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Evaluating the Enzyme Activities and Soil Physicochemical Properties of Four Typical Halophytic Communities in Saline-Sodic Soil

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Abstract: Four typical halophytic communities found in saline-sodic soil, including *Phragmites australis*, *Suaeda glauca*, *Leymus chinensis*, and *Puccinellia parl*, were investigated in this study. A comparison was made among the electrical conductivity (EC) value, pH value, soil organic carbon (SOC), and soil enzyme activity across various soil depths. The findings of this study indicate that the EC and pH levels of the soil at the 0–40 cm depth vary among the four communities, with *Suaeda glauca* having the highest values, followed by *Puccinellia parl*, *Phragmites australis*, and *Leymus chinensis*. The highest value of SOC among the four communities was observed in the *Leymus chinensis* community (0.85–0.94 g/kg), followed by the *Phragmites australis* community (0.50–0.77 g/kg), and the lowest levels were observed in the *Puccinellia parl* community (0.37–0.78 g/kg). As the soil depth increases, there is a decline in the amount of SOC. With an increase in soil depth, the content of SOC in the soil decreased, and the content of total nitrogen (TN) and the activity of six enzymes in the soil of each community increased. Furthermore, at the soil layer of 0–20 cm, the TN content in the soils was negatively correlated with pH and EC ($p < 0.01$), and so was the total phosphorus (TP). Additionally, the TP content is considerably positively connected with alkaline phosphatase (ALP) activity, whereas the TN content is significantly positively correlated with Soil Urease (S-UE) activity. Within the soil depth of 20–40 cm, the levels of TN, TP, and SOC exhibit a negative association with pH and EC. However, this link is weaker compared to that observed in the surface soil. A strong inverse correlation ($p < 0.05$) exists between the TP concentration and the ALP activity. The objective of this study was to investigate the use of halophytes in various saline-sodic soils for diverse avenues of restoration, and to establish a database on the role and efficacy of plant roots in enhancing saline-sodic soil.

Keywords: saline-sodic soil; typical halophytic communities; physicochemical properties; enzyme activity

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1. Introduction

Worldwide, saline-sodic soil covers an approximate area of 950 million hectares, with China's saline-sodic soil occupying 99 million hectares, which represents approximately 10% of the overall global salt-affected area [1]. Saline-sodic soil is extensively found in the Songnen Plain in Northeast China; yet, its proper utilization is challenging, leading to resource loss. Based on the survey conducted by Yan et al. in 2014, the saline-sodic soil in Songnen Plain covers approximately 2.4×10^4 square km, which represents 15.24% of the entire area of the plain [2]. The region experiences a scarcity of surface water, with a limited availability of surface runoff, but has abundant groundwater supplies. The spring season is characterized by dry and windy conditions due to the impact of mid-temperate continental monsoon. These conditions lead to high evaporation rates, causing salt to rise to the surface. The primary salts found in saline-sodic soil are Na_2CO_3 and $NaHCO_3$, which often exhibit traits such as high alkalinity, limited permeability, and low soil nutrient levels [2,3]. Sodic soil with high salinity can exhibit a bulk density ranging from 1.6 to 1.7 $g \cdot cm^{-3}$. Due of its fine particles and compact structure, it can exhibit a saturated hydraulic conductivity as low as 0.05 $mm \cdot d^{-1}$ [4,5]. Moreover, elevated pH levels will impact the uptake of positively and negatively charged ions by plants, resulting in the deficiency or neutralization of essential nutrients in the soil [6]. The process of soil salinization hampers agricultural productivity and poses a significant risk to the long-term sustainability of ecological systems. Hence, investigating the methods to restore saline-sodic soil is highly important for the ecological and economic progress of the Songnen Plain.

Presently, techniques employing the principles of chemistry, physics, and biology have successfully enhanced saline-sodic soil, augmented soil fertility, and boosted agricultural productivity. As people become more aware of the importance of environmental protection, there is a growing interest in researching bioremediation technology for saline-sodic soil. Phytoremediation, a key component of bioremediation, is a cost-effective method that uses plants to improve degraded soil. This technology shows great potential for the future [7,8]. Utilizing plants to enhance saline-sodic soil can significantly enhance ecosystem stability and soil fertility [9]. It has emerged as a crucial technology for enhancing the quality of saline-sodic soil and facilitating ecological restoration. Cao et al. [10] assert that a substantial quantity of above-ground biomass from salt-tolerant woody plants, such as tamarisk, can enhance soil enzyme activity and microbial diversity. This, in turn, aids in mitigating soil salinity stress. The composition and abundance of enzymes are contingent upon the soil quality and environmental factors, thereby making enzyme activity a reliable measure of soil fertility across many ecosystems [11]. Enzymes in soil mostly originate from plant root exudates and the metabolic activities of microorganisms, including bacteria and fungi. They play a crucial role in several biochemical processes within the soil environment [12,13]. The activity of soil enzymes is crucial for maintaining the equilibrium of soil ecosystems, as they contribute to nutrient provision, facilitate the decomposition and movement of organic matter, and support the overall health of soil and ecosystem activities [14,15]. Enzymes play a crucial role in facilitating the chemical reactions that break down and convert soil nutrients. Assessing the activity of enzymes in soil may be used as an indicator of the soil's overall health and quality [16]. Polyphenol oxidase, sucrase, urease, acid phosphatase, and alkaline phosphatase (ALP) all play a significant role in the cycling of soil carbon, nitrogen, and phosphorus. These enzymes have been shown to enhance nutrient utilization in soil during the process of plant restoration [17–19]. Peroxidase has the ability to facilitate biochemical reactions in plant and microbial decomposition processes [20,21] and can enhance the pace at which pollutants are broken down and transformed in saline-sodic soil. Hence, it is worthwhile to further investigate the cultivation of halophytic plants, the utilization of plant metabolites, and the enhancement of soil enzyme activity to augment soil nutrients and facilitate soil nutrient cycling.

The predominant flora cultivated on saline-sodic soil in Songnen Plain include *Phragmites australis*, *Suaeda glauca*, *Leymus chinensis*, and *Puccinellia parl*. *Suaeda glauca* is an herbaceous plant that belongs to the Chenopodiaceae family. Other plants in the same family include *Phragmites australis*, *Leymus chinensis*, and *Puccinellia parl*. *Leymus chinensis* possesses a rhizome that extends downward or horizontally, with a stem height ranging from 40 to 90 cm. It exhibits tolerance to cold, drought, and alkaline conditions, making it suitable for use as fodder. *Puccinellia parl* is upright, measuring 20–30 cm in height and around 1 mm in diameter. They are either clustered or lie flat at the base. *Puccinellia parl* can be used as feed for animals. *Suaeda glauca* may reach a maximum height of 1 meter. The stems are upright, cylindrical, and highly branched towards the top. The branches are thin, and the leaves are thread-like and semicircular, often measuring 1.5–5 cm in length. The seeds of *Suaeda glauca* have an oil content of around 25% and may be extracted for industrial use. The rhizomes of *Phragmites australis* are well-developed, with culms reaching heights of 1–3 m and diameters of 1–4 cm. They possess over 20 nodes. The *Phragmites australis* stalk serves as a material for paper production, matting for curtains, and sheds. The stem and leaf are used as fodder during their early stages, while the rhizome is employed for medicinal purposes [22]. The impact of plants on saline-sodic soil varies depending on their distinct development cycle and morphological structure. Hence, it is crucial to examine the physical and chemical characteristics of the soil in various communities in order to assess a plant's phytoremediation capacity.

The physical and chemical features of soil serve as fundamental markers for assessing its nutrient content and characteristic levels, hence indicating its quality and productivity [11]. Elevated saline and alkalinity levels result in a decline in both the physical and chemical characteristics of soil, rendering it challenging for plants to thrive. Nevertheless, it is possible to cultivate plants that are capable of withstanding high salt levels and effectively adapting to the challenges posed by saline-sodic stress, while simultaneously enhancing the physical and chemical characteristics of soil by altering the microenvironment around the roots through the release of root exudates. Nevertheless, alterations in soil's physical and chemical characteristics transpire gradually and are not readily discernible in the immediate timeframe [23]. Conversely, soil enzyme activity swiftly adapts to environmental shifts and functions as a gauge for soil's physical and chemical attributes as well as biological transformations. The changes of soil enzymes can serve as estimations of alterations in soil physical and biological properties [24] and can also function as markers of the well-being and durability of managed ecosystems. Hence, the evaluation and enhancement of soil ecosystem stability necessitate the careful consideration of soil enzyme activity. The plant species found in various saline-sodic environments differ significantly, mostly because of variations in the composition and intensity of salt and alkalinity. Given the important role of halophytic plants in improving saline-sodic soil, along with the substantial alterations that they can cause in soil and plant ecological processes and environmental factors, as well as the varying distribution of plant roots, it is crucial to identify the disparities in soil physical and chemical characteristics and soil enzyme activity among different halophytic plants at various soil depths.

This study aimed to assess the levels of salt, nutrients, and enzyme activities in typical halophyte soils found in saline-sodic soil. The objective was to investigate the relationship among salt, nutrients, and enzyme activities in various halophyte soils, and to determine if these relationships are influenced by the salt tolerance of plants and the depth of the soil. Additionally, we aimed to determine if these effects alter based on variances in plant salt tolerance and soil depth. For four dominant halophytic plants in soda saline-sodic soil, we conducted a comprehensive analysis of their physical and chemical characteristics as well as the enzyme activity in various soil layers. Meanwhile, this analysis was conducted by examining the pH, electrical conductivity (EC), nutritional composition, and enzyme activity. The anticipated outcomes were as follows: (1) salt stress would attenuate the impact on the soil enzyme activity of halophytic plants; (2) the soil enzyme activity would exhibit variations across different soil layers; (3) the extent of plant root distribution at varying depths could influence the level of soil enzyme activity; and (4) soil enzyme activity and soil salinity would exert significant influences on soil nutrients, with potential variations observed among different halophytic plant species.

2. Materials and Methods

2.1. Overview of the Study Area

The experimental area is situated at the Da'an Sodic Land Experimental Station of the Chinese Academy of Sciences in the southwestern region of the Songnen Plain. Its precise geographical coordinates range from N45°35′58″ to 45°36′28″ north latitude and E123°50′27″ to 123°51′31″ east longitude. The experimental station is surrounded by a flat floodplain that was once part of the Nenjiang River. The Songnen Plain is characterized by the coexistence of various amounts of saline and acidic soils, creating a characteristic saline and acidic soil complex. In fact, the maximum evaporation exceeds six times the amount of precipitation. Summer is hot and experiences concentrated rainfall, with 56% of the annual precipitation occurring in July and August. Autumn and winter have limited rainfall, and the soil freezes during winter, reaching a depth of 160–180 cm. In this area, the yearly mean precipitation stands at 413.7 mm, while the yearly mean evaporation amounts to 1756.9 mm. The sunlight duration reaches 3014 h, and the effective cumulative temperature ≥10 °C is 2935 °C. The unique ecological circumstances of the study area result in a consistent arrangement of plant communities throughout the region.

2.2. Sample Collection

Soil samples were taken on 30 September 2022, from four typical halophytic plant species that have been growing in saline-sodic soil for over 10 years, as well as from bare soil in saline-sodic soil. According to the FAO soil classification system, the soil type in this area is Solonetz, and the groundwater level changes dynamically from 0.4 m to 2.5 m. Each plant community was subjected to three duplicates of the experiment, covering a 1 m × 1 m area. Three soil samples were collected inside each replication. The four typical halophytic plants include the *Phragmites australis* community, the *Suaeda glauca* community, the *Leymus chinensis* community, and the *Puccinellia parl* community. Soil samples were collected at different depths (0–20 cm and 20–40 cm) using soil drills at three points within the vicinity of each halophytic plant. The soil samples were air-dried and subsequently processed by removing animal and plant residues as well as rock fragments. The processed samples were then ground and sifted through 2 mm and 0.25 mm sieves for soil physicochemical analyses.

2.3. Analysis Methods

The air-dried soil samples were screened with 2.0 mm sieve for the analysis of soil pH and EC, and the soil organic carbon (SOC), soil enzyme activity, total nitrogen (TN), available phosphorus (AP), and total phosphorus (TP) were detected with the soil samples screened with 0.25 mm sieve. The soil pH and EC were measured using the PHSJ-3F pH meter and the DDS-307A conductivity meter (manufactured by Shanghai Yidian Scientific Instrument, Shanghai, China). The measurements were taken using a soil-to-water ratio of 1:5. The SOC was quantified using the potassium dichromate oxidation technique with heating and assessed using a UV-visible spectrophotometer (UV2500, Beijing, China). Soil total nitrogen and total phosphorus were determined by the H_2SO_4-H_2O_2 oxidation method using an automatic chemical analyzer (Mode Smartchem 200, Rome, Italy). The values of β-xylosidase (BX), β-1,4-glucosidase(BG), β-D-cellobiohydrolase(CBH), β-1,4-N-acetylglucosaminidase (NAG), Soil Urease (S-UE), and alkaline phosphatase were subjected to treatment using an Assay Kit (in this order: AKEN015M, AKEN014M, AKEN016M, AKEN017M, AKEN023M, AKEN027M, Boxbio, Beijing, China) [25,26], and the activity of six enzymes were then measured using an enzyme marker (HBS-Scan Y, Nanjing, China). The selection of these six enzymes was based on their relevance to the cycles of carbon (C), nitrogen (N), and phosphorus (P).

2.4. Statistical Analysis

A two-way analysis of variance (ANOVA) was conducted to investigate the primary impacts of bare saline-sodic soils on typical plant soils and various soil depths (0–20 cm and 20–40 cm), as well as their interactions with each soil enzyme activity. In order to compare the mean values of soil physicochemical parameters across various plants and soil depths, it may be necessary to apply a logarithmic transformation to the data prior to analysis. If deemed required, the data underwent a log-transformation prior to analysis in order to adhere to the assumption of normality and homogeneity of variance. Additionally, soil enzyme activities and soil physicochemical values were computed. The statistical analyses were performed using SPSS software (version 19.0, IBM SPSS, Chicago, IL, USA). Canonical correspondence analysis (CCA) was employed to identify the soil parameters that exerted the most substantial impact on soil enzyme activity. The R "vegan" package (v2.5-7) was utilized to conduct canonical variance partitioning, which aimed to ascertain the relative impact of each significant variable on the overall variance.

3. Results

3.1. Physicochemical Characteristics of Representative Salt-Tolerant Plant Soils in Saline-Sodic Soil

An analysis was conducted on four typical halophyte soils and saline-sodic soil. The study revealed that the SOC of *Phragmites australis* was 7.4% lower than that of saline-sodic soil at a depth of 0–20 cm. Additionally, the SOC, TP, and TN levels of other halophytes were greater than those of bare soil, with increases ranging from 10.5% to 155.3%. Within the 20–40 cm soil layer, the salt-tolerant plants *Suaeda glauca* and *Puccinellia parl* saw a decline of 7.7% and 28.8% in their SOC and TP levels, respectively. Conversely, the plants *Phragmites australis* and *Leymus chinensis* exhibited an increase in their SOC and TP levels. Furthermore, the levels of TN in all four plants that are resistant to salt rose when compared to the soil that was both saline and sodic, with a range from 34.4% to 206.3%. Except for the pH value of the *Suaeda glauca* soil, which was higher than the bare saline-sodic soil at a depth of 0–20 cm, the pH of salt-tolerant plant soils in the same layer was lower than that of the naked saline-sodic soil. In addition, the EC values of the soil from the four salt-tolerant plants in both soil layers exhibited a substantial reduction in salinity, ranging from 55.6% to 94.1% (Table 1). The plants with a high salt tolerance showed increased soil pH and EC levels compared to *Phragmites australis*, a plant with a lesser salt tolerance. The soil pHs of *Suaeda glauca* and *Puccinellia parl*, which have a better salt tolerance, were, respectively, 11.4% and 10.3% larger than that of *Leymus chinensis*, which exhibits a lower salinity. Furthermore, the soil EC value showed an increase of 664.3% and 428.6% in these plants. The SOC showed a sole rise in the reed soil, whereas the TP content demonstrated an exclusive increase in the *Phragmites australis* soil, with increasing soil depth. Table 1 demonstrates that the levels of SOC and TP in various plant species, as well as the TN levels in all salt-tolerant plant soils, declined as the soil depth increased. Except for *Suaeda glauca*, the available phosphorus in the 20–40 cm soil layer was higher than that in bare soil, and the AP content of the other three plants in both soil layers was lower than that in the saline-sodic soil, while those of *Phragmites australis* and *Leymus chinensis* were significantly lower than that in bare soil (p < 0.01).

Table 1. Variation in soil physicochemical properties of halophytes in different soil-layer depths.

Vegetation	Soil Depth (cm)	pH	EC (mS/cm)	SOC (%)	TN (g/kg)	TP (g/kg)	AP (mg/kg)
Bare soil	0–20	10.39 ± 0.01 a	5.95 ± 0.26 a	0.54 ± 0.06 bc	0.33 ± 0.04 d	0.38 ± 0.03 a	36.97 ± 2.38 a
	20–40	10.54 ± 0.01 a	3.20 ± 0.19 a	0.52 ± 0.08 bc	0.32 ± 0.02 c	0.63 ± 0.10 ab	22.79 ± 0.81 a
Puccinellia parl	0–20	10.38 ± 0.01 a	1.48 ± 0.03 bc	0.78 ± 0.02 ab	0.59 ± 0.03 c	0.74 ± 0.11 a	19.15 ± 0.59 b
	20–40	10.43 ± 0.02 a	1.42 ± 0.06 b	0.37 ± 0.06 c	0.50 ± 0.04 c	0.45 ± 0.01 b	19.65 ± 0.58 a
Suaeda glauca	0–20	10.48 ± 0.03 a	2.14 ± 0.28 b	0.74 ± 0.01 abc	0.53 ± 0.03 c	0.42 ± 0.01 a	18.16 ± 2.24 b
	20–40	10.44 ± 0.01 a	1.90 ± 0.14 b	0.48 ± 0.09 c	0.43 ± 0.03 c	0.41 ± 0.01 b	22.89 ± 1.35 a
Leymus chinensis	0–20	9.41 ± 0.17 c	0.28 ± 0.06 d	0.94 ± 0.08 a	1.17 ± 0.08 a	0.97 ± 0.32 a	3.73 ± 0.55 d
	20–40	9.50 ± 0.18 c	0.35 ± 0.09 c	0.85 ± 0.04 a	0.98 ± 0.04 a	1.28 ± 0.34 a	4.64 ± 1.15 b
Phragmites australis	0–20	9.85 ± 0.08 b	0.69 ± 0.22 cd	0.50 ± 0.05 c	0.94 ± 0.04 b	0.89 ± 0.15 a	10.43 ± 1.04 c
	20–40	10.02 ± 0.08 b	0.62 ± 0.13 c	0.77 ± 0.04 ab	0.78 ± 0.08 b	0.79 ± 0.07 ab	3.50 ± 0.23 b

Lowercase letters are used to denote the relevance of various halophytes and soil depths in saline-alkali bare soil, with a statistical significance level of p < 0.05. The values indicate the average ± the standard error (n = 6). EC refers to electrical conductivity, TP stands for total phosphorus, TN represents total nitrogen, SOC denotes soil organic carbon, and AP stands for available phosphorus.

3.2. Investigation of the Varying Enzymatic Activity in Soil across Distinct Halophytic Plant Species

The enzymes BG, CBH, NAG, and ALP were all decreased in deeper soil layers, with the exception of S-UE. Furthermore, compared to salt-sodic soil, enzyme activity is frequently higher in a variety of plant soils (Figure 1). For example, the enzymatic activity of all six enzymes in the soil, at various depths and with varying plants, exhibited an increase ranging from 34.7% to 484.5% compared to those observed in the bulk soil.

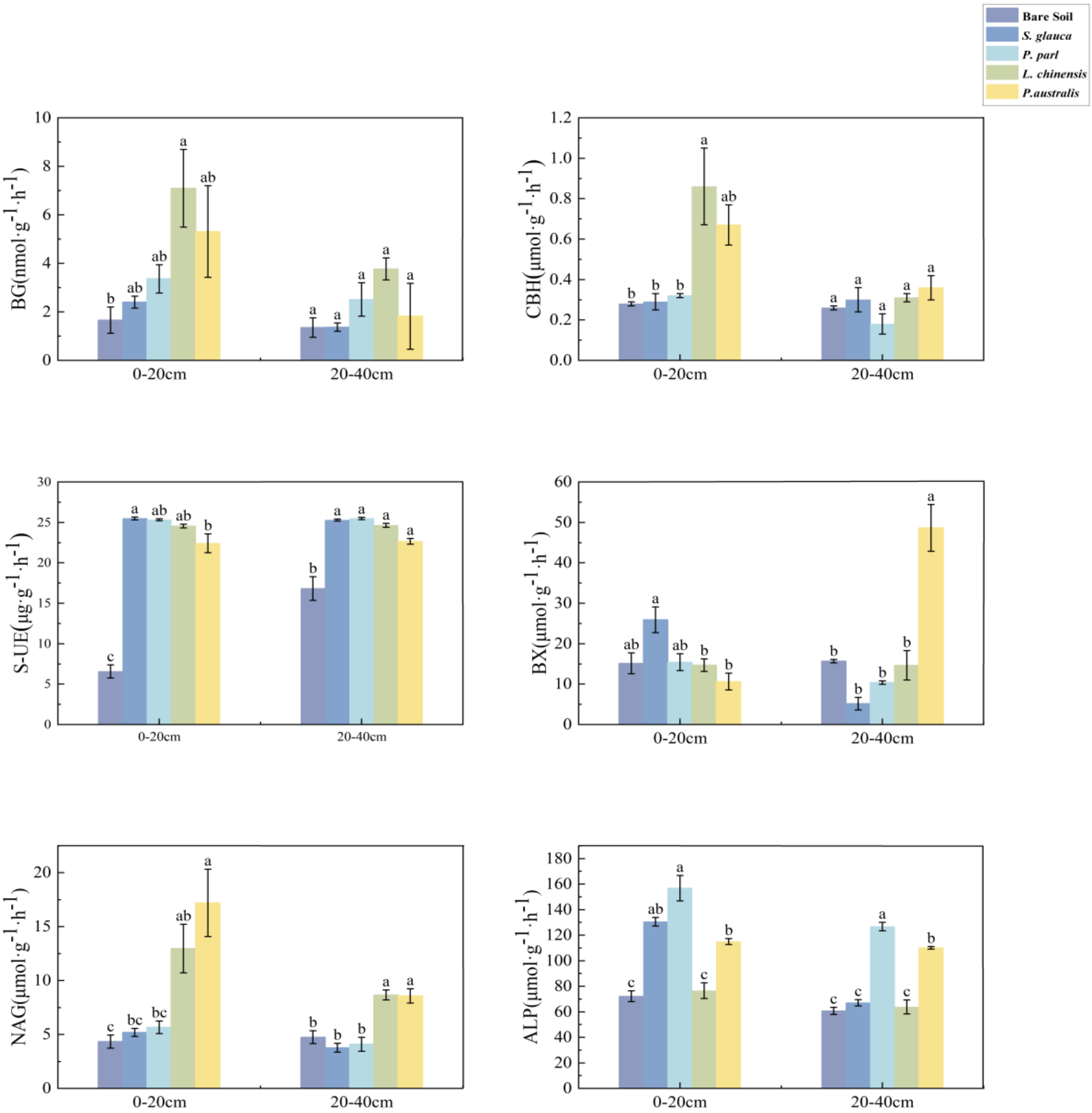

Figure 1. Differential soil enzyme activities of typical halophytes at various soil depths. The impact of varying soil depths on the fluctuation of soil enzyme activity in diverse halophytes. The error line corresponds to the standard error of the mean. The activities measured in this study were BG, which stands for β-1,4-glucosidase activity; CBH, which stands for β-D-cellobiohydrolase activity; NAG, which stands for β-1,4-N-acetylglucosaminidase activity; ALP, which stands for alkaline phosphatase activity; S-UE, which stands for Soil Urease; and BX, which stands for β-xylosidase. Distinct lowercase letters denote the varying importance of distinct halophytes' soil enzyme activity ($p < 0.05$).

When examining the individual activity of each soil enzyme in the 0–20 cm soil layer, the order of soil BG and CBH activities was as follows: bare soil < *Suaeda glauca* < *Puccinellia parl* < *Phragmites australis* < *Leymus chinensis*. The activities of BG and CBH in the rhizosphere soil of *Leymus chinensis* were substantially greater compared to the bare soil. The BG activity increased by 3.3%, while the CBH activity increased by 211.3% in comparison to the bare soil. While the levels of BG and CBH activity in the rhizosphere soil of other salt-resistant plants were increased compared to the bare soil, they did not reach a statistically significant level. The soil BX activity followed the sequence: *Phragmites australis* < *Leymus chinensis* < bare soil < *Puccinellia parl* < *Suaeda glauca*. The rhizosphere soil BX activity of *Suaeda glauca* was enhanced dramatically by 71.3% compared to the bare soil. The BG activity in the rhizosphere soil of *Puccinellia parl* exhibited a small rise, but one that did not reach a statistically significant level. Conversely, the BG activity in the rhizosphere soils of *Leymus chinensis* and *Phragmites australis* dropped. The soil enzyme NAG exhibited a progressive increase in activity, transitioning from bare soil to *Suaeda glauca*, then to *Puccinellia parl*, followed by *Leymus chinensis*, and finally to *Phragmites australis*. The levels of NAG activity in the rhizosphere soils of *Leymus chinensis* and *Phragmites australis* were significantly greater compared to the bare soil. Specifically, the NAG activity increased by 198.8% and 296.3% for *Leymus chinensis* and *Phragmites australis*, respectively, in comparison to the bare soil. The activity of ALP in the rhizosphere soils of *Leymus chinensis* and *Phragmites australis* was significantly higher compared to the bare soil, with increases of 117.5% and 287.6% respectively. Additionally, the activity of soil UE followed the order of bare soil < *Phragmites australis* < *Leymus chinensis* < *Puccinellia parl* < *Suaeda glauca*. The soil UE activity was higher than that of the bare soil by 287.6%, 285.3%, 273.5%, and 240.9% respectively.

The BX activity in the 20–40 cm soil layer is much greater in the soil of *Phragmites australis* compared to the bare soil, with a rise of 221.5%. Additionally, the BG activity in the soil of halophytes is higher than that of the bare soil. The CBH activity of *Puccinellia parl* soil is lower than that of the bare soil. However, the CBH activity of other halophytes is greater than that of the bare soil, but not significantly so. Both *Leymus chinensis* and *Phragmites australis* soils exhibit significantly higher levels of NAG activity compared to bare soil. Their levels of activity are 82.4% and 80.7% higher than that of bare soil, respectively. Conversely, the soils of *Suaeda glauca* and *Puccinellia parl* have lower levels of activity compared to bare soil. Ultimately, the NAG enzyme activity exhibits a much greater magnitude in the soil where *Leymus chinensis* and *Phragmites australis* flourish, as compared to the soil devoid of vegetation. *Leymus chinensis* and *Phragmites australis* are more efficient in facilitating the nitrogen and nutrient cycle in the soil. The activity of soil ALP from bare soil to *Puccinellia parl* was as follows: bare soil, *Leymus chinensis*, *Suaeda glauca*, *Phragmites australis*, and finally *Puccinellia parl*. The ALP activity in the soil of *Leymus chinensis* and *Suaeda glauca* shows a small increase compared to bare soil. Nevertheless, the ALP activity in the soils of *Puccinellia parl* and *Phragmites australis* is 108.7% and 81.5% more than that of soil without vegetation, respectively. The succession of UE activity in the soil progresses from bare soil to *Phragmites australis*, then to *Leymus chinensis*, followed by *Suaeda glauca*, and finally to *Puccinellia parl*. The UE activity values for each of these species are 34.7%, 46.5%, 50.3%, and 51.5% greater than those of the bare soil, respectively.

3.3. Investigating the Relationship between Soil Properties and Soil Enzyme Activity throughout Various Soil Layers

Correlation analysis, as depicted in Figure 2, revealed a strong negative correlation ($p < 0.01$) between the contents of TN and TP in the soil and both pH and EC at a depth of 0–20 cm. Additionally, a significant positive correlation ($p < 0.01$) was observed between the TP content and ALP activity, as well as between the TN content and UE activity. The activities of six enzymes and EC exhibited a negative correlation. Additionally, the pH showed a negative correlation with the ALP and NAG, but the nutritional index had a positive correlation with enzyme activities. In the 20–40 cm soil layer, the levels of TN, TP, and SOC were found to have a negative correlation with the pH and EC. However, this correlation was weaker compared to that in the surface soil. On the other hand, there was a significant negative correlation ($p < 0.05$) between the TP content and ALP activity, and a highly significant positive correlation ($p < 0.01$) between the TN content and S-UE activity. The EC and pH were negatively correlated with soil nutrients and soil enzyme activity, while the TN was negatively correlated with the NAG and S-UE, while the SOC was negatively correlated with enzyme activity Canonical correlation analysis (Figure 3) revealed that the EC exhibited negative correlations with the SOC, TN, and TP. The pH demonstrated positive correlations with the SOC and pH, while exhibiting a negative correlation with the TN in the 0–20 cm soil layer. In the 20–40 cm soil layer, the pH and EC displayed positive correlations with the TP and negative correlations with the SOC and TN. At 0–20 cm, the contribution rates of CCA1 and CCA2 were 86.36% and 7.65%, respectively; at 20–40 cm, they were 79.49% and 18.34% respectively. Additionally, these rates resulted in a cumulative contribution rate of 94.01% and 97.83%, which suggests that the physical and chemical properties of the soil had a significant impact on the activity of soil enzymes.

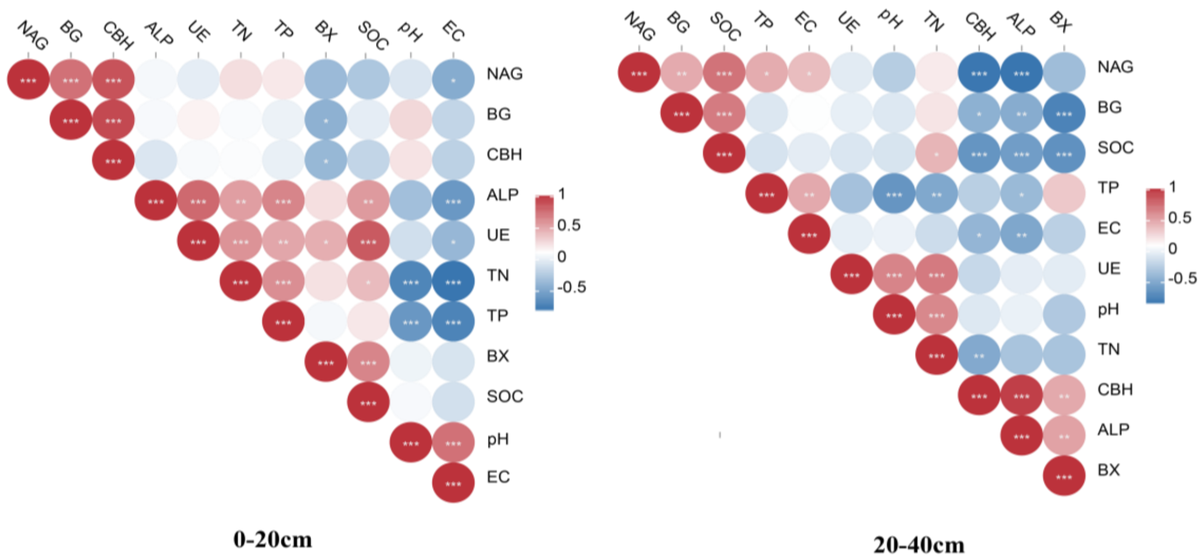

Figure 2. Correlation analysis of soil enzyme activity in different soil layers with soil properties. * indicates a statistical difference, ** indicates a significant statistical difference, and *** indicates an extremely significant statistical difference.

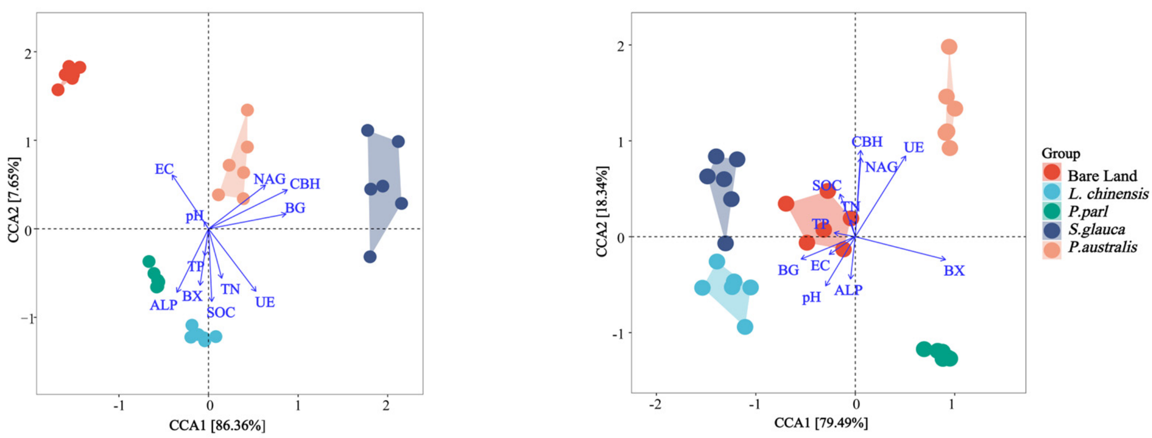

Figure 3. Canonical correlation analysis between soil enzyme activities and soil properties in different soil layers of typical plants.

4. Discussion

4.1. Effect of Vegetation on Soil Enzyme Activity

The saline-alkaline soils examined in this study exhibit elevated pH and EC levels, as well as significant concentrations of sodium bicarbonate and sodium carbonate. The soil pH and EC exhibited a negative correlation with the levels of nitrogen (N), phosphorus (P), potassium (K), and soil organic carbon (SOC). This finding aligns with the results reported by Li et al. [27–29]. Soil nutrient depletion results in a reduction in soil enzyme activity [30], but halophytes have the ability to greatly enhance the enzyme activity in soda salty soil [31]. *Suaeda glauca* and other plants have the ability to absorb Na^+ from the soil, thereby reducing its toxic effects on plants. Additionally, plant roots can secrete organic acids, which lowers the soil pH. The penetration of plant roots also improves the physical properties of the soil [7,8]. Furthermore, the accumulation of subterranean plant remains can promote the production of soil enzymes [32].

According to Hartman [33] and Cui et al. [34], pH has an impact on the soil texture, soil microbiota, and microbial community structure. Wu [35] found that the growth of plant communities reduces the correlation between the soil pH and soil EC with soil nutrients, likely due to root secretions altering the microenvironment of inter-root soils in response to saline and alkaline stresses. This alteration, in turn, affects the microbial diversity in and composition of the soil, as observed by Broeckling [36] and Shi [37].

The soil enzyme activity of halophytes was greater as compared to the saline-sodic soil. The soil enzyme activities of *Suaeda glauca* and *Puccinellia parl* were found to be lower compared to *Leymus chinensis* and *Puccinellia parl* communities. This difference in enzyme activities may be attributed to the higher pH and EC values observed in *Suaeda glauca* and *Puccinellia parl*. The results indicate that the soil microbial community was less abundant and the overall soil enzyme activity was lower [38]. The presence of *Leymus chinensis* root exudates may enhance soil enzyme activities due to the higher concentration of beneficial bacteria and enzymes that they contain. This, in turn, promotes the development and metabolic activity of microorganisms in the soil [39,40]. Furthermore, the root exudates of *Leymus chinensis* and *Suaeda glauca* in soil may vary in their composition and amount, potentially resulting in distinct soil enzyme activities between the two plants. The disparity in soil enzyme activity between *Phragmites australis* and the other three plants might be attributed to variations in the soil moisture and root area.

4.2. Effects of Environmental Factors on Enzyme Activities

Enzyme activities can serve as a possible indication for evaluating the impact of soil salinity on microbial activity [41]. The primary origins of the majority of enzymes in soil are plants and soil microbes [42]. Nevertheless, abiotic factors such as soil nutrients, soil moisture, and soil temperature exert influence on soil enzyme activity [43,44]. Soil pH is one of the most important soil nutrients related to SOC decomposition and mineralization [45].The investigation of SOC under plant cover revealed a decline in SOC as the soil depth increased, with the exception of *Phragmites australis*. This finding aligns with the outcomes reported by Zhao and Teng [12,35]. This study found a negative link between soil pH and soil enzyme activity, which aligns with the findings of Yin et al. [32]. Specifically, the acid condition was shown to be more effective than the alkaline condition in enhancing soil enzyme activity. The soil microbial community is influenced by the soil pH [46], and extreme acidic and alkaline conditions can diminish the variety of microbial communities and the activity of soil enzymes [47].

The activity of all six enzymes was observed to be higher in soils with plant communities compared to soils devoid of vegetation and containing high salt content. These findings indicate that the presence of saltwater-tolerant plant roots leads to increased soil enzyme activity in saline environments, highlighting the significant contribution of plant roots as a primary source of soil enzymes in such conditions. The impacts of various plants on soil enzyme activities exhibited variability, which can perhaps be attributed to parameters such as their salt tolerance, root density, and root volume [48]. This study measured the activities of three enzymes (BG, CBH, and BX) involved in carbon cycling in soil. It was observed that these enzyme activities remained relatively stable in saline-sodic soil. However, in all four plant community soils (except for the BX activity in *Phragmites australis*), the enzyme activities varied with the depth of the soil layer and decreased as the soil depth increased. These findings are consistent with previous studies conducted by Stone, Peng, and Zhang [49–51]. The activity of BX in *Phragmites australis* soil was positively associated with the SOC. However, the activities of BG and CBH did not exhibit a similar relationship. In contrast, the activities of BG, BX, and CBH in the soil of other plant communities were positively correlated with SOC. One possible reason for this is that SOC can provide energy and carbon sources and promote the growth and metabolism of microorganisms in the soil. These microbes secrete BX to degrade SOC, releasing xylose and other carbon sources [52,53]. The activity of NAG, which is related to nitrogen cycling, decreased as the soil depth increased. This decrease was positively linked to the soil TN content, which aligns with the results reported by Wu and Zhang [35,50]. This may be because increased nitrogen content in soil may promote microbial growth and activity, thus increasing the activity of NAG enzymes. This is because NAG enzymes are produced mainly by microorganisms in soil [54,55]. On the other hand, the activity of ALP, which is associated with P, showed a positive correlation with the TP content of *Puccinellia parl* and *Suaeda glauca*, but a negative correlation with the TP content of *Puccinellia parl* and *Suaeda glauca*. The reason for this may be that, when the ALP activity in soil is high, the phosphorus turnover rate increases and the total phosphorus content in soil decreases [56].

To summarize, the byproducts of soil microorganisms and plant roots serve as a significant reservoir of soil enzymes [51]. Soil microorganisms possess enzymes that are essential for plant development and have the ability to attach to the plant root system, hence influencing plant growth [57]. Research has demonstrated a positive correlation between soil organic carbon (SOC) content and soil microbial activity. Consequently, an increase in SOC leads to a subsequent rise in soil enzyme activity [34]. Furthermore, a plant's root system, when well-developed, enhances enzyme activity by producing metabolites [58,59]. Research has demonstrated that increased precipitation in environments with restricted water availability leads to a rise in the concentration of soluble nutrients in soil solution [60]. This, in turn, stimulates plant development and facilitates the deposition of nutrients between roots [61]. Furthermore, elevated temperatures promote the development and multiplication of microorganisms, and these microorganisms prefer to allocate a greater amount of carbon towards building up complex molecules rather than breaking them down, as supported by Ding [62]. The findings of this study indicated that the level of soil enzyme activity was directly influenced by the arrangement of plant roots. However, the impact of the *Phragmites australis* root system on soil enzyme activity requires more research, taking into account soil moisture and soil temperature levels. Furthermore, there was a correlation between soil enzyme activity and all nutritional indicators in the soil.

5. Conclusions

The findings of this study indicated that the enzyme activity in the soil of various plant communities consistently exceeded that of bare soil at a soil depth of 0–20 cm. However, as the soil depth increased, the enzyme activity varied depending on the level of salt-alkali tolerance. Assessing the impact of halophytes on soil nutrient cycling and soil salinity levels is crucial for accurately determining the extent of soil salinization and effectively utilizing various halophytes for specific restoration objectives, hence enhancing the efficiency of saline-sodic soil restoration. As the soil depth increases, the activity of the BX enzyme in *Phragmites australis* communis increases, while the activity of other soil enzymes decreases to some extent compared to the topsoil. This could be due to the distribution of the root zone of *Phragmites communis* and the soil moisture content. Further experiments can explore this relationship. Furthermore, halophytes can serve as pioneering plants for the purpose of rehabilitating saline-sodic soil. Our future research can center around the root exudates of these plants, as the various components of these exudates may significantly influence the diversity and structure of soil microorganisms, consequently impacting soil enzyme activities and nutrient levels. Hence, it is imperative to examine the composition of root exudates generated by various halophyte communities in subsequent investigations. Additionally, it is crucial to investigate the correlation between root exudates and microorganisms. This will facilitate the advancement of sustainable development in saline soil ecosystems within saline-alkali soil. Subsequently, it will enable the exploration of more efficient methods for restoring saline-alkali soil.

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