr. J. Yu, Key Laboratory of Coastal Zone Environmental Processes and Ecological Remediation, Yantai Institute of Coastal Zone Research (YIC), Chinese Academy of Sciences (CAS); Shandong Provincial Key Laboratory of Coastal Zone Environmental Processes, YICCAS, Yantai Shandong 264003, P. R. China
E-mail: junbao.yu@gmail.com; jbyu@yic.ac.cn

Abbreviations: AK, available potassium; **AP**, available phosphorus; **C**, control group; **FG**, fertilization group; **LSD**, least significant difference; **PG**, ploughing group; **RG**, reed debris group; **SD**, standard deviation; **TC**, total carbon; **TN**, total nitrogen

projects based on supplying freshwater are currently being used to improve wetlands functioning and wildlife habitats in the Yellow River Delta [5, 13]. However, the degradation of Yellow River Delta coastal wetlands remains dramatic as a result of unyielding river water and groundwater deficiency. Evapotranspiration without subsurface leaching has resulted in soil salinization, aided by sea salt in the groundwater. Soil salinization has a significant negative correlation with some elements that are essential for plant growth, such as total nitrogen (TN) and phosphorus [14]. To effectively address and alleviate the problems resulting from decreased freshwater in the Yellow River Delta, new approaches to restoration must be introduced.

This study evaluated three methods for the restoration of highly degraded saline wetlands in the Yellow River Delta. The pioneer plant in Yellow River Delta saline wetlands, *S. salsa*, was used for remediation of heavily degraded saline wetlands. Across the 2-year experimental period, we measured and discussed dynamic changes in soil salt content, soil enzyme activities, soil nutrients, and vegetative parameters. The objectives of the study were: (1) to try to successfully establish *S. salsa* in the heavily degraded saline and barren wetlands in the Yellow River Delta, with the help of certain supplementary methods; (2) to investigate the dynamic changes in soil salt content, soil nutrient elements, and soil enzyme activities following restoration; and (3) to evaluate the impact on long-term recovery of the three restoration approaches by measuring relevant eco-physiological parameters.

2 Materials and methods

2.1 Study site description

The experiment was carried out in a field station (37°46′37.6″N, 118°07′37.9″E) in the Yellow River Delta that was representative of heavily degraded saline land. The station is located about 50 km north of Binzhou City in Shandong Province, China (Fig. 1). The climate in the study area is warm temperate continental monsoon climate, with distinct seasons and rainy summers. The annual average temperature for this region is 12.5°C; average annual rainfall is 660 mm, with about 70% occurring between June and August; and average annual evaporation is 1900 mm. Study area soils are dominated by intrazonal tide soil and salt soil. *Phragmites australis* and *S. salsa* are predominant vegetative species. In some highly degraded saline areas, only *S. salsa* could be observed in a scattered manner, and these areas were selected for the restoration experiment (sample depth: 20 cm, average salt content is 2.5%, pH is 8.85, $n = 20$).

2.2 Methods

2.2.1 Experimental design and plant establishment

For plot placement, we carefully selected flat areas that had minimal micro-topographic variation. We measured the soil biochemical properties of the top soil layer (0–20 cm) at the beginning of the experiments in April (2009; Tab. 1). The plot was organized in a complete randomized design with three different ecological restoration treatments, each with three replicates: ploughing, fertilization, and reed debris addition. For the ploughing group (PG), 20 cm of the soil surface was ploughed flat. For the fertilization group (FG), slow release urea (130 kg N/hm^2 or 13 g N/m^2) was added to the plot during ploughing. For the reed debris group (RG), reed debris (2 kg/m^2; 0.67% TN in reed debris, which is about 13.4 g N/m^2) was added to the 20 cm layer of the surface soil during ploughing. There were 12 plots total, including 3 control plots (C) which received no treatment, each with 2 m × 3 m surface area, and each separated by a 1 m wide ridge. PVC sheets were buried 0.5 m deep into the ridges to prevent nutrient flow between plots.

On May 7th 2009, *S. salsa* seeds were sown in all plots (including control plots) at a density of 5000 seeds per plot. To ensure germination and seedling establishment, all plots were irrigated with 20 cm freshwater before planting.

2.2.2 Sampling methods and chemical analysis

Experiments were conducted from April 2009 to October 2010. In 2009, we sampled the top soil layer (0–20 cm) monthly from May to October. Five samples were collected randomly from each plot. Samples were pooled per plot, air-dried at ambient room temperature, and sieved (<2.0 mm) for further analysis.

Soil salt content was determined by weight loss of 1:5 soil/water (by weight) extract after oven-drying at 105°C to constant weight.

Dry soil samples (100 mg) were treated with 20 mL deionized water at 100°C for 20 min, and the extract was taken for ion determination. Soil available Na^+ and K^+ (AK) contents were determined by atomic absorption spectrophotometry (AA-6800, Shimadzu, Japan).

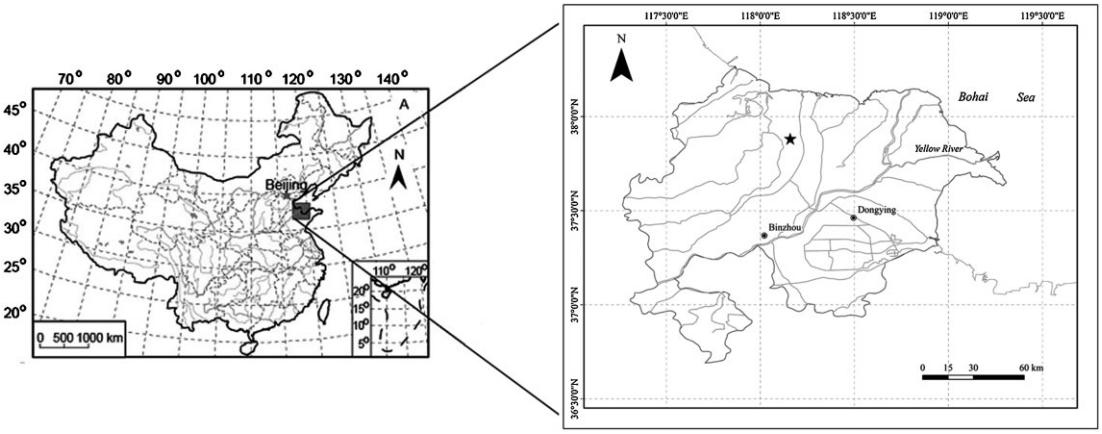

Figure 1. Study site (Pentagram) and the location map of the Yellow River Delta in China.

Table 1. Soil properties of the experimental region

Index	Soluble salt (%)	Total C (g/kg)	Total N (g/kg)	Available P (mg/kg)	Available K (mg/kg)
Value	2.50	18.57	0.663	8.092	353.7

Soil TN and total carbon (TC) contents were analyzed using an elemental analyzer (Elementar Vario Macro, Germany).

Available phosphorus (AP) was determined after extraction using sodium bicarbonate.

Urease activity and alkaline phosphatase activity were determined according to the handbook of Bao [15]. For determination of urease activity, 1.5 mL toluene, 20 mL citrate buffer (pH 6.7), and 1 mL 10% urea substrate solution were added to the 5-g sample, and samples were then incubated for 24 h at 37°C. The formation of ammonium was determined spectrophotometrically at 578 nm, and results were expressed as mg N g^{-1} dry sample.

For determination of alkaline phosphatase activity, 1.5 mL toluene, 10 mL phosphate buffer (pH 7.1), and 10 mL 0.02 M *p*-nitrophenyl phosphate solution were added to the 2-g sample, and samples were incubated for 24 h at 37°C. The formation of *p*-nitrophenol was determined spectrophotometrically at 510 nm, and results were expressed as mg *p*-nitrophenol g^{-1} dry sample.

Plant density was measured by directly counting the number of stems at a height of 0.25 m^2.

Plant height was measured in October 2009 and 2010 using a ruler, and measurements were recorded to the nearest centimeter.

At the end of each year of the experimental period (2009 and 2010), plant aboveground biomass was harvested and dried at 65°C to constant weight.

2.2.3 Statistical analyses

Each plot was considered as a replicate, and all the treatments were repeated three times. One-way analysis of variance (ANOVA) was performed using SPSS statistical software (SPSS, Chicago, IL, USA). The values have been reported as means and calculated standard errors. Significance was tested at the 5-% level, and relationships between soil enzyme activity and soil nutrient variables were studied using Pearson's correlation.

3 Results

3.1 Soil salt content

A marked variation was observed in soil salt content values for the different plots during the experimental period. In April 2009, the average soil salt content of the study area was about 2.5% (Tab. 1). Following the different field treatments, soil salt content had decreased significantly (Fig. 2). The soil salt content of C was significantly negatively correlated with precipitation ($p < 0.05$). In 2009, the highest soil salt content was observed in C, and the lowest in RG treatment. From August 2009 to October 2010, soil salt contents in the three restoration treatment plots were all significantly lower than that of the control group, with the exception of PG in October 2009. No significant differences in soil salt content values were observed in 2010.

3.2 Soil available Na content

Figure 2 displays the changes in soil available Na content in the different treatment plots during the experimental period. No significant differences were observed between the control group and the restoration treatment groups prior to July 2009. As precipitation increased and plant growth progressed, soil available Na in the restoration treatment groups decreased dramatically as compared to the control (Figs. 2 and 3). In October 2009, the Na content of the RG treatment soil was lower than that of other groups. The three restoration treatments had similar effects on soil available Na content in 2010, but restoration treatment values were all significantly lower than those of the control group, with the exception of the May 2010 value.

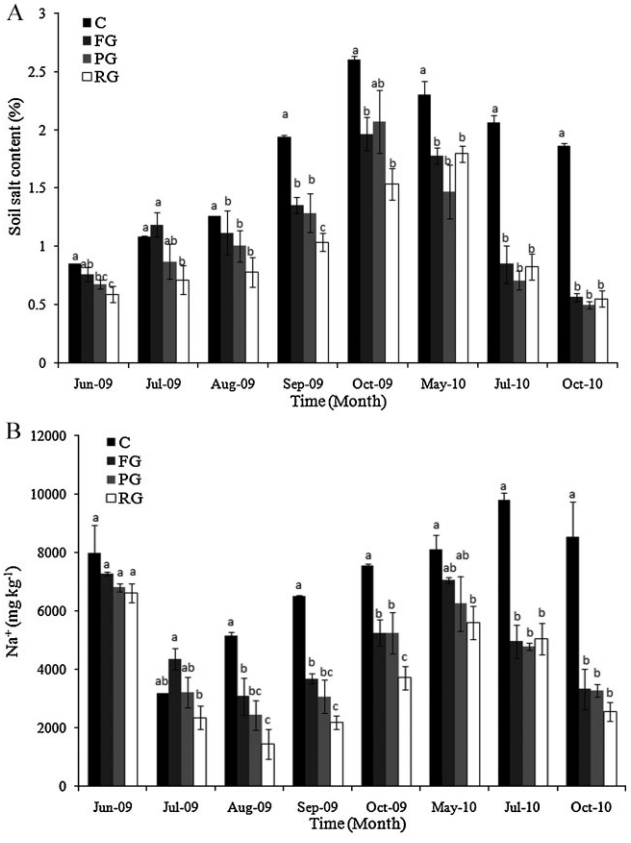

Figure 2. Dynamic changes of soil salt content (A) and soluble Na^+ content (B) with different eco-remediation methods during the growing season in 2009 and 2010. In each column, the data markers identified with the same letters are not significantly different ($p < 0.05$) from different restoration treatments according to an LSD test. The error bars represent ±SD ($n = 5$) of five replicates.

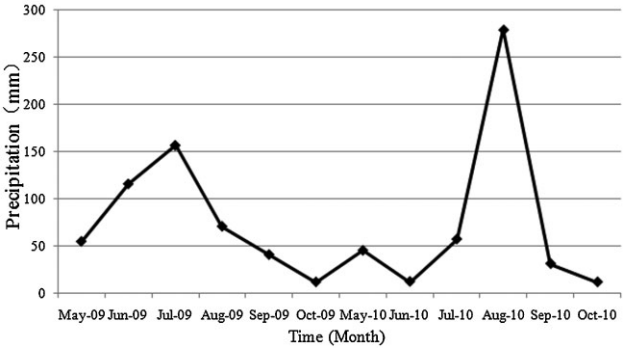

Figure 3. The average monthly precipitation of the study site from May 2009 to October 2010.

3.3 Soil enzyme activity

Urease activity was generally higher in the restoration treatment groups than in the control group in 2009 and 2010, though these differences were not always significant (Fig. 4). The effects of restoration treatments were more significant in 2009, and urease activity was highest in the RG treatment. This increasing tendency was not significant in 2010. In July 2010, there were no significant differences in urease activity between the FG treatment, the RG treatment, and the control group.

Compared to the control group, phosphatase activity increased significantly in all treatments groups. The RG treatment group had the highest phosphatase activity during the experimental period. There were no significant differences between phosphatase activity in the FG and PG treatment groups, and that for the control group was the lowest (Fig. 4).

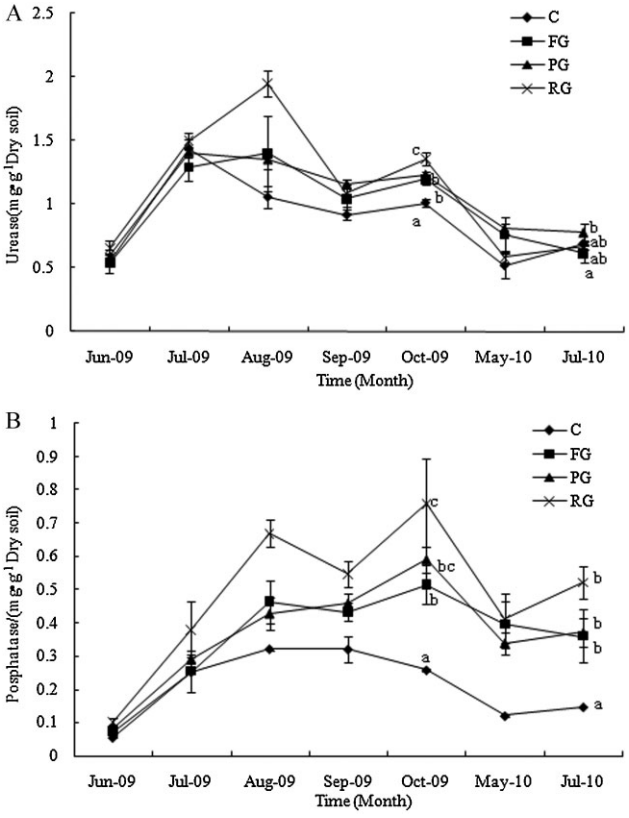

Figure 4. Dynamic changes of soil urease (A) and phosphatase (B) with different eco-remediation methods during the growing season in 2009 and 2010. The data markers identified with the same letters are not significantly different ($p < 0.05$) from different restoration treatments according to an LSD test. The error bars represent ±SD ($n = 5$) of five replicates.

3.4 Soil nutrient elements

Changes in soil nutrient elements (TC, TN, AP, and AK) in the treatment plots during the experimental period are shown in Tab. 2. In 2009, TC content in the restoration treatment plots gradually increased from June to October. In June and July 2009, no significant difference was observed in TC content of the experimental groups as compared to the control group, with the exception of the FG treatment in June. In August and October 2009, the TC content in the three treatment groups was remarkably higher than that in the control group. In 2010, the TC content in the restoration treatment group was significantly higher than that in the control group, with the exception of FG and RG treatment values in October.

The TN content of the control group remained almost constant in 2009 and 2010, while TN content for the restoration treatment groups gradually increased. Compared to that of the control group, TN content of the restoration treatment groups increased significantly in August and October 2009, and May 2010.

In June and October 2009, no significant differences for soil AP content were observed between the restoration treatment groups and the control group. However, from July to September 2009, soil AP content in the restoration treatment plots decreased significantly compared to the control plot. In 2010, no significant differences were observed between the restoration treatment plots and control plots, with the exception of FG and PG treatment groups in May.

Available potassium content of the control group decreased gradually from June to October in both 2009 and 2010. AK contents in the FG and RG treatment groups were higher than those in the PG treatment and control group in August and October 2009. With the exception of the PG treatment in July 2010, no significant differences were observed between the different treatment plots at other investigation times.

Urease and phosphatase activities were highly correlated with one another and with the soil nutrient elements (Tab. 3). Urease activity was positively correlated with TC, TN, and AK ($p < 0.01$). Phosphatase activity was positively correlated with TC and TN, and negatively correlated with C/N ($p < 0.01$).

3.5 Vegetative parameters

The *S. salsa* plant showed a positive response to the different restoration treatments (Tab. 4). The average height of *S. salsa* in the restoration treatment plots was about 60 cm in October 2009, and 46 cm in October 2010; meanwhile, no plants were observed in the control plots.

Plots treated with reed debris had significantly more plants than did plots with the FG treatment ($p < 0.05$) in October 2009; however, no differences were observed between the three restoration treatments in October 2010. Overall plant density was dramatically higher in 2010 than it was in 2009.

Table 2. Dynamic changes of TC, TN, AP, and AK in different treatments during the growing season in 2009 and 2010

Index	Time	Methods of treatment			
		C	FG	PG	RG
Total C (g/kg)	Jun-09	18.58 ± 0.03^{a}	20.63 ± 0.91^{b}	19.15 ± 0.15^{a}	19.94 ± 0.27^{a}
	Jul-09	18.23 ± 0.81^{a}	19.78 ± 1.31^{a}	18.93 ± 1.39^{a}	20.33 ± 1.15^{a}
	Aug-09	18.90 ± 0.33^{a}	22.34 ± 0.65^{bc}	20.96 ± 0.38^{b}	23.12 ± 0.38^{c}
	Sep-09	18.58 ± 0.54^{a}	22.10 ± 1.14^{ab}	21.42 ± 0.59^{ab}	22.47 ± 1.08^{b}
	Oct-09	18.66 ± 0.36^{a}	22.11 ± 0.56^{b}	20.81 ± 0.73^{b}	22.32 ± 0.32^{b}
	May-10	15.23 ± 0.07^{a}	18.35 ± 0.70^{b}	17.92 ± 0.72^{b}	18.01 ± 1.07^{b}
	Jul-10	15.87 ± 1.04^{a}	19.39 ± 0.49^{b}	18.44 ± 0.14^{b}	19.26 ± 0.87^{b}
	Oct-10	18.23 ± 0.89^{a}	19.41 ± 0.34^{ab}	20.44 ± 0.82^{b}	20.13 ± 0.31^{ab}
Total N (g/kg)	Jun-09	0.66 ± 0.03^{a}	0.68 ± 0.06^{a}	0.63 ± 0.02^{a}	0.70 ± 0.08^{a}
	Jul-09	0.60 ± 0.03^{a}	0.66 ± 0.11^{a}	0.67 ± 0.07^{a}	0.76 ± 0.01^{a}
	Aug-09	0.52 ± 0.02^{a}	0.84 ± 0.12^{b}	0.77 ± 0.02^{b}	0.90 ± 0.03^{b}
	Sep-09	0.68 ± 0.04^{a}	0.80 ± 0.08^{a}	0.75 ± 0.03^{a}	0.86 ± 0.08^{a}
	Oct-09	0.64 ± 0.05^{a}	0.89 ± 0.04^{b}	0.83 ± 0.02^{b}	0.90 ± 0.08^{b}
	May-10	0.39 ± 0.01^{a}	0.61 ± 0.04^{b}	0.63 ± 0.06^{b}	0.66 ± 0.08^{b}
	Jul-10	0.61 ± 0.06^{a}	0.72 ± 0.05^{ab}	0.63 ± 0.03^{a}	0.81 ± 0.04^{b}
	Oct-10	0.68 ± 0.08^{a}	0.75 ± 0.02^{a}	0.80 ± 0.07^{a}	0.79 ± 0.08^{a}
Available P (mg/kg)	Jun-09	9.02 ± 0.85^{a}	8.80 ± 0.19^{a}	8.02 ± 1.22^{a}	8.22 ± 0.39^{a}
	Jul-09	11.72 ± 0.31^{a}	6.30 ± 0.12^{b}	7.82 ± 0.59^{c}	6.40 ± 0.42^{b}
	Aug-09	12.16 ± 0.46^{a}	11.07 ± 0.13^{ab}	10.91 ± 0.37^{b}	10.80 ± 0.44^{b}
	Sep-09	8.79 ± 0.33^{a}	8.79 ± 0.52^{a}	8.26 ± 0.75^{ab}	7.15 ± 0.04^{b}
	Oct-09	11.57 ± 0.57^{a}	10.88 ± 1.13^{a}	10.51 ± 0.76^{a}	10.77 ± 0.66^{a}
	May-10	9.36 ± 0.12^{a}	10.62 ± 0.37^{b}	8.57 ± 0.18^{c}	9.78 ± 0.23^{a}
	Jul-10	9.80 ± 0.15^{a}	9.95 ± 0.68^{a}	8.81 ± 0.91^{a}	9.65 ± 0.64^{a}
	Oct-10	6.55 ± 0.75^{a}	5.25 ± 0.50^{a}	4.98 ± 0.52^{a}	7.11 ± 1.95^{a}
Available K (mg/kg)	Jun-09	347.69 ± 27.23^{ab}	398.04 ± 25.99^{b}	329.55 ± 16.47^{a}	373.01 ± 2.09^{ab}
	Jul-09	251.68 ± 1.14^{a}	304.91 ± 40.95^{a}	253.70 ± 16.08^{a}	307.64 ± 15.07^{a}
	Aug-09	260.24 ± 1.95^{a}	333.70 ± 5.46^{bc}	278.71 ± 30.78^{a}	345.68 ± 19.51^{c}
	Sep-09	265.18 ± 5.11^{a}	355.84 ± 11.90^{a}	289.54 ± 36.43^{a}	338.43 ± 47.59^{a}
	Oct-09	242.86 ± 1.78^{a}	354.77 ± 13.69^{b}	293.17 ± 34.23^{a}	358.35 ± 7.94^{b}
	May-10	343.38 ± 7.89^{a}	384.05 ± 21.11^{a}	414.91 ± 46.47^{a}	432.53 ± 33.64^{a}
	Jul-10	438.71 ± 13.93^{a}	420.42 ± 4.78^{a}	375.31 ± 10.35^{b}	439.48 ± 10.50^{a}
	Oct-10	211.41 ± 7.75^{a}	150.13 ± 23.69^{a}	160.54 ± 15.10^{a}	173.67 ± 28.23^{a}

Different letters indicate significant differences from different restoration methods ($p < 0.05$).

Table 3. Correlation coefficients for relationships between different soil enzymes and soil nutrient variables for soil samples from all samplings

	Urease	Phosphatase	TC	TN	C/N	AP	AK
Urease	1	$0.598^{a)}$	$0.603^{a)}$	$0.528^{a)}$	−0.298	0.142	$-0.553^{a)}$
Phosphatase		1	$0.648^{a)}$	$0.747^{a)}$	$-0.565^{a)}$	0.262	0.004

a) Significant correlation at $p < 0.01$.

Table 4. Effect of different restoration methods on plant height, density, and yield in October 2009 and 2010

Index	Time	C	FG	PG	RG
Plant height (cm)	Oct-09	0	59.35 ± 3.18^{a}	59.67 ± 3.23^{a}	62.87 ± 4.98^{a}
	Oct-10	0	46.92 ± 1.14^{a}	45.00 ± 5.14^{a}	46.67 ± 1.92^{a}
Density (plant/m^2)	Oct-09	0	292 ± 74^{a}	365 ± 41^{ab}	531 ± 115^{b}
	Oct-10	0	2676 ± 433^{a}	3360 ± 704^{a}	2992 ± 213^{a}
Yield (g/m^2)	Oct-09	0	639.99 ± 77.60^{ab}	396.29 ± 12.13^{a}	771.12 ± 142.44^{b}
	Oct-10	0	408.75 ± 108.72^{a}	431.57 ± 107.21^{a}	465.01 ± 72.53^{a}

Different letters indicate significant differences from different restoration methods ($p < 0.05$).

Similarly, *S. salsa* plant yield was highest in the RG treatment group and lowest in the PG treatment group in 2009. No significantly differences were observed between the groups in 2010.

4 Discussion

Overall, the applied restoration treatments affected many of the measured soil and vegetative parameters. Examination of the effects of three restoration methods (ploughing, fertilization, and reed debris addition) on biological, chemical, and vegetation parameters of saline soil showed that the treatments had a positive influence on the measured parameters.

First, all of the restoration methods led to reduced soil salt content and soil available Na content. Na^+, which is the major cation type present in the Yellow River Delta soil, has seriously reduced the overall plant growth in the area [16]. Figure 2 shows that the salt content and available Na content in the soils decreased significantly following the restoration treatments. In 2009, salt content of all the experimental plots increased with decreasing precipitation from June to October. But, compared to the control group, the soil bulk density of the restoration plots was significantly lower (data not shown). The ploughing method increased soil porosity, which can effectively control salt uprising in soil. Increased soil porosity can allow for the direct exchange of gases between air and soil in the plant rooting zone, and this activity is beneficial for plant growth. Plant growth in the restoration treatment plots can also reduce the speed of soil salt uprising. The new seeds of *S. salsa* dropped naturally in autumn 2009 and germinated in the spring of 2010. When this happened, soil salt content and available Na content in the restoration plots were twice as low as the respective values in the control plots.

Second, the increased soil porosity that is associated with restoration treatments effectively increased soil enzyme activity. Soil enzyme activity can be used as an indicator of the potential to host soil microbial communities [17]. In the present study, the restoration treatments significantly increased soil urease and phosphatase activities. In the first year of restoration, the highest soil urease and phosphatase activities were observed in the RG restoration treatment, indicating that the RG treatment provided more soil organic nutrients for the metabolism of soil microorganisms. The chemical fertilizer afforded by the FG treatment could not provide continuous nutrients for soil microorganisms and plant growth. As a result, no significant differences in soil organic nutrients were observed between the FG and PG treatment groups. Previous studies on soil from various regions have shown that soil enzyme activities are sensitive to tillage-induced soil changes [18, 19]. The opposite result was observed in the highly degraded land, indicating that the soil rhizosphere ventilation that was improved by the restoration treatments increased soil enzyme activity [20].

Third, many studies have reported that growing salt tolerant species could improve soil physical and chemical properties in saline soils [21–23]. An increase in soil nutrients could also positively affect plant growth. Usually, phosphorous availability declines as a result of weathering and drainage loss [24, 25], while carbon and nitrogen accumulate with time [26, 27]. The results of our study demonstrated that restoration treatments significantly increased soil TC and TN (Tab. 3), ultimately benefiting *S. salsa* plant growth. Similar results have been illustrated in previous research showing that TN in the top 20 cm of soil was significantly correlated with salinity [14]. Further, AP decreased in the treatment groups as compared to the control plots, likely resulting from increased soil porosity, precipitation, and plant growth. Many studies have shown strong connections between nutrient availability and enzyme activities [28, 29]. The results of our study also found that urease and phosphatase activities were significantly correlated with soil TC and TN (Tab. 3).

Finally, the *S. salsa* plant was successfully established in heavily degraded saline areas following restoration treatments. In 2009, plant density and yield in the RG treatment group was the highest of the treatment groups, as expected. However, in 2010, no significant differences in vegetative parameters were observed between the different restoration treatments. Similar results were also found for soil salt content, Na^+ content, and tested enzyme activities. It was supposed that in comparison to the PG treatment group, the nutrients added in early spring 2009 to the FG and RG treatment groups had no significant influence on plant growth and soil properties in the second year.

5 Concluding remarks

In the Yellow River Delta, the total land area of heavily degraded wetlands continues to increase in the face of seawater erosion and intense anthropogenic activity. It is urgent to establish useful methods to accelerate the restoration processes of these highly degraded wetlands. The restoration methods used in the present study had a rapid and positive remedial impact, as shown by measured soil properties and vegetation. The results of this study demonstrated that restoration treatments did significantly reduce soil salt content and available Na content over 2 years. Moreover, soil urease and phosphatase activities increased dramatically in the restoration plots, and enzyme activities were significantly correlated with soil TC and TN. The RG treatment is likely the most effective approach in the first year, as shown by the greatly reduced salt content, high enzyme activities, and plant yield. However, no significant differences were observed among the three restoration approaches in the second year. After restoration, the *S. salsa* plant was successfully established in the area and was expected to sustain long-term growth. Consequently, restoration approaches involving ploughing techniques seem to effectively remediate degraded saline wetlands in the Yellow River Delta.

However, as the study was taken from a small study area, further investigation using a pilot experiment is still needed. The restoration methods used here could have important implications for restoring highly degraded coastal saline wetlands from the perspective of the biogeochemical cycle.

Acknowledgments

We are grateful for support from the National Commonweal (Agricultural) research project (200903001); the CAS/SAFEA international partnership program for creation research team; the 100 Talents Program of the Chinese Academy of Sciences; Project of National Science and Technology Pillar Program in ''12th Five Year'' period (2011BAC02B01, 2012BAC19B08).

The authors have declared no conflict of interest.

References

[1] W. Mitsch, Wetland Creation, Restoration, and Conservation: A Wetland Invitational at the Olentangy River Wetland Research Park, *Ecol. Eng.* **2005**, *24*, 243–251.

[2] G. Bruland, C. Richardson, Hydrologic, Edaphic, and Vegetative Responses to Microtopographic Reestablishment in a Restored Wetland, *Restor. Ecol.* **2005**, *13 (3)*, 515–523.

[3] X. Zhang, P. Li, P. Li, X. Xu, Present Conditions and Prospects of Study on Coastal Wetlands in China, *Adv. Mar. Sci.* **2005**, *23 (1)*, 87–95.

[4] C. H. Chung, Thirty Years of Ecological Engineering with *Spartina* Plantations in China, *Ecol. Eng.* **1993**, *2*, 261–289.

[5] Y. Y. Hua, B. S. Cui, W. J. He, Changes in Water Birds Habitat Suitability Following Wetland Restoration in the Yellow River Delta, China, *Clean – Soil Air Water* **2012**, *40 (10)*, 1076–1084.

[6] T. Xie, X. H. Liu, T. Sun, The Effects of Groundwater Table and Flood Irrigation Strategies on Soil Water and Salt Dynamics and Reed Water Use in the Yellow River Delta, China, *Ecol. Model.* **2011**, *222*, 241–252.

[7] X. H. Wang, J. B. Yu, D. Zhou, H. F. Dong, Y. Z. Li, Q. X. Lin, B. Guan, Y. L. Wang, Vegetative Ecological Characteristics of Restored Reed (*Phragmites australis*) Wetlands in the Yellow River Delta, China, *Environ. Manage.* **2012**, *49*, 325–333.

[8] C. H. Chung, R. Z. Zhuo, G. W. Xu, Creation of *Spartina* Plantations for Reclaiming Dongtai, China, Tidal Flats and Offshore Sands, *Ecol. Eng.* **2004**, *23*, 135–150.

[9] C. Y. Xu, X. B. Liu, Z. G. Liu, J. Wang, Z. P. Jiang, J. L. Cao, Remedial Effect of *Suaeda salsa* (L.) Pall. Planting on the Oil-polluted Coastal Zones, *J. Safety Environ.* **2007**, *7 (1)*, 37–39.

[10] S. N. Li, G. X. Wang, W. Deng, Y. M. Hu, W. W. Hu, Influence of Hydrology Process on Wetland Landscape Pattern: A Case Study in the Yellow River Delta, *Ecol. Eng.* **2009**, *35*, 1719–1726.

[11] Z. F. Yang, C. H. Li, G. H. Huang, Y. P. Cai, Analysis of Relationships between NDVI and Climatic/hydrological Parameters in the Yellow River Basin, *Int. J. Environ. Pollut.* **2010**, *42 (1–3)*, 166–183.

[12] I. Zacharias, E. Dimitriou, T. Koussouris, Integrated Water Management Scenarios for Wetland Protection: Application in Trichonis Lake, *Environ. Model. Softw.* **2005**, *20*, 177–185.

[13] H. Wang, R. Q. Wang, Y. Yu, M. J. Mitchell, L. J. Zhang, Soil Organic Carbon of Degraded Wetlands Treated with Freshwater in the Yellow River Delta, China, *J. Environ. Manage.* **2011**, *92*, 2628–2633.

[14] P. P. Liu, J. H. Bai, Q. Y. Ding, H. B. Shao, H. F. Gao, R. Xiao, Effects of Water Level and Salinity on TN and TP Contents in Marsh Soils of the Yellow River Delta, China, *Clean – Soil Air Water* **2012**, *40 (10)*, 1118–1124.

[15] S. D. Bao, *Soil Agrochemical Analysis*, 3rd Ed., China Agriculture Press, Beijing **2005**.

[16] C. S. Xin, H. Z. Dong, Z. Luo, W. Tang, D. M. Zhang, W. J. Li, X. Q. Kong, Effects of N, P, and K Fertilizer Application on Cotton Growing in Saline Soil in Yellow River Delta, *Acta Agron. Sin.* **2010**, *36 (10)*, 1698–1706.

[17] D. W. Bergstrom, C. M. Monreal, D. J. King, Sensitivity of Soil Enzyme Activities to Conservation Practices, *Soil Sci. Soc. Am. J.* **1998**, *62*, 1286–1295.

[18] E. Kandeler, D. Tscherko, H. Spiegel, Long Term Monitoring of Microbial Biomass, N Mineralization and Enzyme Activities of a Chernozem under Different Tillage Management, *Biol. Fertil. Soils* **1999**, *28*, 343–351.

[19] A. M. Verónica, C. Leo, S. R. David, P. A. Luis, Enzyme Activities as Affected by Soil Properties and Land Use in a Tropical Watershed, *Appl. Soil Ecol.* **2007**, *35*, 35–45.

[20] W. Q. Niu, X. Zang, Z. X. Jia, H. B. Shao, Effects of Rhizosphere Ventilation on Soil Enzyme Activities of Potted Tomato under Different Soil Water Stress, *Clean – Soil Air Water* **2012**, *40 (3)*, 225–232.

[21] J. J. Sansom, M. A. Naeth, D. S. Chanasyk, J. C. Bateman, *In Situ* Amelioration of Sodic Minespoil with Chemical Amendments and Crop Management, I. Soil Chemical Properties, *Can. J. Soil Sci.* **1998**, *78*, 359–365.

[22] J. Akhter, R. Murray, K. Mahmood, K. A. Malik, S. Ahmed, Improvement of Degraded Physical Properties of a Saline-Sodic Soil by Reclamation with Kallar Grass (*Leptochloa fusca*), *Plant Soil* **2004**, *258 (1)*, 207–216.

[23] R. Mendoza, V. Escudero, I. Garcia, Plant Growth, Nutrient Acquisition and Mycorrhizal Symbioses of a Waterlogging Tolerant Legume (*Lotus glaber* Mill.) in a Saline-Sodic Soil, *Plant Soil* **2005**, *275 (1–2)*, 305–315.

[24] T. W. Walker, J. K. Syers, The Fate of Phosphorus during Pedogenesis, *Geoderma* **1976**, *15*, 1–19.

[25] T. E. Crews, K. Kitayama, J. H. Fownes, R. H. Riley, D. A. Herbert, D. Mueller-Dombois, P. M. Vitousek, Changes in Soil Phosphorus Fractions and Ecosystem Dynamics across a Long Chronosequence in Hawaii, *Ecology* **1995**, *76*, 1407–1424.

[26] F. S. Chapin, III, L. R. Walker, C. L. Fastie, L. C. Sharman, Mechanisms of Primary Succession Following Deglaciation at Glacier Bay, Alaska, *Ecol. Monogr.* **1994**, *64*, 149–175.

[27] S. Aikio, H. Väre, R. Strömmer, Soil Microbial Activity and Biomass in the Primary Succession of a Dry Heath Forest, *Soil Biol. Biochem.* **2000**, *32*, 1091–1100.

[28] R. L. Sinsabaugh, R. K. Antibus, A. E. Linkins, C. A. McClaugherty, L. Rayburn, D. Repert, T. Weiland, Wood Decomposition: Nitrogen and Phosphorus Dynamics in Relation to Extracellular Enzyme Activity, *Ecology* **1993**, *74*, 1586–1593.

[29] L. P. Olander, P. M. Vitousek, Short-Term Controls over Inorganic Phosphorus during Soil and Ecosystem Development, *Soil Biol. Biochem.* **2005**, *37*, 651–659.

