Soil characteristics and ecological thresholds of *Suaeda salsa* wetlands

Fengkui Qian\textsuperscript{a,b}, Yang Zhou\textsuperscript{a,b}, Wanning Li\textsuperscript{a,b}, Xiangguo Wang\textsuperscript{a,b}, Zhentao Sun\textsuperscript{a,b}, Guize Liu\textsuperscript{c} and Haifeng Wei\textsuperscript{d}

\textsuperscript{a}College of Land and Environment, Shenyang Agricultural University, Shenyang, China; \textsuperscript{b}Liaoning Panjin Wetland Ecosystem National Observation and Research Station, China; \textsuperscript{c}National Marine Environmental Monitoring Center, Dalian, Liaoning, China; \textsuperscript{d}School of Marine Science and Environment Engineering, Dalian Ocean University, Dalian, China

**ABSTRACT**

*Suaeda salsa* is an annual euhalophyte in estuarine wetlands. Soil properties of wetlands have an important influence on *S. salsa* growth. Therefore, the soil ecological thresholds is valuable for the restoration of degraded *S. salsa* wetlands. The objectives of this present study were to analyze the soil physicochemical properties and evaluate the soil ecological thresholds in the typical degraded areas for *S. salsa* growth. Soil text components became coarser with increased sand contents and less clay contents, as the higher degree of wetland degradation. Meanwhile, the salt contents in different soil depths gradually increased with the increased degree of degradation of wetlands. Evident changes in soil water content, organic matter content, and cations concentrations were not observed, while the concentrations of these factors were higher in the soil layer of 0–10 cm than those in the 20–30 cm. The soil pH in the 0–10 cm soil layer was lower than that in the 20–30 cm. The content of the three available nutrients did not change evidently with the increasing degree of degradation. The optimum thresholds of soil salinity and water content were 7.033–16.613 g/kg and 31.8–63.2%, respectively.

**Introduction**

Wetlands, which function as the “kidneys” of Earth, form one of the most important ecosystems on the planet and play an important role in global ecology (Ye et al., 2015; Cowardin et al., 2005). The global wetland area is estimated to be $8.6 \times 10^6$ km$^2$, constituting 6% of the Earth’s land surface. Wetlands in China cover $6.6 \times 10^5$ km$^2$, nearly 6.5% of its total land area, making it the fourth largest wetland area in the world (Mitsch and Gosselink 1986). As a typical coastal wetland in China, the Liaohe Estuary wetland is the largest warm temperate coastal wetland in Asia with rich biodiversity, covering an area of $3.0 \times 10^5$ ha. The Liaohe Estuary wetland provides significant supporting for regional ecological security and biodiversity protection, such as important migration channel for birds. However, the wetland is suffering from water source reduction, wetland area loss, and landscape fragmentation caused by human disturbances, such as urban construction, paddy field reclamation, fish farming, and industrial development, and the changes in natural conditions (Li et al. 2018; Liu et al. 2020b). Furthermore, since estuarine wetlands are distributed in the areas where rivers enter the sea, soil salinity is influenced by tides, which can regulate the physiochemical characteristics of wetland soils (Chambers et al. 2014).

*Suaeda salsa* is an annual euhalophyte with a wide ecological amplitude and adaptability both in inland saline soils and intertidal areas (Liu et al. 2020a). *Suaeda salsa* not only absorbs soluble salt from the soil but also increases the soil organic matter content (Kefu et al. 2003). Therefore, it is commonly applied for the restoration of heavily salinized land (Song and Wang 2015). The existing studies have paid more attention to soil quality and ecological environment development of wetland, such as soil properties (e.g., soil organic matter content, pH and Eh values) and human activities (e.g., wetland reclamation, fertilizers application, and tourism development) in wetland soil under controlled conditions (Khan et al. 2010; Sui et al. 2010; Laing et al. 2009). Some other studies have focused on the physiological responses of *S. salsa* to salt stress or other environmental factors (Song 2009; Guan et al. 2011). Spatial and seasonal variations of soil properties at different depth profiles of total concentrations were investigated in salt marshes, and there were no variations in concentrations with different seasons under natural conditions. However, some parameters of soil levels increased from spring to autumn in tidal wetlands due to flow-sediment regulation in the upstream Xiaolangdi Reservoir (Bai et al. 2011). Soil water is one of the most limiting factors for *S. salsa* growth, and it regulates many ecological processes (Wu et al. 2014). The fluctuation of water level plays an important role in the formation of wetland vegetation (Nicol and Ganf 2000). In addition to the water limitation, the water absorption for plant growth was prevented by the high osmotic potential of soils with high salt content, reducing the plants’ reproduction and inhibition (Laura et al. 2005). Besides the damage caused by the high salt levels, a high pH

**CONTACT** Haifeng Wei (weihaifeng@dlou.edu.cn) School of Marine Science and Environment Engineering, Dalian Ocean University, Dalian 116023, China

This article has been corrected with minor changes. These changes do not impact the academic content of the article.

© 2022 The Author(s). Published by Taylor & Francis Group and Science Press on behalf of the Ecological Society of China.

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
condition also influences the availability of some soil nutrients for plants’ growth (Lv et al. 2013). Most of the previous studies were conducted to probe the causes, characteristics, evaluation, and restoration of wetland degradation in Chatra Wetlands, alpine wetlands on the Tibetan Plateau, saline wetlands in the Monegros Desert, Keoladeo National Park, floodplain wetlands in the Yellow River, Caohai Wetlands on the Guizhou Plateau, and the Zoige Plateau wetland. These studies mainly focused on the causes, characteristics, evaluation, and restoration of wetland degradation. The studies on the degradation of S. salsa wetlands in the Liaohe Estuary area have mainly focused on soil, water, salt, nutrient elements, enzymes, organic carbon, and pollution (Sun et al. 2020; Su et al. 2018; Wang et al. 2013b).

Currently, limited information is obtained on the characteristics of soil physicochemical properties and their relationship to the growth of S. salsa under different types of degradation in the Liaohe Estuary. In this study, five different degraded areas were selected based on remote sensing images taken in 2014 and 2019, and the soil water content, total salt content, base cations, mechanical components, alkaline nitrogen, available phosphorus, available potassium, organic matter, and pH of the soil from these regions were measured. A Gaussian model was proposed to calculate the threshold of soil physicochemical properties of the most suitable environment for the growth of S. salsa, which will be beneficial for habitat protection and restoration of the S. salsa wetlands in the Liaohe Estuary area. The objectives of this study were as follows: (1) to analyze the differences in soil physicochemical properties in various degraded areas of the S. salsa wetlands in the Liaohe River Estuary, and (2) to establish a suitable soil threshold for S. salsa growth in these regions.

Materials and methods

Study area

The S. salsa wetlands are located on the east side of the Liaohe Estuary (121°48’–121°57’ E, 40°46’–40°54’ N) in Zhaoquanhe Town, Panjin City, Liaoning Province (Figure 1). It is flat and low-lying, with an annual average temperature of 8.5°C, average annual rainfall of 650 mm (~70–80% of which occurs between June and August), and annual evaporation of 1705 mm. The freshwater supply to the wetland is primarily derived from rainfall, surface runoff, and periodic tidal water. These wetlands are dominated by Phragmites australis and S. salsa, and tidal flats are successively distributed in the area, which provides beneficial conditions for endangered wildlife, such as spotted seals, and facilitates seawater aquaculture. However, the estuary ecosystem has gradually deteriorated due to urbanization and industrialization of the coastal areas and the increased aquaculture, agriculture, and shipping activities. The soil has a high concentration (7–20 cmol/kg) of salt and poor air permeability, which makes it challenging for vegetation to survive.

Suaeda salsa is a pioneer plant that naturally grows on extremely saline soil and therefore has a strong adaptation to environmental stresses. However, the area covered by S. salsa has been decreasing in recent years owing to human interference and environmental changes. According to the analysis of remote sensing images from the past 20 years, the area covered by S. salsa in the Liaohe Estuary wetland reached its peak in 2014 at approximately 10 km², while the total area of S. salsa in 2019 was less than 3 km², with nearly 70% of the area having been lost. Therefore, analyzing the differences in soil physicochemical properties in the different degraded areas of S. salsa in the Liaohe Estuary Wetland and establishing the soil threshold of suitable environments for S. salsa growth have become key concerns.

Degradation zoning and soil sampling

Wetland degradation can change soil physicochemical properties. Remote sensing image data from 2014 to 2019 were used to analyze the different S. salsa wetland areas, and five types of degradation areas were finally demarcated by the proportion of degraded area to the total area, which was correspondingly distinguished and named as follows: A_0 (<10% degradation ratio), A_1 (30% degradation ratio), A_2 (50% degradation ratio), A_3 (70% degradation ratio), and A_4 (90% degradation ratio).
degradation ratio), and $A_4$ (90% degradation ratio). Soil sampling was conducted in early September 2020, and soil layer samples from depths of 0–10 cm, 10–20 cm, and 20–30 cm were collected with a drill core from each degraded area. The number of sampling points was determined according to degraded areas. For each soil layer, three soil cores were composited into one sample. Subsequently, 63 samples were collected. A 50 cm × 50 cm square was placed at each sampling point in each degraded area where *S. salsa* was in a state of continuous and stable growth from 2014 to 2019, and the *S. salsa* aboveground parts were cut to determine plant height, plant weight, and biomass.

**Soil sample processing**

All soil samples were processed in the laboratory. Initially, the soil samples were measured gravimetrically to determine the soil water content, and were later air-dried. Debris was removed from the samples, and the samples were ground and further sieved through a 2 mm mesh to determine the soil pH, total salt content, soil mechanical components, K⁺, Ca²⁺, Na⁺, and Mg²⁺ concentrations, alkaline nitrogen, phosphorus, and potassium contents, and organic matter. The *S. salsa* samples were dried at 105°C for 48 h to a constant weight to calculate the average dry weight of the biomass. The pH was measured in H₂O with a soil/solution ratio of 1:2.5 after 30 min of equilibration (USDA 1996), the total salt content was measured using the gravimetric method, and K⁺, Ca²⁺, Na⁺, and Mg²⁺ concentrations were determined by ion chromatography. The soil mechanical components were determined by a CIS-100 laser diffraction particle analyzer produced by the Holland Ann Mead Company, and carried out using the analytical procedure described by (Lu and An 1997). The soil water content was analyzed by drying method (105°C, 12 h) (Culley 1993). Soil alkaline nitrogen content was measured by the Conway diffusion method (Lu 1999), available phosphorous was determined according to the protocol described by (Olsen et al. 1954), and available potassium was determined by the ammonium acetate method described by (Helmke and Sparks 1996). Soil organic matter content was determined by an Element analyzer (Vario EL III, Germany). Each experiment was repeated three times to obtain the average value.

**Gaussian model analysis**

According to the existing literature (Zhang 2004; Francesco et al. 2014), the relationship between species distribution and environmental factors conforms to the conditions of the Gaussian model, and the change in biological indicators with the gradient of environmental factors can be described by the Gaussian equation. In order to assess the optimum soil conditions for *S. salsa* growth in the Liaohe Estuary wetland, a Gaussian model was applied to calculate the threshold of soil physicochemical properties suitable for *S. salsa* growth. The general threshold of the plant is $[u - 2 \ t, u + 2 \ t]$, and the optimum threshold is $[u - t, u + t]$. Therefore, according to the Gaussian model equation and calculated $u$ and $t$ values, the environmental gradient can be divided into optimal growth interval, general growth interval, and restricted growth interval. The optimal threshold interval for plants is when the environmental factor value is $[u-t, u + t]$, the environment is the most suitable for plant growth. It can be represented by Equation (1).

$$y = ce^{-\frac{(x-u)^2}{2t^2}}$$

where $y$ represents the plant ecological characteristic properties, such as height, weight, and biomass, $c$ is the maximum value corresponding to the above biological properties, $u$ is the optimal value of the plant to a certain environmental factor, and $t$ is the tolerance of the plant.

**Statistical analysis**

Normality and variance homogeneity tests were used to test data for normal distribution and equivalent variances. When these conditions were satisfied, statistical analyses were performed with one-way analysis of variance (ANOVA), followed by Duncan’s multiple comparison test when the ANOVA results were significant. All P values were two-sided, and $P < 0.05$ was considered statistically significant. To assess the correlation between *S. salsa* biomass and the soil physicochemical properties, the correlation between the biological indicators of *S. salsa* and Pearson’s correlation coefficients was calculated using the Simple Correlation Method (SPSS 20.0). Graphs and tables were drawn using Excel 2016 and SigmaPlot 12.5.

**Results**

**Soil physical properties analysis in the degradation areas of the *S. salsa* wetland**

**Soil water content**

Figure 2 shows the variation in the measured soil water content in the different degraded areas. In the 0–10 cm soil layer, the soil water content in the different areas was in the following order: $A_1$ (31.62%) < $A_4$ (32.23%) < $A_3$ (37.91%) < $A_6$ (44.72%) < $A_2$ (54.31%), while in the 10–20 cm soil layer, the order was $A_1$ (28.62%) < $A_4$ (31.17%) < $A_0$ (35.27%) < $A_3$ (38.10%) < $A_2$ (38.56%), and in the 20–30 cm soil layer, it was $A_1$ (23.93%) < $A_4$ (26.67%) <
A2 (31.75%) < A3 (35.62%) < A0 (35.82%). Soil water content in the 0–10 cm soil layer in different S. salsa degraded areas was significantly higher than that in the 10–20 cm and 20–30 cm soil layers (P < 0.05). The degree of degradation increased, and the water retention capacity decreased with the accumulation of sand in the soil. The soil water content in the 20–30 cm soil layer was low. However, the high soil water content in A2 was due to the low terrain and increased seawater supply (according to the digital elevation model, the elevation of this area is 0 m, which is lower than that of the 1–2 m elevation in the adjacent area). In the vertical soil profile, soil water content decreased with the soil depth due to the higher vegetation coverage. Thus, the soil water content in the 0–10 cm soil layer was not easily volatilized; thereby, large amounts of water were required to be absorbed through the roots to promote S. salsa growth.

**Soil physical properties**

Figure 3 indicates that in the 0–10 cm soil layer, the clay content of the soil in A1, A2, and A3 was reduced by 30%, 10%, and 10%, respectively, compared with A0. The content of soil sand in A1, A3, and A4 was reduced by 166.67%, 66.67%, and 233.34%, respectively, compared with that in A0. In the 10–20 cm soil layer, the soil clay content in A1, A2, A3, and A4 decreased by 15.00%, 54.00%, 54.00%, and 54.00%, respectively, compared with that in A0. Further, the soil sand content of A1, A2, A3, and A4 increased by 129%, 29%, 71%, and 200%, respectively, compared with that of A0. In the 20–30 cm soil layer, the soil clay content in the A2, A3, and A4 areas decreased by 11.00%, 33.00%, and 44.00%, respectively, compared with A0. The soil sand content in A1, A3, and A4 increased by 150%, 63%, and 113%, respectively, compared with that in A0. Therefore, the soil sand content was high, clay content was low, and coarse particles had developed in the degraded areas.

**Soil chemical properties**

**Soil total salt content**

According to Figure 4, total soil salt content in different degraded areas and different soil layers showed different changing trends. In the 0–10 cm soil layer, the total soil salt content in A1, A2, A3, and A4 was between 8.00 g/kg and 12.00 g/kg, which was 25%, 50%, 50%, and 50% higher than that in A0, respectively. In the 10–20 cm soil layer, the total soil salt content in A1, A2, A3, and A4 was between 8.00 g/kg and 10.00 g/kg, and 100%, 150%, 150%, and 150% higher than that in A0, respectively. In the 20–30 cm soil layer, the total soil salt content in A1, A2, A3, and A4 was between 4.00 g/kg and 8.00 g/kg, and 100%, 300%, 200%, and 400% higher than that in A0, respectively. Except for the 10–20 cm soil layer, the soil total salt content in A0 in the 0–10 cm and 10–20 cm soil layers was significantly lower than that in other degraded areas (P < 0.05). Moreover, the total salt content of the 0–10 cm soil layer in the different degraded areas was almost significantly higher than that of the 10–20 cm and 20–30 cm soil layers (P < 0.05).

**Soil base ions**

In the vertical soil profile (Figure 5), Na+, K+, Ca2+, and Mg2+ concentrations showed no evident trends, except that the ion concentration in the upper layer was higher than that in the lower layer because plant roots act as
differences in soil concentration, thus, implying that Mg$^{2+}$ accumulated on the soil surface. In the 0–10 cm, 10–20 cm, and 20–30 cm soil layers, the Na$^+$, K$^+$, Ca$^{2+}$, and Mg$^{2+}$ concentrations in the soil of A$_2$ were significantly lower than in the other degraded areas. Furthermore, the Na$^+$, K$^+$, Ca$^{2+}$, and Mg$^{2+}$ concentrations in the 20–30 cm soil layer were significantly lower than those in the 0–10 cm and 10–20 cm soil layers.

**Soil pH**

Through the analysis of soil pH in the different degraded areas, the soil pH was found to range from 8.26 to 8.76 (Figure 6). In the vertical soil profile, the pH at the 0–10 cm soil depth was higher than that at the 20–30 cm soil depth. The average pH in the 0–10 cm and 20–30 cm soil layers were 8.87 and 8.71, respectively, because the surface soil water content was higher than the bottom soil water content. The higher the soil water content, the lower is the clay concentration in the soil, thereby reducing the contact probability of the adsorbed H$^+$ to the electrode surface. Based on the classification of soil acidity and alkalinity (7.5 < pH < 8.5 is alkaline soil), the soil in the degraded area was generally alkaline.

**Available soil nutrients**

According to Figure 7, the contents of the three available nutrients in the soil did not show a significant change with the increasing degree of degradation, but an enrichment layer was observed. The positions of the

*Figure 5. Soil salt ion concentration in different degraded areas. Letters a, b, c, and d indicate significant differences between the different degraded areas for the same soil depth (P < 0.05), while A, B, C, and D represent significant differences between different soil layers in the same degraded area (P < 0.05).*
alkaline nitrogen enrichment layer were 0–10 cm (52.16 mg/kg), 10–20 cm (52.16 mg/kg), 0–10 cm (62.31 mg/kg), 0–10 cm (69.55 mg/kg), 10–20 cm (47.82 mg/kg) in A₀, A₁, A₂, A₃, and A₄ respectively. The depth of the alkaline nitrogen-enriched layer initially showed an increasing trend, which later decreased with the increase in the soil depth. The positions of the available phosphorus enrichment layer in A₀, A₁, A₂, A₃, and A₄ were 10–20 cm (27.83 mg/kg), 10–20 cm (30.45 mg/kg), 0–10 cm (30.39 mg/kg), 0–10 cm (34.30 mg/kg), 10–20 cm (29.08 mg/kg), respectively. The depth of the available phosphorus enrichment layer initially increased and later decreased with the increase in the degradation degree. The available phosphorus content of the available phosphorus enrichment layer ranged from 27.83 to 34.30 mg/kg, while the available phosphorus content of the unavailable phosphorus enrichment layer ranged from 15.58 to 27.89 mg/kg. The available potassium enrichment layers in A₀, A₁, A₂, A₃, and A₄ were 20–30 cm (1029.73 mg/kg), 10–20 cm (929.97 mg/kg), 10–20 cm (1000.00 mg/kg), 10–20 cm (1020.00 mg/kg), and 0–10 cm (849.94 mg/kg), respectively. The depth of the enriched layer decreased with soil depth. In the vertical profile, the concentrations of the three available nutrients (alkaline nitrogen, available phosphorus, and available potassium) showed a decreasing trend with soil depth.

The available potassium and alkali-hydrolyzable nitrogen concentrations in the 0–10 cm soil layer in the most degraded areas were significantly higher than that in the other soil layers (P < 0.05). Except for the 10–20 cm soil layer, significant differences were observed in the available soil phosphorus concentration in the degraded areas of different types of S. pubescens in the other soil layers (P < 0.05). The alkali-hydrolyzable nitrogen concentration in A₃ in different soil layers was significantly higher than that in the other degraded areas (P < 0.05).

**Soil organic matter**

As the degree of degradation increased, the soil organic matter content in the different soil layers and different degraded areas initially increased and later

---

**Figure 6.** Soil pH in different degraded areas. Letters a and b indicate significant differences between different degraded areas at the same soil depth (P < 0.05), while A and B represent significant differences between different soil layers in the same degraded area (P < 0.05).

**Figure 7.** Changes in available soil nutrient concentration in different degraded areas. Letters a, b, c, and d indicate significant differences between different degraded areas at the same soil depth (P < 0.05), while A and B represent significant differences between different soil layers in the same degraded area (P < 0.05).
decreased and finally increased again (Figure 8). The organic matter content in \( A_0 \) was the highest, ranging from 18.98 g/kg to 21.28 g/kg, while that in \( A_4 \) was the lowest, ranging from 10.61 g/kg to 15.72 g/kg. In the vertical profile, no evident changing trend was observed in the different degraded areas, but the organic matter content in the 0–10 cm soil layer in the most degraded areas was higher than that in the 20–30 cm soil layer. This was caused by the increased enrichment of surface vegetation litter. Except in \( A_0 \) and \( A_6 \), the organic matter content in the 0–10 cm soil layer was significantly the highest (P < 0.05). Additionally, the soil organic matter content in \( A_0 \) in different soil layers was significantly the highest (P < 0.05).

Threshold of the optimum soil physicochemical properties for \( S. \) \( salsa \) growth

Selection of biomass indicators

The relationship between plant biological indicators and the environment generally conforms to the Gaussian model. The changing trend of biological indicators with the gradient of environmental factors can be described by the Gaussian equation. A linear correlation is generally observed between plant biological indicators (Rogel, Ariza, and Silla 2000). The correlation between the three biological indicators of \( S. \) \( salsa \) was analyzed using SPSS 20.0. If the correlation is strong (P < 0.05) indicates a significant correlation between the two variables, P < 0.01 indicates an extremely significant correlation between the two variables, and P > 0.05 indicates that the two variables are not related), one of the biological indicators can be used to replace the other biological indicators, and the Gaussian model can be used to calculate the optimum threshold of soil indicators suitable for the growth of \( S. \) \( salsa \). To measure and calculate the optimum threshold of soil indicators suitable for the growth of \( S. \) \( salsa \), this study measured the individual plant weight, density, and biomass indexes of \( S. \) \( salsa \) plants during the vigorous growth period, and calculated the correlation between the indicators. As shown in Table 1, a highly significant correlation was observed between the biological indicators of \( S. \) \( salsa \).

This study first used WPS Office 2016 to fit the soil physicochemical indicators and the biological indicators of \( S. \) \( salsa \) to a quadratic curve fitting to check which indicator had a significant correlation with the logarithm of the biological indicators of \( S. \) \( salsa \). The one-variable quadratic curve fulfilled the regression conditions of the Gaussian model, and the optimum threshold was obtained. Finally, the one-variable quadratic curve that fulfilled the regression conditions of the Gaussian model was subjected to the Gaussian model regression to obtain the optimum threshold of the soil index of the \( S. \) \( salsa \) suitable growth environment. According to Table 2, the \( S. \) \( salsa \) biomass showed a good curve fitting effect with the total salt content and water content of the soil, with a significant correlation (correlation coefficient \( R^2 = 0.402 \) and 0.598, respectively). Furthermore, a weak correlation with no particular significance was observed between soil base ions, soil particle composition, \( \text{pH} \), available nitrogen, available phosphorus, available potassium, and organic matter and \( S. \) \( salsa \) biomass.

Threshold of soil water content and total salt content for \( S. \) \( salsa \) growth

After taking the natural logarithm of the biomass of \( S. \) \( salsa \), the one-variable quadratic curve fitted to the total soil salt content conformed to the Gaussian model, with a correlation coefficient of 0.402 and P < 0.05, which indicated a strong correlation and a Gaussian relationship (Figure 9). It can be inferred from Equation (2) that the optimum soil salinity for \( S. \) \( salsa \) growth was 11.84 g/kg, with an optimum threshold of [7.073, 16.613] g/kg, which was similar to the research results of Wang et al. and other scholars (Zheng 2014). The general threshold was 2.303 and 21.383 g/kg, respectively.

\[
y = 659.38e^{(-11.045)^2} + 0.679 \tag{2}
\]

| Properties       | Weight per plant | Density | Biomass |
|------------------|------------------|---------|---------|
| Weight per plant | 1                |         |         |
| Density          | 0.521**          | 1       | 0.870** |
| Biomass          | 0.644**          | 0.870** | 1       |

* indicates a significant correlation at P < 0.05.
** indicates a significant correlation at P < 0.01.
After taking the natural logarithm of the biomass of *S. salsa*, the one-variable quadratic curve fitted to the soil water content conformed to the Gaussian model, with a correlation coefficient of 0.534 and *P* < 0.05, indicating a Gaussian relationship between the soil water content and the *S. salsa* biomass (Figure 9). It can be inferred from Equation 3 that the optimum soil water content for *S. salsa* growth was 47.5%, and the optimum soil water was 47.5%, with their respective optimum thresholds being 31.8% and 63.2%, which was similar to the results of Wang Bai’s research on the Daling River estuary wetland (Wang et al. 2013a). This study also calculated the general threshold as [16.1%, 78.9%].

\[
y = 416.547e^{-0.0022x^2 + 0.5211x + 3.4056}
\]

**Conclusion and discussion**

**Conclusion**

Degradation has significantly affected wetland soil physicochemical properties and the growth environment of *S. salsa*. Wetland soil properties have an important influence on *S. salsa* growth, and the total salt content and water content of soil are the major determinants influencing *S. salsa* growth in different degraded areas. The Gaussian model could effectively measure and calculate the optimum threshold of the total salt content and water content of the soil suitable for the growth of *S. salsa*. These findings may be beneficial for restoring the *S. salsa* community and the wise utilization of wetlands. Further studies are required on the effects of soil characteristic heterogeneity on wetland degradation and *S. salsa* growth in this area.

**Discussion**

During the process of wetland degradation, significant changes in the associated soil properties were observed in the present study. Previous studies also found the similar effects of soil moisture, salinity, and alkalinity, etc., on *S. salsa* growth. For instance, An et al. found that soil moisture and EC were major determinants for earlier establishment of *S. salsa* population and root/shoot ratio of *S. salsa* was in positive correlation with soil moisture and salinity (An et al. 2019). In present soil samples, the water contents were relatively high in the 0–10 cm soil layer in different *S. salsa* degraded areas, which could contribute to the large amounts of root water absorption and promote *S. salsa* growth. Sandy

![Figure 9. Quadratic curve fitting of *Suaeda salsa* biomass with soil water content and total salt content.](image-url)

**Table 2. Correlation between *Suaeda salsa* biomass and soil physicochemical properties.**

| x                         | y                                      | R²           | P       |
|---------------------------|----------------------------------------|--------------|---------|
| Natural                   | Total salt content                     | y = -0.022x² + 0.5211x + 3.4056 | 0.402   | P < 0.05 |
| logarithm of biomass      | Water content                          | y = -23.451x² + 22.736x + 1.1439 | 0.598   | P < 0.05 |
|                           | K⁺                                     | y = -0.0019x² + 0.1044x + 4.9639 | 0.089   | P > 0.05 |
|                           | Na⁺                                    | y = -2E-06x² + 0.0028x + 5.3733 | 0.114   | P > 0.05 |
|                           | Mg⁺                                    | y = -0.0051x² + 0.2197x + 4.1129 | 0.171   | P > 0.05 |
|                           | Ca²⁺                                   | y = -5E-05x² + 0.0091x + 6.0347 | 0.183   | P > 0.05 |
|                           | Sand                                   | y = 0.0042x² - 0.1133x + 6.8594 | 0.062   | P > 0.05 |
|                           | Silt                                   | y = 0.0003x² - 0.0595x + 8.9336 | 0.032   | P > 0.05 |
|                           | Clay                                   | y = 0.0013x² - 0.0369x + 6.3943 | 0.017   | P > 0.05 |
|                           | pH                                     | y = -0.078x² + 0.6716x + 6.202 | 0.080   | P > 0.05 |
|                           | Alkaline nitrogen                       | y = 0.0005x² - 0.0351x + 6.6323 | 0.029   | P > 0.05 |
|                           | Available                               | y = 0.0004x² - 0.0278x + 6.4987 | 0.024   | P > 0.05 |
|                           | phosphorus                             | y = 0.0004x² - 0.0278x + 6.4987 | 0.024   | P > 0.05 |
|                           | Available potassium                     | y = 2E-06x² - 0.0024x + 6.5602 | 0.056   | P > 0.05 |
|                           | Organic matter                         | y = 0.006x² - 0.1056x + 6.4972 | 0.072   | P > 0.05 |
loam and silt loam soils predominantly in all the degraded areas both exhibited strong water permeability and weak water retention, which contain high sand contents and low silt and clay contents (Wei et al. 2016). With the increase in the soil depth, the total salinity in $A_0$, $A_1$, $A_2$, $A_3$, and $A_4$ gradually decreased, which may be due to the decreased vegetation coverage of the upper soil, and enhanced soil water transpiration (Fu et al. 2017). $Na^+$ was higher than $K^+$, $Ca^{2+}$, and $Mg^{2+}$, indicating that it was the most important cation for soil salinity. Complicated factors might contribute to the large amounts of $Na^+$ in surface soils, such as the soil parent material, ion interaction, adsorption and exchange characteristics of the colloidal surface, and leaching (Wang et al. 2009).

The amount of soil base ions precipitated in the soil solution reduced in high soil moisture, inducing the increased pH values. As the degradation increased, the vegetation population gradually vanished, and the top soils were then eroded by wind and river water. Nutrient elements, such as alkaline nitrogen, available phosphorus, and available potassium, lost with the loss of surface soils, and soil properties gradually deteriorated (Zheng 2014). Simultaneously, an evident staggered distribution of organic matter enrichment layers was observed in the vertical soil profile, which was consistent with the findings of Wang Ying and other scholars on the degraded wetland in the Tuwei River source area and the degraded wetland in the Mu Us sandy land (2011).

Previous studies have shown that the habitat of $S. salsa$ has changed in the Liaohe estuary, where $S. salsa$ abundance has reduced significantly – facing severe fragmentation and showing a shrinking trend. Our results show that wetland soil properties have an important influence on $S. salsa$ growth and reveal that the Gaussian model can effectively measure and calculate the optimum threshold of the total salt content and water content of the soil suitable for the growth of $S. salsa$. Furthermore, we demonstrate that an assessment of the threshold of wetland soil properties for $S. salsa$ growth suitability has theoretical and practical applicability for improving the wetland soil environment and restoring $S. salsa$ in estuarine wetlands.

**References**

An, Y., Y. Gao, Y. Zhang, S. Z. Tong, and X. H. Liu. 2019. “Early Establishment of Suaeda Salsa Population as Affected by Soil Moisture and Salinity: Implications for Pioneer Species Introduction in Saline-sodic Wetlands in Songnen Plain, China.” *Ecological Indicators* 105456. doi:10.1016/j.ecolind.2019.105654.

Bai, J., L. Huang, D. Yan, Q. Wang, H. Gao, R. Xiao, C. Huang, et al. 2011. “Contamination Characteristics of Heavy Metals in Wetland Soils along a Tidal Ditch of the Yellow River Estuary, China.” *Stochastic Environmental Research and Risk Assessment* 25 (5): 671–676. doi:10.1007/s00477-011-0475-7.

Chambers, L. G., S. E. Davis, T. Troxler, J. N. Boyer, A. Downey-Wall, and L. J. Scinto. 2014. “Biogeochemical Effects of Simulated Sea Level Rise on Carbon Loss in an Everglades Mangrove Peat Soil.” *Hydrobiologia* 726 (1): 195–211. doi:10.1007/s10750-013-1764-6.

Coward, L. M., V. Carter, F. C. Golet, and E. T. Laroe. 2005. “Classification of Wetlands and Deepwater Habitats of the United States.” In *Water Encyclopedia* (Washington, D.C.: Fish and Wildlife Service), 25–35, ed. by J. H. Lehr, and J. Keeley. doi:10.1007/0-471-78444-X sw2162.

Culley, J. L. B. 1993. “Density and Compressibility.” In *Soil Sampling and Methods of Analysis*, edited by M. R. Carter, 529–539. Boca Raton, FL: Lewis Publishers.

Francesco, T., D. Fabio, J. Giovanna, H. Hartwig, and H. Rudolf. 2014. “Predicting the Geographical Distribution of Two Invasive Termite Species from Occurrence Data.” *Environmental Entomology* 43 (5): 1135–1144. doi:10.1603/EN13312.

Fu, J. L., R. A. Feng, S. H. Jing, and T. J. Zhang. 2017. “Response Study on the Soil Soluble Salts to Different Plant Communities in Coastal Wetlands.” *Subtropical Soil and Water Conservation* 29 (1): 15–33. doi:10.13870/j.cnki. stbcsb.2016.06.047.

Guan, B., J. Yu, X. Wang, Y. Fu, X. Kan, Q. Lin, G. Han, and Z. Lu. 2011. “Physiological Responses of Halophyte Suaeda Salsa to Water Table and Salt Stresses in Coastal Wetland of Yellow River Delta.” *CLEAN - Soil, Air, Water* 39 (12): 1029–1035. doi:10.1002/clen.2010000577.

Helmke, P. A., and D. L. Sparks. 1996. “Lithium, Sodium, Potassium, Rubidium, and Cesium.” In *Methods of Soil Analysis* (Madison: ASA and SSSA), 551–556, edited by D. Sparks, A. Page, P. Helmke, R. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston, and M. E. Sumner. doi:10.2136/sssabookser5.3.c19.

Kefu, Z., F. Hai, Z. San, and S. Jie. 2003. “Study on the Salt and Drought Tolerance of Suaeda Salsa and Kalanchoe Daigremontiana under Isoosmotic Salt and Water Stress Plant Science.” 165: 837–844. https://www.ingentaconnect.com/content/el/01689452/2003/ 00000165/00000004/art00020.

Khan, M. A., M. Islam, G. Panaullah, J. M. Duxbury, M. Jahiruddin, and R. Loeppert. 2010. “Accumulation of Arsenic in Soil and Rice under Wetland Condition in Bangladesh.” *Plant and Soil* 333 (1–2): 163–274. doi:10.1007/s11104-010-0340-3.

Laing, G., J. Rinklebe, B. Van de Casteele, E. Meers, and F. M. G. Tack. 2009. “Trace Metal Behaviour in Estuarine and Riverine Floodplain Soils and Sediments: A Review.” *Science of the Total Environment* 407 (13): 3972–3985. doi:10.1016/j.scitotenv.2008.07.025.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

**Funding**

This work was funded by the National Key R&D Program of China (2019YFC1407700).
