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Growth and sustainability of *Suaeda salsa* in the Lop Nur, China

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Abstract: Extremely saline soils are very harsh environments for the growth and survival of most plant species, however, halophytes can grow well. The underlying mechanism of halophyte to resist high saline is not well understood by us. This study was conducted at the potash mine near the Lop Nur, China, where the effects of the halophyte *Suaeda salsa* L. on the saline-alkaline soils and its growth and sustainability were investigated. Four plots (in which the salt encrustation layers were removed), with different soil treatments were evaluated: (1) undisturbed soil, with no additional treatment (T1); (2) the slag soil zone, in which a 40-cm layer of slag was placed on the undisturbed soil surface (T2); (3) slag+sandy soil, in which a 20-cm layer of slag was placed in the lower layer and 20 cm of sandy soil, taken from an area about 70 km away from Lop Nur potash mine, where *Tamarix* species were growing, was placed in the upper layer (T3); and (4) a 40-cm sandy soil layer taken from the area where *Tamarix* species were growing was placed on undisturbed soil (T4). Soil nutrient contents increased in the four treatments, but salt content only decreased in the T1 treatment. Salt content in the T4 treatment increased over the two-year period, which may be partly attributed to salt deposition from wind-blown dust within the mine and salt accumulation within the surface soil (0–20 cm) in response to high evaporative demands. The *S. salsa* plants exhibited greater improvements in growth under the T4 treatment than under the T1, T2, and T3 treatments, which demonstrated that low levels of salinity are beneficial for the growth of this species. The T1 treatment was sustainable because of its low cost and superior soil improvement characteristics. Therefore, *S. salsa* plants not only reduced soil salinity and increased soil nutrient levels, but also ameliorated the plant growth environment, which would be beneficial for both the ecological restoration of the Lop Nur area and similar areas throughout the world.

Keywords: *Suaeda salsa*; saline-alkaline soil; plant-soil interaction; sustainability; Lop Nur

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1 Introduction

Soil salinization is a worldwide problem that reduces the area suitable for cultivation and degrades ecosystems (Mondal, 2001; Miyamoto et al., 2005; Yavitt et al., 2009). Consequently,

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there is much interest in finding low-input and sustainable methods of reducing soil salinity and alkalinity; thus, improving soil quality (Metternicht and Zinck, 2003). Halophytes are effective for improving saline soils (Tian et al., 2004), occur naturally in high salinity areas, and can survive well in strongly saline-alkaline soils (Darwish et al., 2005; Liang et al., 2005; Tejada et al., 2006; Zhu et al., 2012). They are abundant in nature, and can tolerate higher levels of salt stress than glycophytes (Tejada and Gonzalez, 2005). The planting of halophytes has recently received much attention because of increasing soil salinization and the global shortage of freshwater (Khan and Weber, 2006; Duan et al., 2007).

Lop Nur, the central catchment area of the Tarim Basin, China, is in the eastern part of the basin at an elevation of 780 m a.s.l. The climate is extremely dry, annual precipitation is 20 mm, and the annual evaporation is 2901 mm (Xia et al., 2007). The soil is generally covered by a hard salt crust, and there are no surface water resources except for a few salty springs and some temporary seepage areas following rainstorms in the piedmont zone. Some areas within the basin contain large quantities of potash that were found at the end of the 1990s. A large potash mine (Singapore Deposit Insurance Corporation (SDIC) Xinjiang Luobupo Potash Co. Ltd.) began operating within the basin in 2002, in an area characterized by extreme drought, which has about 80 cm of salt encrustation at the soil surface and >30% salt content in the under layer. The area experiences large quantities of saline dust and large seasonal temperature variations. The soils generally have low nutrient levels, and together with the other previously mentioned factors, this results in a harsh environment for plant growth and survival (Zhao et al., 2006). Therefore, the salt encrustation layer must be eradicated, and it is hypothesized that planting halophytic plants in such an extreme high-salinity area would not only play an important role in improving the ecological environment but also significantly improve the soil.

Growing plants in saline and sodic soils is an emerging, low-cost method of remediation. Halophytic plants grow naturally in salinized areas, and can survive in salt concentrations equal to or greater than those found in seawater. The re-vegetation of salinized areas with halophytic plants is an example of proactive phytoremediation (Song and Wang, 2015). The use of the halophytic succulent annual herb *Suaeda salsa* L. in the recovery of saline soils has previously been demonstrated (Zhao et al., 2002; Cheng et al., 2014; Song and Wang, 2015). *S. salsa* is an annual euhalophytic herb, with a high salt tolerance during seed germination and the seedling stages (Song et al. 2011; Wang et al., 2015; Xu et al., 2016; Zhou et al., 2016; Song et al., 2017). *S. salsa* is the most effective plant species for facilitating the leaching of salts from the rhizosphere in arid and semi-arid regions, where the rainfall is low (Zhao et al., 2003; Song and Wang, 2015). The shoots and seeds of this species contain relatively high levels of protein and unsaturated fatty acids, which may be beneficial for the restoration of soil health (Zhao, 1991; Wang et al., 2015). Planting *S. salsa* on saline-alkaline soils has not only been shown to help reduce soil salt content but also increases soil organic matter and nutrient levels (Zhang et al., 1998).

Several previous studies have addressed the problem of salt toxicity and the need for saline soil improvement (Liang et al., 2005; Tejada and Gonzalez, 2005; Ashraf et al., 2008; Uddin et al., 2009; Song and Wang, 2015), but they have generally focused on coastal saline soils, with few studies conducted on the soils of the Lop Nur hinterland. The purpose of this study was to address this knowledge gap. The study objectives were to: (1) evaluate the growth and survival of *S. salsa* in the harsh soil and climatic conditions of the Lop Nur hinterland; (2) determine the effects of growing *S. salsa* on the saline-alkaline soils that are typical of the Lop Nur potash mine area; and (3) evaluate the effects of different soil saline conditions on plant growth and the sustainability of the different treatments.

2 Materials and methods

2.1 Study area

The study was conducted in the hinterland of Lop Nur (40°22′N, 90°52′E; 1152 m a.s.l.; Fig. 1), which is an extremely arid area. According to meteorological records taken at the weather station in Ruoqiang County from the last 15 years, the climate in the lake area of Lop Nur is very severe, with annual precipitation averaging less than 20 mm and annual evaporation averaging more than 3000 mm. Within a year, there are 102.5 days on average that have winds sufficiently strong to cause dust storms, and there are 18.6 days on average that have winds exceeding Beaufort force 8. The area was once described as the world's most desolate area, with the exception of the two polar regions (Chen, 1936; Fig. 2). No living organisms were found in this area before the construction of the potash mine in 2002 due to the extreme environment of the deep salt encrustation layer, while more than 3000 workers have worked there since the SDIC Xinjiang Luobupo Hoevellite Co., Ltd., mining facility was completed. Because it is a working mine, full restoration of the environment is impossible, thus, planting halophytes becomes the only possible soil improvement procedure.

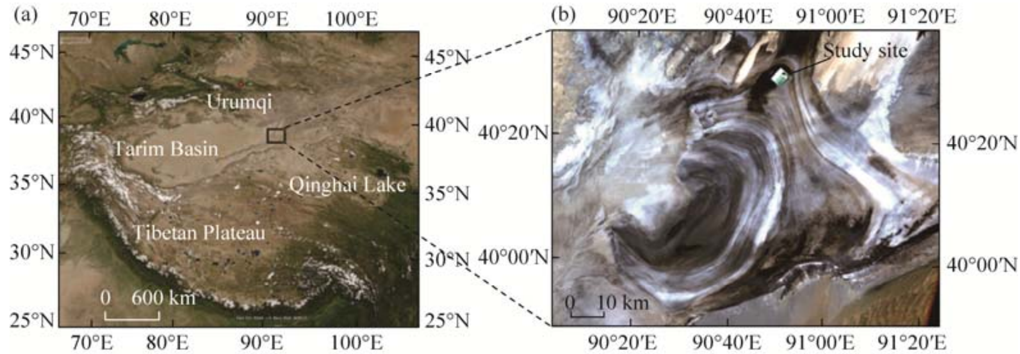

Fig. 1 Locations of the Lop Nur and the study site

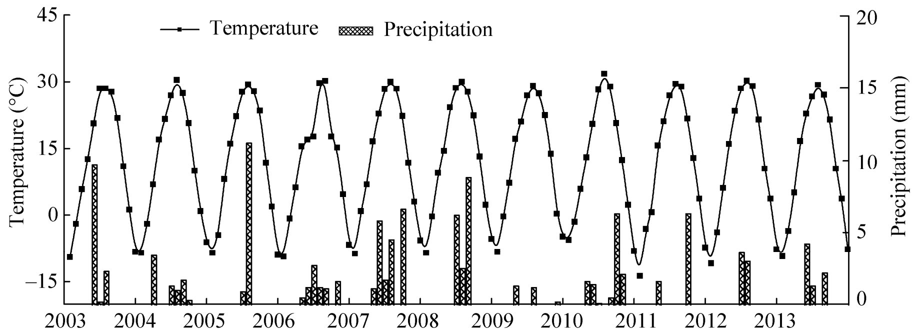

Fig. 2 Monthly average temperature and monthly precipitation at the study site

2.2 Experimental design

The experiment was conducted at an artificial ecological vegetation demonstration area near the mine. An experimental area (60 m×5 m) was divided into four plots of 15 m×5 m. To ensure the survival of artificial plants and to reduce investment, we covered the soil surface with 80 cm of a salt encrustation layer. The materials used were sourced from close to the potash mine, with slag collected from the power station operated by the mine and the sandy soil collected from the nearest area where plants (*Tamarix* species) could survive, which was about 70 km away from the potash mine. Prior to the initiation of the experiment, we removed the salt crust and randomly applied four experimental treatments to each of the four plots. The treatments were as follows: (1) undisturbed soil, with no additional treatment (T1); (2) the slag-soil zone, in which a 40-cm layer of slag was placed on the undisturbed soil surface (T2); (3) slag+sandy soil, in which a 20-cm layer of slag was placed in the lower layer and 20 cm of sandy soil taken from the area where *Tamarix* species were growing was placed in the upper layer (T3); and (4) a 40-cm sandy soil layer taken from the area where *Tamarix* species were growing was placed on undisturbed soil (T4). The chemical properties of the different soil types are presented in Table 1. The undisturbed soil had high salt and low nutrient levels, while the slag and soil taken from the *Tamarix* growing area had low salinity.

In early May 2013 and 2014, *S. salsa* seeds were sown at a density of 15 kg/hm^2 in the four plots. The same irrigation and management models were applied in the four plots. Drip irrigation with freshwater was applied for 2 h every five days from May to June, and every three days from July to September, respectively. The amount of irrigation was equivalent to about 7 mm precipitation.

Table 1 Chemical properties of the different soil types

Soil type	pH	EC (mS/cm)	Total salt (mg/g)	SOC (g/kg)	TN (g/kg)	TP (g/kg)	TK (g/kg)
Undisturbed soil	8.93	61.30	295.16	1.45	0.074	0.18	8.72
Slag	8.38	5.43	49.25	7.22	0.110	0.23	20.58
Sandy soil	7.86	2.07	14.89	1.59	0.080	0.19	7.98

Note: EC, electrical conductivity; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; TK, total potassium.

2.3 Soil and plant sampling

Soil samples from 0 to 20 cm layer were collected from each plot at the beginning of 2013 prior to planting *S. salsa*, and later in 2013 and 2014 after *S. salsa* had been harvested. Soil samples were taken from areas, 10–20-cm away from the plants rather than from the rhizosphere, because a salt island may exist, which could result in ion exclusion by roots. There were five replications of each soil sample. Fifteen plants in each plot were randomly selected for measurements of plant height, crown length, and crown width on 8 July, 28 July, and 14 August, 2014. The plants were harvested on 25 and 26 August, and above- and below-ground biomass measurements were taken. The biomass (fresh weight) in a 1-m^2 representative area of each of the five replicates was measured in every treatment plot, and the plant samples were then dried in a drying oven at 60°C for 24 h to estimate the yield per hectare, and then stored for later chemical analysis of their salt and salt ion contents.

2.4 Sample analysis

The soil chemical properties and plant salts were analyzed after the soil was air-dried and hand-sieved using a 0.25-mm mesh to remove roots and other debris. Soil electrical conductivity (EC) and pH were determined using a conductivity bridge (dS/m) and a glass electrode pH meter (Fresenius et al., 1988), respectively. Soil and plant chloride (Cl^-), sulfate (SO_4^{2-}), and bicarbonate radical (HCO_3^-) contents were determined using ion chromatography (Hucoa-Erloss, 2000I/SP, Dionex, Sunnyvale, California). Calcium (Ca^{2+}) and magnesium (Mg^{2+}) contents were measured using a disodium dihydrogen ethylenediaminetetraacetate (EDTA) extraction followed by a murexide indicator for calcium and an eriochrome black T indicator for the combined calcium and magnesium contents. Sodium (Na^+) and potassium (K^+) contents were determined by atomic absorption spectrometry (1100B, PerkinElmer, Waltham, MA, USA). All the quantitative procedures were adapted from Patnaik (1997). Total dissolved salt contents were calculated by summing the number of anions and cations, and soil organic carbon (SOC) content was determined using the Walkley-Black $K_2Cr_2O_7$-H_2SO_4 oxidation method (Nelson and Sommers, 1982). Total nitrogen (TN) was determined using the Kjeldahl procedure, with a UDK140 automatic steam distillation unit and a TitroLine 96 titration unit. Total phosphorus (TP) was determined by flow injection analysis (Nelson and Sommers, 1982) and total potassium (TK) was determined by the method of Nelson and Sommers (1982).

2.5 Data analysis

All the data analyses were performed using SPSS 17.0 software. An analysis of variance was conducted to determine the significance (P<0.05) of differences in the mean values of soil properties between before and after planting in the different years within treatments, and biomass production and salt accumulation between treatments. Tukey's HSD (honest significant difference) was used for a comparison of means (P<0.05). All results are presented as means plus or minus the standard error (SE). Origin 8.0 software was used to produce the figures.

3 Results

3.1 Effects of plant treatments on soil chemical properties

Soil pH, EC, K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and total salt contents decreased over the two planting years in the T1 treatment (Figs. 3 and 4), indicating that *S. salsa* plays an important role in reducing soil salinity and alkalinity. All the chemical properties of the undisturbed soil were significantly different from those of the other soil treatments. In the T4 treatment, soil pH, EC, K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and total salt contents increased over the two-year period, and were significantly different to those in the other treatments. It is possible that wind-blown dust from the mine area, which is characteristically high in mineral salts, and the high evaporation level, which is also a characteristic of this area, caused salt accumulation in the surface soil in quantities larger than the plants could absorb.

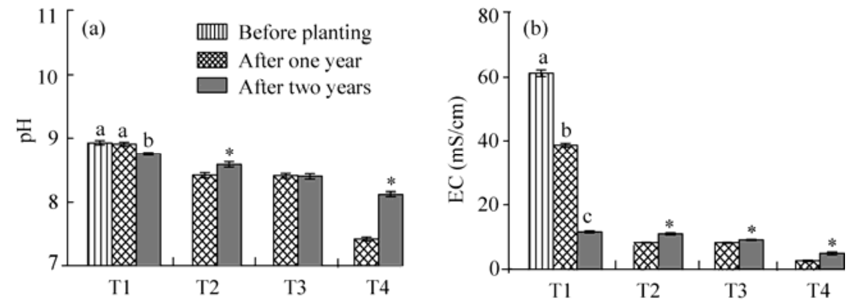

Fig. 3 Soil pH (a) and soil electrical conductivity (EC) (b) over a two-year period in an undisturbed soil with the salt crust layer removed and the following treatments applied to the soil surface: T1 (the salt layer removed and the soil left undisturbed), T2 (a 40-cm surface slag layer), T3 (a 20-cm slag layer placed below a 20-cm sandy soil layer), and T4 (a 40-cm surface sandy soil layer). Treatments of T1, T2, T3, and T4 are the same as in Figures 4–9. * indicates significant difference between years at P<0.05 level. Different lowercase letters indicate significant differences between years at P<0.05 level in the T1 treatment. Bars mean standard errors.

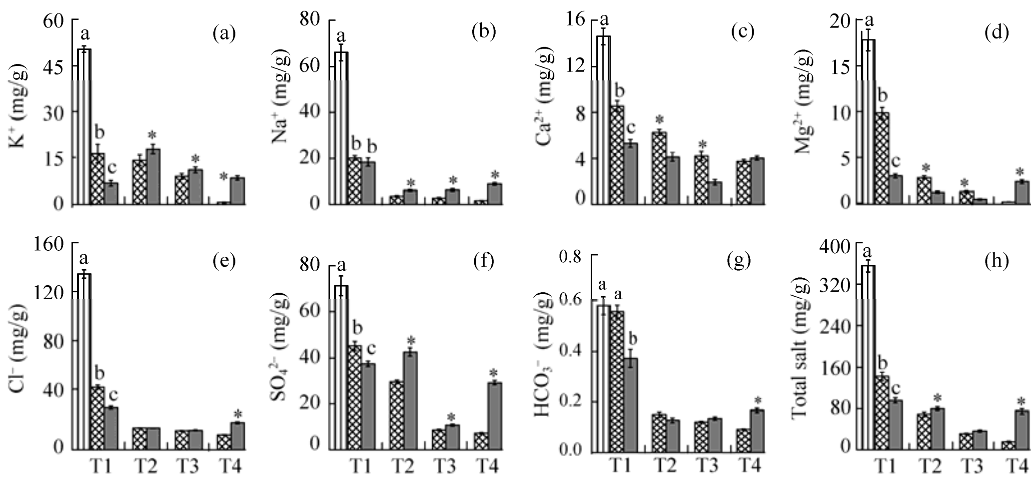

Fig. 4 Contents of K^+ (a), Na^+ (b), Ca^{2+} (c), Mg^{2+} (d), Cl^- (e), SO_4^{2-} (f), HCO_3^- (g), and total salt (h) over a two-year period within the upper 20-cm surface layer of four treatments. * indicates significant difference between years at P<0.05 level. Different lowercase letters indicate significant differences between years at P<0.05 level in the T1 treatment. Bars mean standard errors.

There were no statistically significant changes in soil Cl^- and HCO_3^- contents over the two-year period in the T2 and T3 treatments, or in the pH and total salt content in the T3 treatment (Fig. 4). The contents of K^+, Na^+, and SO_4^{2-} significantly increased over the two-year period in the T2 and T3 treatments, while Ca^{2+} and Mg^{2+} contents significantly decreased in the T2 and T3 treatments. These results suggest that *S. salsa* absorbed Ca^{2+} and Mg^{2+}, but not K^+, Na^+, or SO_4^{2-}, which is not entirely surprising because large quantities of K^+, Na^+, and SO_4^{2-} are present in salt dust. The contents of K^+, Na^+, Cl^-, and SO_4^{2-} were higher than those of Ca^{2+}, Mg^{2+}, and HCO_3^- in the T1 treatment, indicating that the saline-alkaline soil accumulated large quantities of K^+, Na^+, Cl^-, and SO_4^{2-} due to the reasons previously stated.

The contents of TN and TP significantly increased in most treatments except TP in T1 plots ($P<0.05$) (Fig. 5). In the T2 and T3 treatments, TN and TP contents significantly increased over the two-year period ($P<0.05$), while the SOC and TK contents had little or no changes (Fig. 4). The contents of SOC, TN, and TP significantly increased in the T4 treatment. Overall, the contents of SOC, TN, and TP exhibited large increases because of the growth of the *S. salsa* plants.

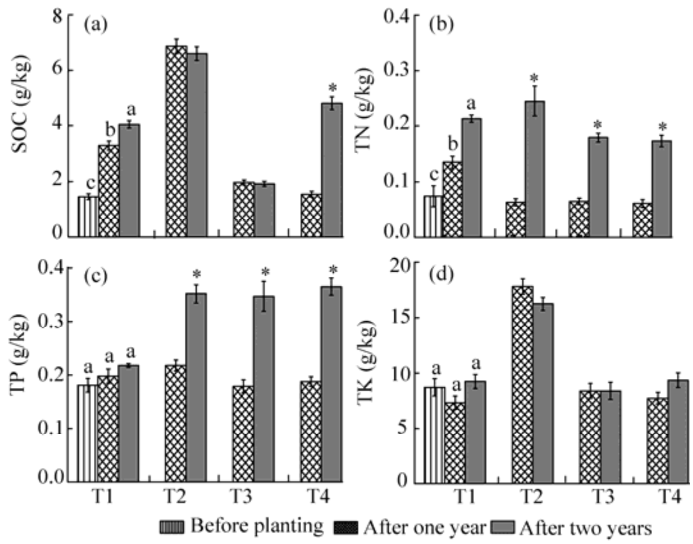

Fig. 5 Contents of soil organic carbon (SOC, a), total nitrogen (TN, b), total phosphorus (TP, c), and total potassium (TK, d) over a two-year period within the upper 20-cm surface layer of four treatments. * indicates significant difference between years at $P<0.05$ level. Different lowercase letters indicate significant differences between years at $P<0.05$ level in the T1 treatment. Bars mean standard errors.

3.2 Plant growth under different soil treatments

Before August, the *S. salsa* plants grew well in response to the T4 treatment, with plant height, crown length, and width values that were significantly higher than those observed in the T1, T2, or T3 treatments (Table 2), which was confirmed by a visual evaluation at the end of the growing season (Fig. 6). This result indicates that the removal of the salt crust reduced salinity and improved the soil texture, being beneficial for plant growth. Since *S. salsa* is a halophyte that is tolerant to soil high salinity, it grew well in saline environment under the T1 treatment following an initial period of establishment.

The biomasses of individual plants grown under the T1 treatment were higher than those of plants grown under the T2 and T3 treatments (Fig. 7). Although the high salt content that was characteristic of the T1 treatment, limited germination and the survival of *S. salsa* seedlings was less competitive for water and nutrients, which resulted in a significant increase in the above-ground biomass. However, there were no significant differences in the root/shoot ratios among T1, T2, T3, and T4 plants.

Table 2 Growth parameters of *S. salsa* at the second year of a two-year growth period in an undisturbed soil

Soil type	8 July			28 July			14 August		
	Height (mm)	Crown length (mm)	Crown width (mm)	Height (mm)	Crown length (mm)	Crown width (mm)	Height (mm)	Crown length (mm)	Crown width (mm)
T1	12.7^{c}	20.1^{b}	20.4^{b}	23.2^{b}	38.4^{a}	26.2^{b}	36.7^{b}	50.9^{a}	48.3^{a}
T2	21.1^{b}	19.1^{b}	20.5^{b}	26.1^{b}	25.8^{b}	26.2^{b}	37.4^{b}	31.7^{b}	30.8^{b}
T3	22.7^{b}	19.8^{b}	20.3^{b}	29.8^{b}	25.6^{b}	26.3^{b}	39.9^{b}	31.6^{b}	33.9^{b}
T4	25.7^{a}	25.8^{a}	24.3^{a}	37.3^{a}	27.1^{b}	28.1^{a}	56.3^{a}	32.1^{b}	36.2^{b}

Note: T1, the crust layer removed and the soil surface left undisturbed; T2, a 40-cm surface slag layer; T3, a 20-cm slag layer placed below a 20-cm sandy soil layer; T4a 40-cm surface sandy soil layer. Different lowercase letters in the same column indicate significant differences among four treatments at P<0.05 level.

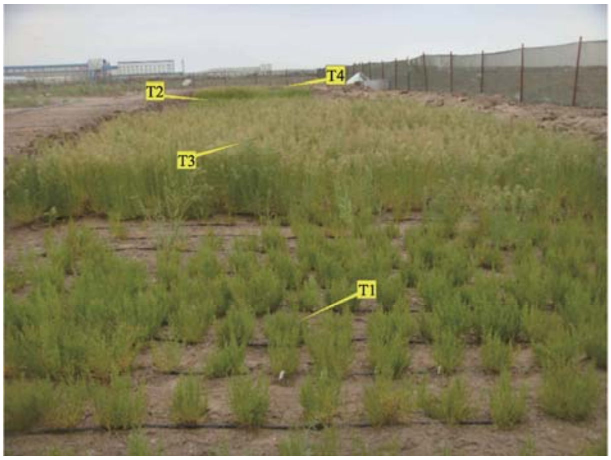

Fig. 6 Growth of *Suaeda salsa* under four treatments

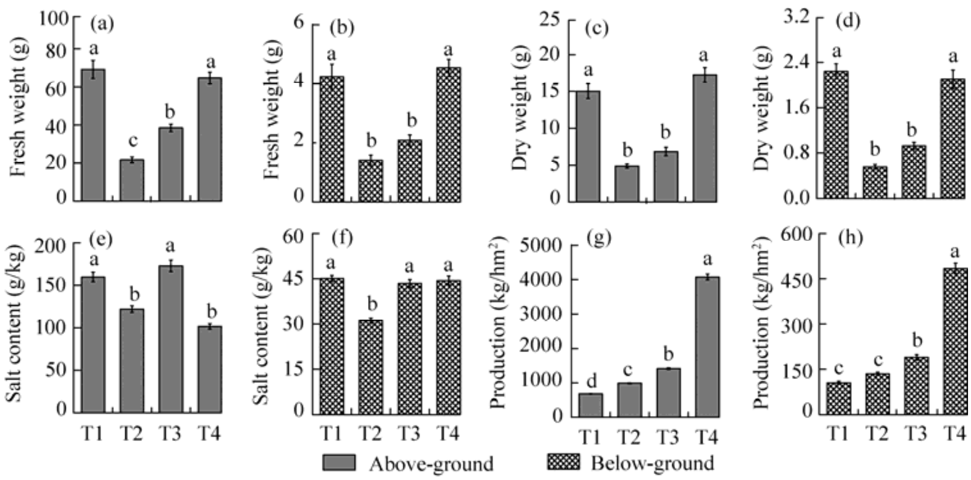

Fig. 7 Comparison of *Suaeda salsa* biomass and salt contents under four treatments. Different lowercase letters indicate significant differences among four treatments at P<0.05 level. Bars mean standard errors.

3.3 Salt absorption capacity and salt absorption percentage observed for *S. salsa*

The salt absorption capacity and salt absorption percentage of *S. salsa* measured in the four treatments ranged from 120–460 kg/hm^2 and 9%–15%, respectively (Fig. 8). The salt absorption capacity was greater for plants grown under the T4 treatment than under the other three treatments. Plants grown under the T1 and T2 treatments contained the smallest quantities of salts absorbed by the plant (Fig. 8c). The salt contents of different ions that were taken up by *S. salsa* are presented in Figure 9. It was found that K^+, Na^+, Cl^-, and SO_4^{2-} readily accumulated in both the above- and below-ground components of *S. salsa*, with the above-ground plant components accumulating larger salt quantities than the below-ground components. The larger quantities of these ions particularly in the above-ground components mimicked the relatively large quantities of K^+, Na^+, Cl^-, and SO_4^{2-} salts that were characteristic of the soil at this location and were represented in the T1 treatment. The Ca^{2+} content within the above-ground components of *S. salsa* was representative of the surface salt content within the upper 20-cm surface layer of the four treatments. The Mg^{2+} content was generally larger than the soil Mg^{2+} content in the upper 20-cm surface layers of the four treatments, except for the soil Mg^{2+} content in the T1 treatment before planting.

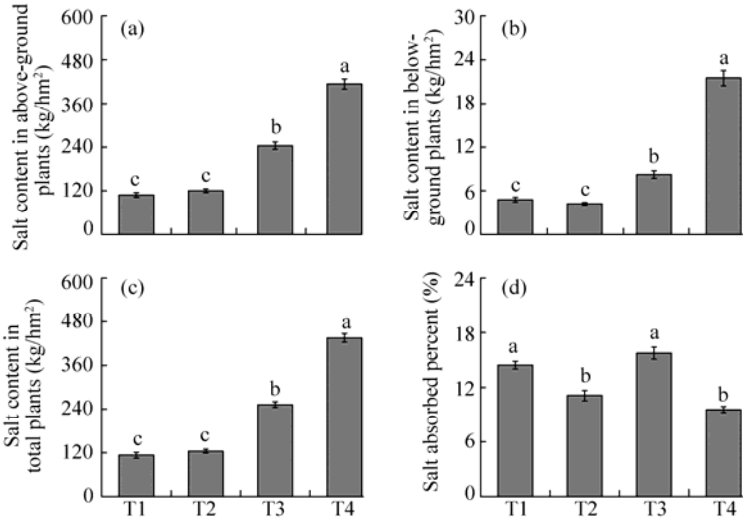

Fig. 8 Salt contents in s (a), below-ground plants (b), and total plants (c), and the salt absorption percent (d) of dry weight of *Suaeda salsa* at the second year of a two-year growth period under four treatments. Different lowercase letters indicate significant differences among four treatments at $P<0.05$ level. Bars mean standard errors.

4 Discussion and conclusions

4.1 Effect of *S. salsa* growth on saline soil

Many halophytic plant species grow naturally in high-salinity areas, and can absorb salt from the rhizosphere (Song and Wang, 2015; Song et al., 2017). Ravindran et al. (2007) reported that the halophytes *Suaeda maritima* and *Sesuvium portulacastrum* (Aizoaceae) had greater accumulations of salt within their tissues, and caused greater salt reductions within the soil, than four other vegetative species. Rabhi et al. (2009) compared *S. portulacastrum* with two other halophytes, *Abutilon indicum* and *Suaeda fruticosa*, with respect to their ability to desalinate saline soils, and they found that of the three species studied, *S. portulacastrum* was the most effective species to grow when leaching salts from the rhizosphere in arid and semi-arid regions. The results of our study indicate that *S. salsa* exhibits similar soil salinity and alkalinity reduction characteristics. The salt absorption percentage for *S. salsa* ranged from 9% to 15%, and total salt contents decreased from 355.27 to 95.73 mg/g. There were also an increasing trend in SOC, TN, and TP contents in the T1 treatment. Several factors may be responsible for the above results, including changes in soil microbe populations (Marschner and Römheld, 1996), increases in root activity in the rhizosphere (Ma and Palada, 2006; Li et al., 2011), increases in litterfall deposition and the uptake of soil nutrients by plant roots (Bochet et al., 1999; Zaady et al., 2001; Li et al., 2015), and changes in the biogeochemical cycle (Schlesinger et al., 1996; Li et al., 2014).

The SOC and TK contents did not increase in response to the T2 and T3 treatments, although there were significant changes in the TN and TP contents that may be partly attributed to the high SOC and TK contents that resulted from the addition of slag in the T2 treatment (Table 1). Total soil salt content increased with planting year in the T4 treatment, possibly because of the

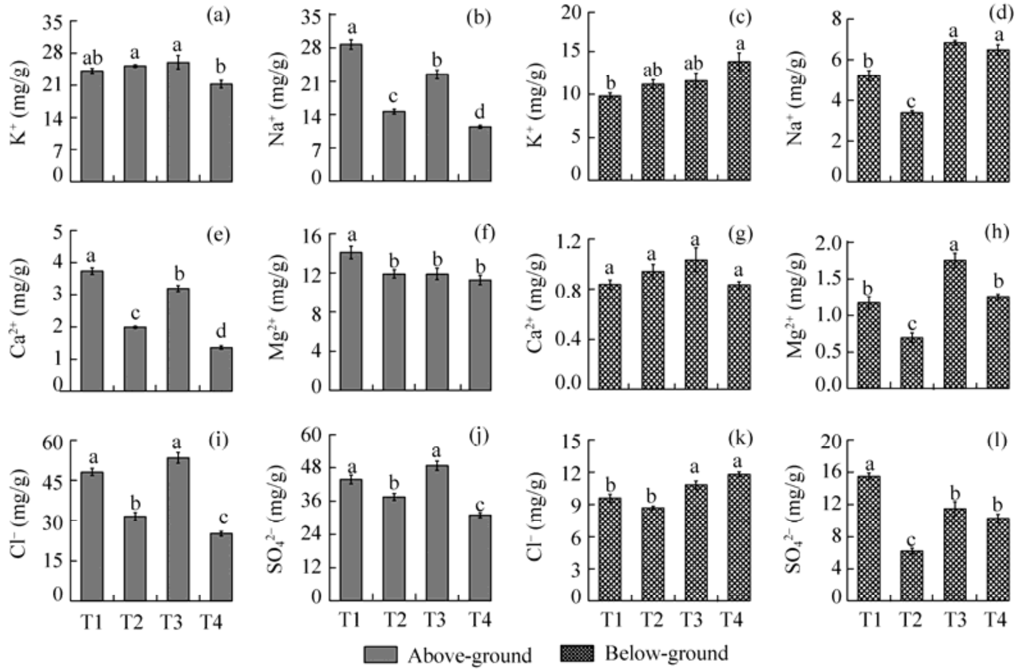

Fig. 9 Contents of K^+ (a), Na^+ (b), Ca^{2+} (e), Mg^{2+} (f), Cl^- (i), and SO_4^{2-} (j) within the above-ground components and contents of K^+ (c), Na^+ (d), Ca^{2+} (g), Mg^{2+} (h), Cl^- (k), and SO_4^{2-} (l) within the below-ground components of *Suaeda salsa* at the second year of a two-year growth period under four treatments. Different lowercase letters indicate significant differences among four treatments at $P<0.05$ level. Bars mean standard errors.

deposition of salt dust and the accumulation of salt at the soil surface derived from the high evaporative demand that is characteristic of the area. In support of this explanation, the quantities of salt that had accumulated in the surface soil layer (0–20 cm) were larger than that of salt absorbed by the plants, moreover, it has been found that *S. salsa* not only absorbs salt from the rhizosphere, but also from atmospheric dust. Therefore, we speculated that planting and harvesting of *S. salsa* in the Lop Nur area might decrease the salt contents and would beneficial for plant reconstruction and ecological restoration in the highly saline soil of the area.

4.2 Effect of saline soil on plant growth

High soil salinity is characterized by large amounts of Na^+, Mg^{2+}, Ga^{2+}, Cl^-, HCO_3^-, and SO_4^{2-} ions within the soil. These ions are major abiotic stressors that reduce plant productivity, affect crop germination and density, inhibit vegetative development, and in the most serious cases, lead to generalized plant death (Xu et al., 2016; Zhou et al., 2016; Song et al., 2017). *Suaeda salsa* plants grew well under the T4 treatment, with better growth than those grown under the T1, T2, and T3 treatments. This result indicates that growth improvements result from an improved plant environment, where there is less stress placed on the plants because salinity has been reduced. Meanwhile, large pores, which were characteristic of the slag in the T2 and T3 treatments, resulted in a reduced capability of the plants to retain water.

4.3 Plant-soil interactions

The soil provides a reserve of water and nutrients necessary for plant growth. At the same time, plants exert a significant impact on the physical and chemical properties in soil (Dagar et al., 2001). In a saline soil environment, halophytes can absorb and accumulate salts, and over time may gradually reduce soil salinity. Planting halophytes can increase soil nutrient and fertility levels over time, because root exudates, rhizosphere microorganisms, and litter decomposition have a gradual impact on the soil environment.

It was found that the salt absorption capacity of *S. salsa* ranged from 120 to 460 kg/hm^2 in this area. This absorption capacity was much smaller than that reported in a study performed in Karamay, China, where S. salsa plants absorbed up to approximately 5000 kg/hm^2 of salt from the soil (Zhao et al., 2013). The salt absorption capacity was greatest under the T4 treatment (Fig. 7), which was largely due to the large amount of biomass produced under the T4 treatment. Significant quantities of K^+, Na^+, Cl^-, and SO_4^{2-} accumulated within both the above- and below-ground parts of the *S. salsa* plants, and were the predominant ions absorbed by *S. salsa*, while Ca^{2+} ions were absorbed in much lower quantities (Fig. 8).

Meanwhile, planting *S. salsa* plays an important role in the improvement of saline-alkaline soil. Although high salinity and alkalinity present within the soil of the T1 treatment strongly affected plant germination and survival of *S. salsa*, the remaining plants that survived developed a large above-ground part. This may be partly attributed to *S. salsa* being a euhalophyte, with a strong salt tolerance capability (Song et al., 2011; Zhao et al., 2013; Song and Wang, 2015).

4.4 Sustainability of planting *S. salsa* in the Lop Nur

Comparing the four treatments by plant growth, soil improvement, and the costs required (Table 3), we found that the T1 treatment was sustainable because it was the cheapest and the best soil improvement, although the germination rate was low. With the decreases in soil salinity, germination and growth of halophytes should be improved. Therefore, planting *S. salsa* in the highly saline soils of Lop Nur after removing the salt layer may gradually reduce soil salinity and increase the soil nutrient content. Growing plants of this species may also result in subsequent improvements within the soil environment, and would therefore be beneficial for plant reconstruction and ecological restoration in the Lop Nur area as well as similar areas throughout the world.

Table 3 Plant growth, soil improvement, and the costs required for the four treatments

Treatment	Plant growth	Soil improvement	Cost (Chinese Yuan/km^2)	Sustainability
T1	The germination rate was the lowest, although surviving plants grew well	Soil nutrients accumulated significantly and salinity was meliorated	No cost other than the cost of seeds, water, and labor	Sustainable
T2	The germination rate was higher in T2 treatment than in T1 treatment, but surviving plants grew poorly	Soil nutrients and salinity accumulated	Fewer costs, except for the cost of seeds, water, labor, and the cost of transporting the slag (about 8×10^6)	Unsustainable
T3	The germination rate was higher in T3 treatment than in T2 treatment, and the surviving plants grew well	Soil nutrients and salinity accumulated	Higher costs, including the cost of seeds, water, and labor, in addition to the cost of transporting the slag and soil, which was substantial (about 24×10^6)	Unsustainable
T4	The germination rate was the highest, and all the surviving plants grew well. Thus, the production was the highest	Soil nutrients and salinity accumulated	The highest cost, which included the cost of seeds, water, and labor, in addition to the cost of transporting the slag and soil (about 40×10^6)	Unsustainable

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