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Effects of drought and salt stresses on growth characteristics of euhalophyte *Suaeda salsa* in coastal wetlands

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A B S T R A C T

The pot experiment was carried out in the Yellow River Delta to investigate the effects of drought and salt stresses on growth characteristics of *Suaeda salsa*, and to reveal the role of nitrogen (N) application in alleviation effects of drought and salt stresses on *Suaeda salsa* in coastal wetlands. In this study, plants were exposed to two water contents treatments (i.e., 14% and 26% water content), four salinity treatments (i.e., 2 g/kg, 4 g/kg, 6 g/kg, and 8 g/kg NaCl) and two N application treatments (i.e., 0 and 200 N mg/kg) in field conditions. Growth characteristics of *Suaeda salsa* were assessed as fresh weight, dry weight, height, total nitrogen (TN) and total carbon (TC). Our results showed that fresh weight, dry weight and height of *Suaeda salsa* promoted at lower salinity treatments but reduced at higher salinity treatments, while TN and TC contents kept stable with increasing salinity levels. Drought stress diminished the fresh weight, dry weight and height of *Suaeda salsa*, whereas enhanced TN contents. Under the interactive stresses of drought and salt, fresh weight and dry weight showed slight increases at lower salinity treatments, whereas decreases at higher salinity treatments. N application promoted the fresh weight, dry weight and TN contents other than the height and TC contents of *Suaeda salsa*. The interaction between N application and salt stress exhibited a significant influence on the fresh weight and dry weight of *Suaeda salsa*, whereas no significant interaction between N application and drought stress was observed. These findings of this study suggested that higher salinity, drought and the interaction of drought and higher salinity would retard the growth of *Suaeda salsa*, whereas N application could only mitigate the deleterious effects of salt stress on *Suaeda salsa*.

1. Introduction

Drought and salinity are considered as two most sever environmental hazards for plant growth and productivity, particularly in the arid and semi-arid regions (Hamed et al., 2013). However, in coastal wetlands, the increasing drought frequency and accelerating sea-level rise (Ardón et al., 2013) are threatening the ecosystem with growing serious drought and salt stresses, which could result in water deficit in soil, physiological drought and ionic injury in plants (Baruch, 1994). Therefore, a better understanding of the effects of salinity and drought on plants growth is critical for the restoration and health of coastal wetlands.

Salt stress is a considerable environmental factor that impacts plant growth through both osmotic stress and ionic toxicity, and subsequently through nutritional stress (Song et al., 2009). Drought in soil influences plant growth through nutrient uptake via restricted transpiration rates and injured active transport and membrane permeability (Hu and Schmidhalter, 2005). It has been reported that salinity and drought restricted plant growth and development, and significantly reduced plant height and leaf area (Rizwan et al., 2015; Hutsch et al., 2015). Pérez-Pérez et al. (2007) found that the combination of salt and drought stresses reduced the ability of *Carrizo citrange* seedlings growth as compared with plants subjected to single stress individually. Liu et al. (2014) presented that the combination of salt and drought stresses can enhance the salt resistance of *Tamarix chinensis* under appropriate drought stress. Most researches have focused on the effect of single drought stress or salt stress on plant growth or the interactive effects on non-halophytes, however the integrated effect on

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euhalophyte *Suaeda salsa* (one of the dominant species) in coastal wetlands is little known.

Nitrogen (N) is one of the most limiting nutrients in coastal salt marshes and could influence the plant growth and development (Mitsch and Gosselink, 2015). N has been reported to significantly mitigate the deleterious effects of salt stress on several crops (Irshad et al., 2009). Saneoka et al. (2004) demonstrated that higher levels of N nutrition may have a contribution to drought tolerance in creeping bent grass. However, little information is available on N mediated alleviation of drought and salt stresses for *Suaeda salsa* in coastal wetlands. Therefore, the objectives of this study were: (1) to analyze the ecological effects of drought and salt stresses and their interaction on the euhalophyte *Suaeda salsa* growth in coastal wetlands; (2) to investigate the alleviation effect of N application on *Suaeda salsa* under drought and salt stresses.

2. Materials and methods

2.1. Site description

The study was conducted during the period from April to November in 2012 in the Yellow River Delta (118° 33′–119° 20′ E, 37° 35′–38° 12′ N), located in Dongying City, Shandong Province of China. It faces the Bohai Sea on the north and borders Laizhou Bay on the east, with a typical continental monsoon climate and distinctive seasons. The annual average temperature and effective accumulative temperature are 12.1 °C and 4300 °C, respectively. The frost-free period is 196 days. The annual average evaporation is 1962 mm and the annual average precipitation is 551.6 mm, with about 70% of precipitation occurring from June to August. The main soil types are intrazonal tidal soil and salt soil (Tian et al., 2005). And the dominate vegetation is *Suaeda salsa*, *Tamarix chinensis* and *Phragmites australi*, of which *Suaeda salsa* is a typcial succulent halophytic herb (Wang et al., 2004).

2.2. Experimental design and sample collection

The experiment site, a 2 m height and 12 m^2 area outdoor shed covered with plastic film on the top, is located in the Yellow River Delta Management Station. Soils for experiment were collected at the depth of 15 cm nearby the Yellow River Delta Management Station in April 2012. The *Suaeda salsa* seedlings with similar leaf number and height for experiment were collected around the soil sampling site. Soil samples were brought to the laboratory and air-dried at room temperature, and grounded through a 2-mm sieve to remove the coarse debris and stones. The salinity, TN, and water content of initial experimental soils were 1.87 g/kg, 209 mg/kg and 26%, respectively. Plants were divided into 16 groups and transplanted into plastic pots filled with 2 kg air-dried experimental soil. After 14 days when plant growth conditions tended to be health and stable, the experiment began with two water contents treatments (i.e., 14% and 26%), four salinity treatments (i.e., 2 g/kg, 4 g/kg, 6 g/kg, and 8 g/kg NaCl) and two N application treatments (i.e., 0 and 200 N mg/kg) in an orthogonal design. Salinity was controlled by adding NaCl solution, and N application was applied in the form of $NaNO_3$ solution. Water control was carried out throughout the whole culture period by watering per 2–4 d. N application experiment was designed to explore the alleviating effect of salt and drought stresses. After about five months, plants were harvested for experimental determination.

2.3. Sample processing and statistical analysis

Plants height was measured by steel ruler. The harvested plants were washed with distilled water, dried with absorbent paper, and weighed in the balance to get the fresh weight (FW). The dry weight (DW) was determined by drying the plants in an oven at 70 °C for 72 h. After drying, plants were ground and sieved to determine the TC and TN contents on Elemental Analyzer (VARIO EL). Multi-way variance analysis (ANOVA) was conducted using SPSS 16.0 software package to identify the significance of the water contents, salinity and N application on the above-mentioned indexes.

3. Results

3.1. Effects of drought, salt stresses and N application on fresh weight and dry weight of Suaeda salsa

Table 1 showed FW of *Suaeda salsa* was significantly affected by individual salinity, water content, N application and their interactions ($p < 0.01$) and DW was significantly related to the individual salinity, water content, N application, and salinity × N application ($p < 0.01$), and salinity × water content ($p < 0.05$). As shown in Fig. 1A, both FW and DW increased with increasing salinity, peaked at 6 g/kg salt level, and then decreased. Drought significantly decreased the FW and DW of *Suaeda salsa* by 10–20% compared with control ($p < 0.05$) (Fig. 1B), whereas N application significantly promoted them ($p < 0.05$) (Fig. 1C).

Fig. 2A showed that both FW and DW increased with increasing salinity but dropped at the 8 g/kg salt level under two water contents treatments. N application exhibited small effect on both FW and DW at lower salinity treatments, whereas had positive effects on them at higher salinity treatments (Fig. 2B). Comparatively, N application only promoted the FW and DW of *Suaeda salsa* under control (Fig. 2C).

3.2. Effects of drought, salt stresses and N application on the height of Suaeda salsa

The height of *Suaeda salsa* was only significantly influenced by water content, N application and water content × N application ($p < 0.05$) (Table 2). The height of *Suaeda salsa* peaked at the 6 g/kg salt level, and then reduced at the 8 g/kg salt level (Fig. 3A). Drought stress decreased the height of *Suaeda salsa* by almost 10% (Fig. 3B). However, N application had no significant influence on the height of *Suaeda salsa* ($p > 0.05$) (Fig. 3C). There were no significant differences in the height of *Suaeda salsa* affected by salinity × N application and salinity × water content ($p > 0.05$) (Table 2; Fig. 4A and B). In contrast, N application promoted the height of *Suaeda salsa* without drought stress and reduced it under drought stress (Fig. 4C).

3.3. Effects of drought, salt stress and N application on the TN and TC contents of Suaeda salsa

As shown in Table 3, only water content and N application had

Table 1
Statistical results of three-way ANOVA analysis testing effects of salinity, water content and N application on FW and DW.

	F (FW)	Sig. (FW)	F (DW)	Sig. (DW)
Salinity	77.778	0.000**	88.473	0.000**
Water content	4.982	0.005**	5.482	0.003**
N application	11.851	0.001**	12.682	0.001**
Salinity × water content	7.508	0.009**	6.510	0.014*
Salinity × N application	11.664	0.000**	9.762	0.000**
Water content × N application	4.277	0.010**	1.834	0.155

*$p < 0.05$; **$p < 0.01$.

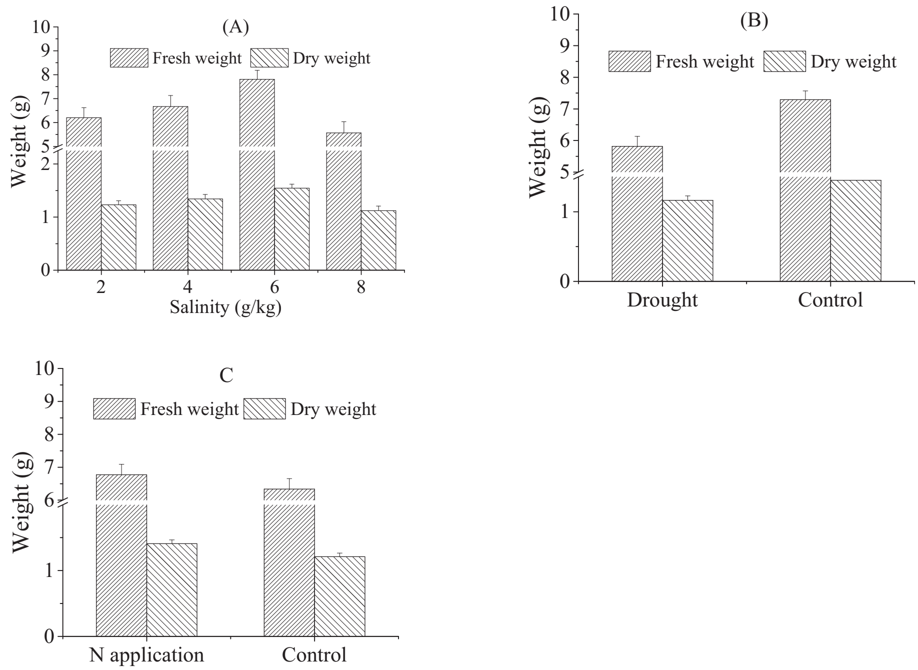

Fig. 1. Individual effects of salinity, drought and N application on the fresh weight and dry weights of *Suaeda salsa*.

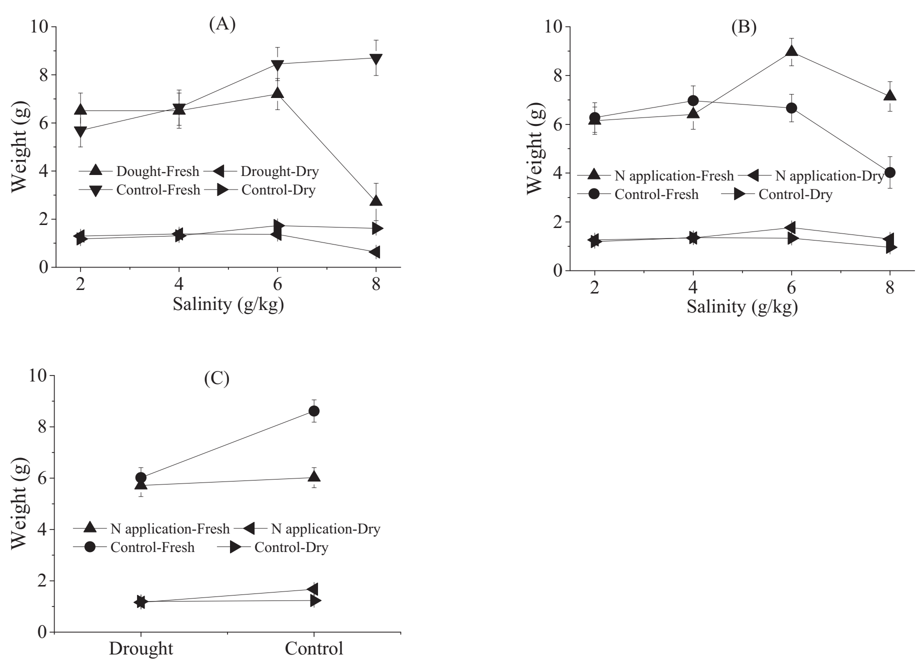

Fig. 2. The interactions among salinity, drought and N application on the fresh and dry weights of *Suaeda salsa*.

Table 2
Statistical results of three-way ANOVA analysis testing effects of salinity, water content and N application on the height of *Suaeda salsa*.

	F	Sig.
Salinity	239.359	0.000
Water content	3.798	0.017*
N application	6.825	0.012*
Salinity × water content	0.138	0.201
Salinity × N application	1.610	0.150
Water content × N application	1.860	0.012*

*$p < 0.05$; **$p < 0.01$.

significant effects on the TN level of *Suaeda salsa* ($p < 0.05$). The TN contents of *Suaeda salsa* had no significant differences under different salinity treatments (Fig. 5A). Drought and N application significantly increased the TN levels of *Suaeda salsa* (Fig. 5B and C). The interactions of drought, salt stresses and N application did not exhibit significant effects (Table 3; Fig. 6A and B). However, the TN contents levels of *Suaeda salsa* under N application treatments were higher than control under two water contents treatments (Fig. 6C). The TC contents levels of *Suaeda salsa* were less dependent on the drought, salt stresses and N application and their interactions

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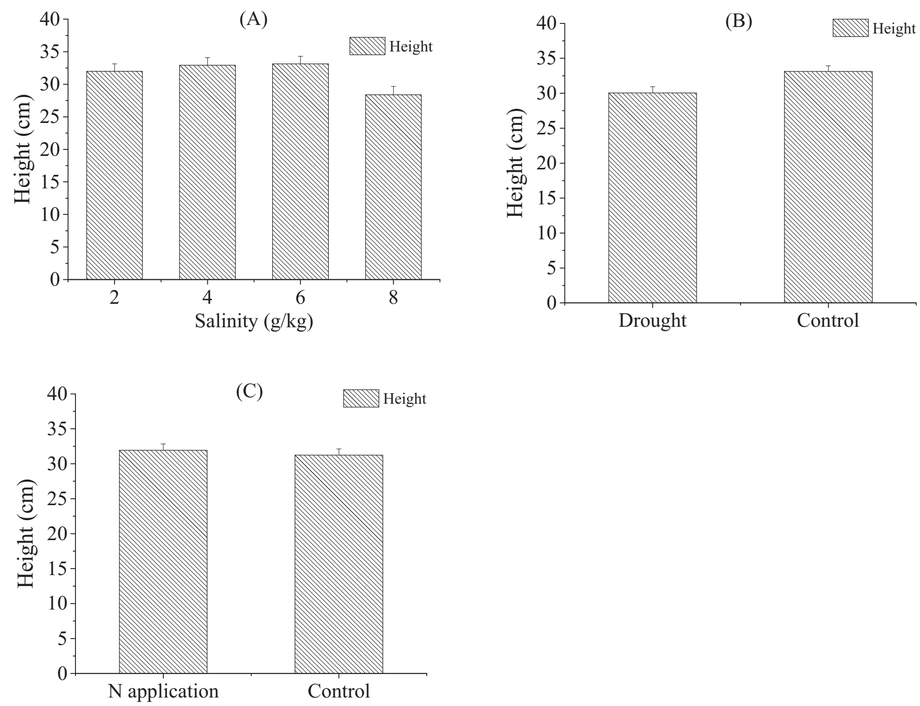

Fig. 3. Individual effects of salinity, drought and N application on the height of *Suaeda salsa*.

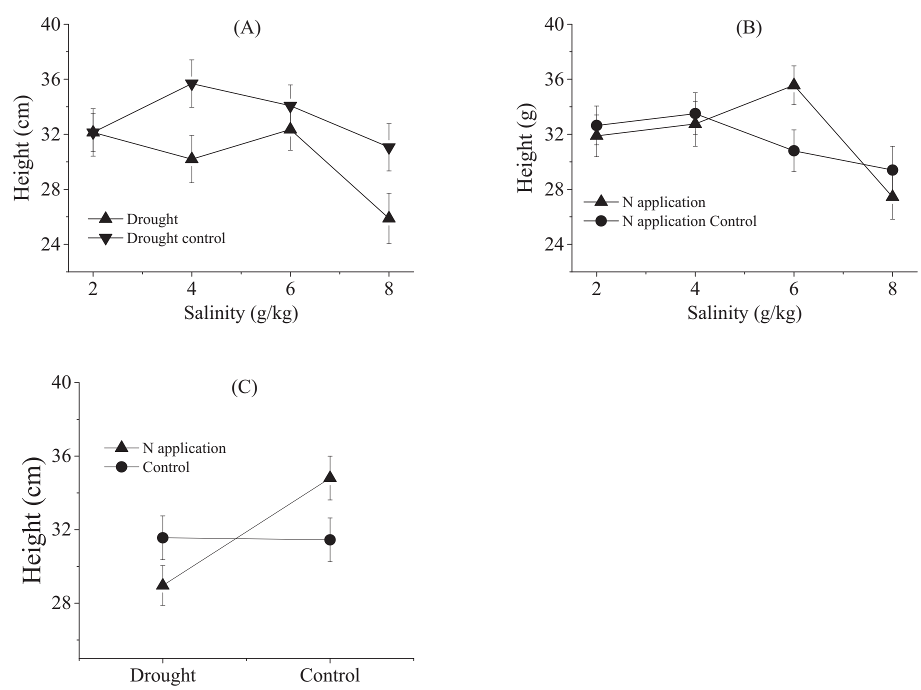

Fig. 4. The interactions among salinity, drought and N application on the heights of *Suaeda salsa*.

(Table 3; Fig. 5).

4. Discussion

4.1. Effects of drought, salt stresses and their interaction on Suaeda salsa

Suaeda salsa is a halophyte, which thrives with NaCl rather than without NaCl (Zhao et al., 2003). In our study, FW, DW and height of *Suaeda salsa* increased at lower salinity levels but decreased at higher salinity levels. This is in agreement with the result of Song et al. (2011), who studied two *Suaeda salsa* populations in intertidal and inland wetlands, and found their shoot dry weight increased firstly and reduced along an increasing salinity gradient. At lower salinity levels, *Suaeda salsa* could absorb Na^+ and Cl^- and store them in the vacuoles to lower the plant water potential, and

Table 3
Statistical results of three-way ANOVA analysis testing effects of salinity, water content and N application on the TN and TC contents of *Suaeda salsa*.

	F (TN)	Sig. (TN)	F (TC)	Sig. (TC)
Salinity	0.963	0.432	0.096	0.962
Water content	10.882	0.004**	7.025	0.011
N application	17.800	0.001**	0.445	0.508
Salinity × water content	2.469	0.095	1.885	0.146
Salinity × N application	0.925	0.449	0.2	0.896
Water content × N application	0.419	0.525	4.417	0.041*

*$p < 0.05$; **$p < 0.01$.

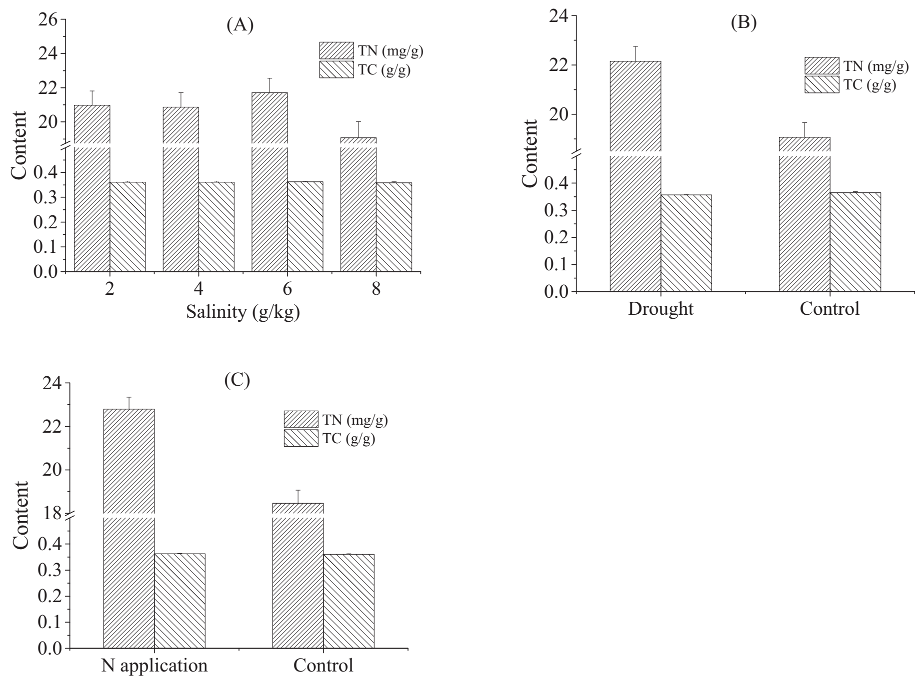

Fig. 5. Individual effects of salinity, drought and N application on the TN and TC contents of *Suaeda salsa*.

then its capability of absorbing water from soil improves (Zhao et al., 2003). In addition, salinity could enhance ATPase and PPase activities, which endow *Suaeda salsa* with more energy to transfer Na^+ and Cl^- to vacuoles (Chen and Liu, 1999). Whereas at higher salinity levels, increasing osmotic stress and ionic toxicity would retard the absorption of water and nutrition, and subsequently weaken the photosynthesis and metabolic activity (Hamed et al., 2013). In previous study, salinity was reported to reduce nitrate absorption in halophytes (Rubinigg et al., 2003). Whereas, our study found TN contents kept stable with increasing salinity levels. The possible explanation is, to adopt salt stress plants tend to adjust biomass allocation, leaf water content, height and shape to achieve efficient materials utilization, and promote the production of soluble protein, soluble sugar, proline and peroxidase to overcome salt stress (Mansour, 2000). In our study, drought decreased FW, DW and height of *Suaeda salsa* but increased its TN contents level, which can be explained by the fact that water deficit affects stomatal conductance, diminishes photosynthetic rate and injures active transport and membrane permeability (Tezara et al., 2003). This is consistent with the result by Sun et al. (2015), who demonstrated a decrease in biomass, height and an increase in TN content of *Suaeda salsa*.

Several studies demonstrated that the interaction of drought and salt stresses likely elicited additive negative effect on plant growth and development (Shani and Dudley, 2001). But some studies showed salinity might result in an enhancement in Na^+ in plant, which can improve photosynthesis and water status through its involvement in osmotic adjustment (Slama et al., 2007). In our study, significant reductions in FW and DW of *Suaeda salsa* were observed under salt and drought stresses, especially at higher salinity treatments. These indicate that under the interaction of drought and salt stresses, the stimulation of salinity on plant growth dominated at lower salinity treatments, and drought stress aggravates the deleterious effect of salinity at higher salinity treatments. Therefore, our study provided a possible explanation to the differences among the inconsistent conclusions about the interaction of salinity and drought stresses on plant growth.

4.2. N application alleviation effects on drought and salt stresses for Suaeda salsa

Nitrogen is an essential nutrient for plants and its absorption and utilization is very critical for plant growth and productivity. Our results exhibited that N application could significantly promote the FW, DW and TN contents level of *Suaeda salsa* other than the height and TC contents level. Many studies have proved the positive effect of N application on plant growth (Irshad et al., 2009). Whereas, the result of that N application has no effect on the height of *Suaeda salsa* could be explained by the fact that it promoted the lateral branch growth instead of bough.

In previous studies, they found nitrate application could alleviate salt injury by increasing the antioxidative defense mechanisms, leading to the reduction of photooxidation of chloroplast pigments and leaf senescence (Marschner, 1995). In addition, nitrate contributed more greatly to osmotic adjustment than chloride in *Suaeda salsa* (Song et al., 2009). Similar to these results, our findings also indicated that N application showed the alleviation effect on plant growth suffering from salt stress. Studies

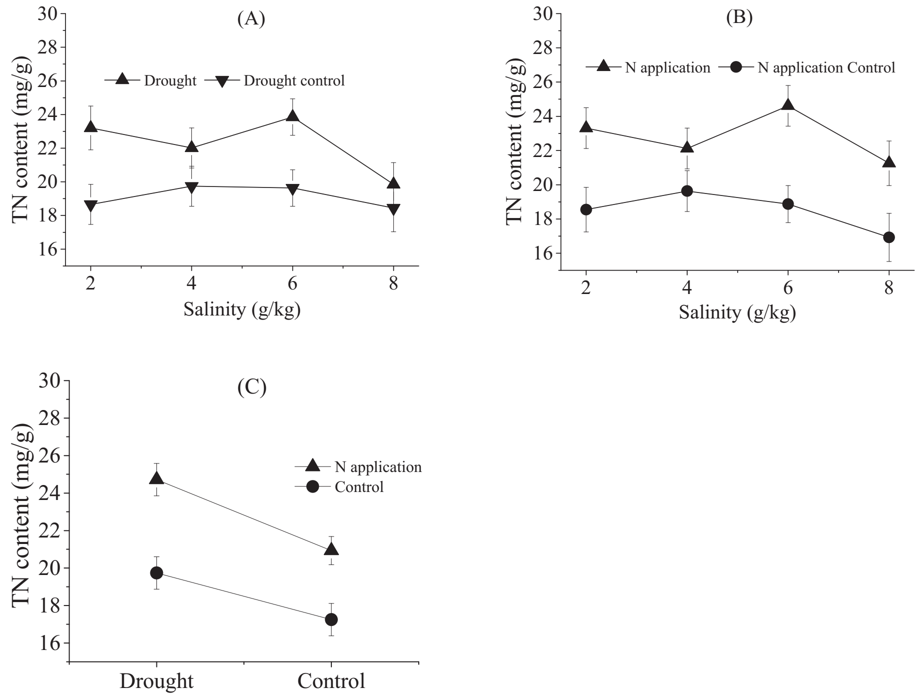

Fig. 6. The interactions among salinity, drought and N application on the TN contents of *Suaeda salsa*.

have suggested that higher levels of N nutrition might have contributed to drought tolerance by preventing cell membrane damage and enhancing osmoregulation (Saneoka et al., 2004). Kathju et al. (1990) reported that increasing N application to water-stressed plants improved nitrate uptake and nitrate reductase activity, which is the first enzyme in the pathway of N assimilation (Azedo-Silva et al., 2004). However, in our study, the alleviative effect of N application on drought was not significant ($p > 0.05$, Tables 1 and 3). Abd El-Hadi et al. (1997) also observed no effect of N application on roots of maize. These discrepancies might derive from different vegetation, stages of plant growth and experimental methods. Further studies are needed to testify this effect in different vegetation and investigate the concrete response mechanisms to the interactions of N application, drought and salt stress.

5. Conclusions

We investigated the ecological effects of salt and drought stresses and the alleviative effect of N application on the stresses of *Suaeda salsa*. Lower salinity promoted the growth of *Suaeda salsa*, whereas higher salinity exhibited an inhibiting effect through both osmotic stress and ionic toxicity. Although drought retarded the growth of *Suaeda salsa*, the TN contents of *Suaeda salsa* increased under drought stress. N application can improve the soil nutrition conditions and subsequently stimulated the growth of *Suaeda salsa*. The inhibition interaction of salinity and drought stresses was more obviously at higher salinity levels compared with at lower salinity levels. N application can alleviate the negative effects of salt stress, which might be explained by the increasing the antioxidative defense mechanisms. However, the interaction between N application and drought was slight. Further studies are still needed to explore the influencing mechanisms of the interactions between different environmental stresses.

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References

Abd El-Hadi, A.H., Ismail, K.M., El-Akahawy, M.A., 1997. Effect of potassium on the drought resistance of crops in Egyptian conditions. In: Johnston, A.E. (Ed.), Food Security in the WANA Region, the Essential Need for Balanced Fertilization. Int Potash Inst Basel, pp. 328–336.

Ardón, M., Morse, J.L., Colman, B.P., Bernhardt, E.S., 2013. Drought-induced saltwater incursion leads to increased wetland nitrogen export. Glob. Change Biol. 19 (10), 2976–2985.

Azedo-Silva, J., Osorio, F., Fonseca, F., Correia, M.J., 2004. Effects of soil drying and subsequent re-watering on the activity of nitrate reductase in root and leaves of Helianthus annuus. Funct. Plant Biol. 31, 611–621.

Baruch, Z., 1994. Responses to drought and flooding in tropical forage grasses. I. Biomass allocation, leaf growth and mineral nutrients. Plant Soil 164, 87–96.

Chen, Q., Liu, Y., 1999. Effect of H_2O_2, -OH and their scavengers on the H+- transport activity of tonoplast vesicles in barley leaves. Acta Plantphysiol. Sin. 25 (3), 281–286.

Hamed, K.B., Ellouzi, H., Talbi, O.Z., Hessini, K., Slama, I., Ghnaya, T., Bosch, S.M., Savouré, A., Abdelly, C., 2013. Physiological response of halophytes to multiple stresses. Funct. Plant Biol. 40 (9), 882–896.

Hu, Y., Schmidhalter, U., 2005. Drought and salinity: a comparison of their effects on mineral nutrition of plants. J. Plant Nutr. Soil Sci. 168 (4), 541–549.

Hutsch, B.W., Jung, S., Schubert, S., 2015. Comparison of salt and drought-stress effects on maize growth and yield formation with regard to acid invertase activity in the Kernels. J. Agron. Crop Sci. 201, 353–367.

Irshad, M., Eneji, A.E., Khattak, P.A., Khan, A., 2009. Influence of nitrogen and saline water on the growth and partitioning of mineral content in maize. J. Plant Nutr. 32, 458–469.

Kathju, S., Vyas, S.P., Garg, B.K., Lahiri, A.N., 1990. Fertility induced improvement in performance and metabolism of wheat under different intensities of water stress. Proc. Int. Congr. Plant Physiol. 88, 854–858.

Liu, J.H., Xia, J.B., Fang, Y.M., Li, T., Liu, J.T., 2014. Effects of salt-drought stress on growth and physiobiochemical characteristics of T*amarix chinensis* seedlings. Sci. World J. 2014, 1–7.

Mansour, M.M.F., 2000. Nitrogen containing compounds and adaptation of plants to salinity stress. Biol. Plant. 43 (4), 491–500.

Marschner, H., 1995. Mineral Nutrition of Higher Plants, vol. 2. Academic Press, London, U.K., p. 889

Mitsch, W.J., Gosselink, J.G., 2015. Wetlands, fifth ed. John Wiley & Sons, Inc., New York.

Pérez-Pérez, J.G., Syvertsen, J.P., Botía, P., García-Sánchez, F., 2007. Leaf water relations and net gas exchange responses of salinized *Carrizo citrange* seedlings during drought stress and recovery. Ann. Bot. 100, 335–345.

Rizwan, M., Ali, S., Ibrahim, M., Farid, M., Adrees, M., Bharwana, S.A., Zia-ur-Rehman, M., Qayyum, M.F., Abbas, F., 2015. Mechanisms of silicon-mediated alleviation of drought and salt stress in plants: a review. Environ. Sci. Pollut. Res. 22 (20), 15416–15431.

Rubinigg, M., Posthumus, F., Ferschke, M., Elzenga, J.T.M., Stulen, I., 2003. Effects of NaCl salinity on ^{15}N-nitrate fluxes and specific root length in the halophyte *Plantago maritima L.* Plant Soil 250, 201–213.

Saneoka, H., Moghaieb, R.E.A., Premachandra, G.S., Fujita, K., 2004. Nitrogen nutrition and water stress effects on cell membrane stability and leaf water relations in *Agrostis palustris* Huds. Environ. Exp. Bot. 52 (2), 131–138.

Shani, U., Dudley, L.M., 2001. Field studies of crop response to water and salt stress. Soil Sci. Soc. Am. J. 65, 1522–1528.

Slama, I., Ghnaya, T., Messeddi, D., Hessini, K., Labidi, N., Savouré, A., Abdelly, C., 2007. Effect of sodium chloride on the response of the halophyte species *Sesuvium portulacastrum* grown in mannitol-induced water stress. J. Plant Res. 120, 291–299.

Song, J., Shi, G.W., Gao, B., Fan, H., Wang, B.S., 2011. Waterlogging and salinity effects on two *Suaeda salsa* populations. Physiol. Plant 141 (4), 343–351.

Song, J., Shi, G.W., Xing, S., Yin, C.H., Fan, H., Wang, B.S., 2009. Ecopgysiological responses of the euhalophyte *Suaeda salsa* to the interactive effects of salinity and nitrate availability. Aquat. Bot. 91, 311–317.

Sun, C.X., Gao, X.X., Fu, J.Q., Zhou, J.H., Wu, X.F., 2015. Metabolic response of maize (*Zea mays L.*) plants to combined drought and salt stress. Plant Soil 388 (1–2), 99–117.

Tezara, W., Martinez, D., Dengifo, E., Herrera, A., 2003. Photosynthetic responses of the tropical spiny shrub *Lycium nodosum* (Solanaceae) to drought, soil salinity and saline spray. Ann. Bot. 92 (6), 757–765.

Tian, J.Y., Wang, X.F., Cai, X.J., 2005. Protection and Restoration Technique of Wetland Ecosystem in Yellow River Delta. China Ocean University Press, Qingdao (in Chinese).

Wang, B.S., Lüttge, U., Ratajczak, R., 2004. Specific regulation of SOD isoforms by NaCl and osmotic stress in leaves of the C3 halophyte *Suaeda salsa L.* J. Plant Physiol. 161, 285–293.

Zhao, K.F., Fan, H., Zhou, S., Song, J., 2003. Study on the salt and drought tolerance of *Suaeda salsa* and *Kalanchoe claigremontiana* under iso-osmotic salt and water stress. Plant Sci. 165 (4), 837–844.

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