

Special Issue Reprint

Monitoring, Reclamation and Management of Salt-Affected Lands

Edited by

Xiaobing Chen, Jingsong Yang, Dongli She, Weifeng Chen,
Jingwei Wu, Yi Wang, Min Chen, Yuyi Li, Asad Sarwar Qureshi,
Anshuman Singh and Edivan Rodrigues De Souza

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Monitoring, Reclamation and Management of Salt-Affected Lands

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1. Introduction

Soil is the foundation of agriculture, and the world's farmers depend on soil to produce about 95% of the food we eat. Globally, saline soils cover more than 833 million hectares of land (8.7 per cent of the Earth's surface), most of which is found in naturally arid or semi-arid zones in Africa, Asia, and Latin America. Between 20 and 50 per cent of irrigated soils on all continents are hypersaline, which means that more than 1.5 billion people around the world face major challenges in food production due to soil degradation. The causes of rapid soil salinization are diverse and include poor management practices, excessive or inappropriate fertilization, deforestation, rising sea levels, shallow water tables affecting root zones, and the intrusion of seawater into groundwater used for irrigation. Climate change further exacerbates these risks. By the end of this century, the global arid land area may increase by 23%, primarily concentrated in developing countries.

This Special Issue focuses on the monitoring, reclamation, and management of salt-affected soil. It discusses water and salt regimes, carbon and nutrient cycling, and fertility improvement, with a particular focus on soil, water, and salt and associated agricultural and ecological issues in coastal saline-alkaline land. This Special Issue has aroused widespread interest among researchers and includes a total of 28 related academic papers.

2. Overview of This Special Issue

This Special Issue includes twenty-eight original contributions focused on the monitoring, reclamation, and management of salt-affected soils. The included studies mainly comprise research by Chinese universities and research institutions, with some contributions from international institutions. The twenty-eight articles in this Special Issue can be divided into five categories: category A, "Salt-affected soil remediation"; category B, "Rational fertilization in saline farmland"; category C, "Salt sources and treatments in saline agriculture"; category D, "Salinity monitoring and spatial distribution"; category

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E, “Impact of soil salinity stress on plant growth and nutrient element availability”; and category F, “Ecosystem strategies for sustainable saline agriculture development”.

In category A, “Salt-affected soil remediation”, Mengzhu Li et al. (contribution 1) studied various straw mulching techniques with indoor soil column tests and field tests to screen optimal mulching measures for salt and vapor suppression in saline soils. Ji Qi et al. (contribution 2) investigated the various ridging configurations affecting soil salinity in the Yellow River Delta. The study showed that a triangular ridge fostered a favorable soil environment for crop growth. Meng xiao et al. (contribution 3) analyzed the addition of fulvic acid to organic fertilizer, which increased the content of soil organic matter and promoted salt ion leaching. Yunpeng Sun et al. (contribution 4, 5) reported two studies on field experiments in coastal soil with the addition of biomaterials. Biochar, fulvic acid, and *Bacillus subtilis* showed good effects on soil salinity amelioration and fertility improvement. Xiangping Wang et al. (contribution 6) analyzed the reduction in soil salinity and improvement in barley–maize growth in newly reclaimed coastal lands resulting from the utilization of manure plus plastic film mulch.

In category B, “Rational fertilization in saline farmland”, Junyao Liu et al. (contribution 7) analyzed the effects of using organic fertilizer with ryegrass–alfalfa rotation and compound measures on lowering salinity and boosting fertility in coastal salinized soils. Haogeng Zhao et al. (contribution 8) reported that low-nitrogen microbial fertilizers led to more ammonium nitrogen in the soil, whereas a high-nitrogen fertilizer application resulted in higher nitrate nitrogen in the soil, leading to nitrogen leaching in saline soils. Panbo Deng et al. (contribution 9) used organic fertilizer with *Ganoderma lucidum* residue for ameliorating the physical and chemical properties of saline–alkaline soils and adjusting microbial communities. Yunpeng Sun et al. (contribution 10) found that nitrogen fertilizer application could ameliorate salt damage and promote the growth of wheat.

In category C, “Salt sources and treatments in saline agriculture”, Sourour Mzahma (contribution 11) studied membrane technologies aimed at decreasing the salt content of textile effluents for agricultural reuse. Bakytzhan Amralinova et al. (contribution 12) investigated the composition of Burabay rock, which releases salt ions into a lake. The deposition could be developed to produce valuable components.

In category D, “Salinity monitoring and spatial distribution”, Ying Song et al. (contribution 13) identified the spatial and temporal characteristics of cultivated saline lands in coastal areas and provided decision-making support for strengthening the dynamic monitoring and regulation of agricultural soils. Yingxuan Ma et al. (contribution 14) monitored soil salinity using soil measurement data and Sentinel-2 remote sensing data. The results are of great significance to understanding the salinization situation in the Weigan River–Kuqa River Delta Oasis. Wenxiu Li et al. (contribution 15) studied the results of water and salt distribution in a column experiment under three different tillage methods. Ying Song et al. (contribution 16) investigated soil salinity in the spring and summer in a coastal area using a geographic information system and groundwater modeling system. Mengyao Wang et al. (contribution 17) clarified the key mechanisms of the natural regeneration of *M. alba* for the transformation of a declining *R. pseudoacacia* plantation. Their study found that the germination ability of maternal trees in saline–alkali land was higher than that in non-saline–alkali land under salt stress.

In category E, “Impact of soil salinity stress on plant growth and nutrient element availability”, Sharaf M. Al-Tardeh et al. (contribution 18) designed a biological experiment to assess the effects of various salinity levels on seed germination using ten certified Palestinian barley cultivars. Some cultivars showed moderate to high resilience to salinity, reaching >80% seed germination at 120 mM NaCl. Chunyan Yin et al. (contribution 19) carried out a split-plot experiment with straw return and various nitrogen application rates

to study the nitrification and mineralization of nitrogen in saline soil. They found that straw return and a reduced nitrogen application to saline soil can retain more ammonium nitrogen, thus inhibiting the nitrification of soil nitrogen. Raphaela Revorêdo Bezerra et al. (contribution 20) found that the water efficiency and production components of coriander plants were affected by increases in electrical conductivity in the nutrient solution. Kongming Zhu et al. (contribution 21) determined the ^{15}N uptake rates in various parts of mature wheat plants and residual ^{15}N in three different saline soils, as well as ^{15}N loss in soil–wheat systems, using the ^{15}N labeled urea N tracing method in the Yellow River Delta. An increase in soil salinity inhibited wheat uptake and soil residues and intensified the losses from ^{15}N fertilizer. Wenping Xie et al. (contribution 22) found significant correlations between soil salinity and other environmental factors. In their study, soil salinity and alkaline phosphatase activity were the main influencing factors of soil available phosphorus.

Finally, in category F, “Ecosystem strategies for sustainable saline agriculture development”, Adil K. Salman et al. (contribution 23) investigated the impact of osmotic potential on salt-affected soils. The study found a strong correlation between osmotic potential and evapotranspiration. Qianwen Du et al. (contribution 24) found that a BP neural network model could simulate and predict dissolved N_2O concentrations in overlying water under a saline–alkali environment. Luofan Li (contribution 25) analyzed the dynamic degree, landscape type transfer matrix, and landscape indices of landscape types in the Yellow River Delta region. Their results showed that the areas of construction land, salt fields, and breeding ponds in this region had significantly increased. Their study can guide a more sustainable use of land resources. Jian Liu (contribution 26) provide a reference for the scientific evaluation of ecosystem service value (ESV) for saline–alkali lands, as well as a basis for the rational development and utilization of Huanghe Island. Yueying Wang et al. (contribution 27) solved the problem of the regulation of abiotic factors on plant aboveground biomass and diversity on the slopes of coastal agricultural ditches through field surveys of vegetation at different sampling sites. Simeng Chne et al. (contribution 28) investigated different irrigation and drainage practices in a land development project and examined their effects on ecosystem service value in the Yellow River Delta. They revealed that the “Pipeline irrigation + concealed pipe” irrigation and drainage model increased the area of cultivated land by 4.04 km^2 .

3. Research Progress on Salt-Affected Land: Key Scientific Issues

3.1. Salt-Affected Soil Remediation

Salt-affected soils are defined by elevated concentrations of soluble salts, which can significantly impair their physical and chemical properties. Salt-affected soils exhibit several physical and chemical characteristics that render them unsuitable for conventional agricultural practices. High concentrations of salts can lead to osmotic stress in plants, inhibiting water uptake even in well-watered conditions. This stress can result in stunted growth, reduced crop yields, and even plant death [1]. The significance of remediating salt-affected soils needs more attention, particularly in the context of global food security and environmental sustainability. Soil amendments play a crucial role in enhancing the quality of salt-affected soils [2]. Among the various amendments available, gypsum (calcium sulfate) and organic matter are two of the most effective in addressing issues related to soil salinity, particularly in displacing sodium ions and improving soil structure and fertility [3]. Another integral element of an integrated management strategy is crop rotation. Selecting salt-tolerant crops as part of a well-planned rotation can help mitigate salinity levels while enhancing soil structure and fertility. The cultivation of diverse crops not only disrupts pest and disease cycles but also encourages a healthier soil microbiome, which contributes

to nutrient cycling and organic matter improvement [4]. Cover crops can also be integrated into the rotation system, providing ground cover that reduces evaporation and helps maintain moisture levels while sequestering salts in their biomass. When these crops are terminated or incorporated into the soil, they contribute organic matter, further enhancing the soil's structure and eventual fertility.

3.2. Rational Fertilization in Saline Farmland

Many fertilizers contain salts and can thus increase soil salinity. However, certain practices and types of fertilizers can help manage or reduce soil salinity. High salinity can hinder the availability of essential nutrients. Salts compete with plant roots for the uptake of nutrients, particularly macronutrients like potassium and calcium, which are vital for healthy growth and development. Potassium nitrate (KNO_3) is one of the most effective fertilizers for managing soil salinity. This nitrate-based fertilizer not only provides essential nutrients—potassium (K) and nitrogen (N)—but also has a low salt index compared to other commonly used fertilizers. Its unique chemical structure allows it to play a dual role in salinity management [5]. Moreover, bio-organic fertilizer is an effective saline-alkali soil conditioner [6]. Understanding the dynamic changes in fertilizers is the key to implementing suitable management options for re-building the fertility of saline soils.

3.3. Salt Sources and Treatments in Saline Agriculture

In agriculture, salt can originate from various sources and pose significant challenges for crop production [7]. (1) Many irrigation waters contain dissolved salts, which can accumulate in the soil over time, especially in arid regions. (2) Natural salts present in the soil can be mobilized through weathering processes. (3) Some fertilizers are salts themselves (e.g., ammonium nitrate), contributing to soil salinity. (4) In hot climates, evaporation can concentrate salts in the soil surface, leading to salinity issues.

3.4. Salinity Monitoring and Spatial Distribution

Predicting and monitoring soil salinity is important in order to take protective measures against further deterioration of the soil. Soil salinity monitoring and spatial distribution can be effectively achieved through various methods, primarily utilizing remote sensing, geographic information systems (GISs), and field sampling [8]. Tools like Landsat and Sentinel satellites provide multispectral images that can be analyzed to detect soil salinity. Specific indices, such as the Normalized Difference Vegetation Index (NDVI) and salinity index, can help identify salinized areas [9]. Collecting soil samples from various locations for laboratory analysis provides ground truth data that can validate remote sensing and GIS findings. In situ measurements of soil electrical conductivity (EC) can be used to estimate salinity levels directly [10]. Combining remote sensing, GIS, and field data creates a robust framework for monitoring soil salinity. This integrated approach allows for the identification of salinity hotspots and aids in effective land management practices.

3.5. Impact of Soil Salinity Stress on Plant Growth and Nutrient Element Availability

Soil salinization has become a severe problem affecting soil quality and restricting sustainable agricultural development around the world. High salinity creates an osmotic pressure that makes it difficult for plants to absorb water, leading to dehydration and reduced turgor pressure. Salinity reduces the water potential of the soil, creating a situation where water is less available for plant uptake. This condition leads to a reduction in turgor pressure within the plant cells, essential for maintaining structural integrity and growth. Excessive salts can lead to the accumulation of toxic ions (e.g., sodium and chloride), which disrupts cellular functions and can damage plant tissues [11]. High salinity can hinder the uptake of essential nutrients such as potassium, calcium, and magnesium. This is

due to competition between sodium ions and these nutrients at the root level [12]. Under saline conditions, plants may experience diminished calcium ion availability, leading to a cascade of negative physiological effects impacting growth and development [13]. Prolonged exposure to soil salinity presents several critical challenges to agricultural systems, significantly affecting crop yield, food security, and soil health. Understanding these long-term implications is essential for developing effective management strategies and enhancing sustainable agricultural practices.

3.6. Ecosystem Strategies for Sustainable Saline Agriculture Development

Sustainable saline agricultural practices provide significant benefits in terms of biodiversity preservation and carbon sequestration, both crucial elements in efforts to combat climate change and enhance ecosystem resilience [14]. Sustainable saline agriculture promotes the cultivation of a variety of salt-tolerant crops, known as halophytes, which can thrive in environments with high salinity. This practice enhances the diversity of plant species in saline ecosystems, contributing to overall biodiversity. The development and cultivation of these salt-tolerant varieties must be coupled with the preservation of traditional biodiversity. For instance, utilizing indigenous plants that have co-evolved with local saline conditions can strengthen ecosystem resilience and adaptability [15].

4. Prospects

The increasing problem of soil salinization is seen as a major challenge for the environment and economy globally, and it is expected to worsen due to projected climate change [16]. Soil salinity problems can arise in various climates, including both natural and human-influenced conditions, but are most common in dry areas where there is not enough rainfall to wash away salt build-up from the plant's root zone, whether from irrigation or rain. To establish a sustainable and productive agricultural system that ensures food security for the future, it is essential to prioritize certain key areas of saline agriculture. (1) Soil salinity mapping: The rising extent of soil salinity poses a significant worldwide risk to agricultural production, as soil degradation hinders efforts to achieve food security. The expansion of saline soils is also attributable to the increased utilization of marginal waters for irrigation purposes. The reduction in the availability of freshwater has prompted the adoption of treated wastewater or low-salinity water for irrigation, thereby contributing to the expansion of saline soils [17]. We urge that priority be given to the development of remote sensing instruments for future satellite missions that focus on observing spatial and temporal changes in land degradation, including soil erosion and salinity, on a global scale. (2) Improving soil salinity management practices: Optimal soil salinity management is key to sustaining irrigated agriculture. Salinity management options have expanded beyond the provision of essential field drainage to include new technologies in irrigation practices, drainage, soil and crop monitoring, and model prediction. The advancement of precision irrigation (PI) is largely contingent upon the development of cost-effective technologies that integrate soil moisture, salinity, and nutrient measurements within a cloud-based multi-sensor platform [18]. (3) Reassessment of crop salt tolerance: The tolerance of crops to soil salinity varies considerably. The physiological response of crops to salinity is associated with two processes: osmotic and specific ion effects. Key genes for control of Na^+ and Cl^- uptake from a saline soil, their transport throughout the plant, and their sequestration within cells have been identified [19]. Although soil saturation extracts were of considerable value in the past, they do not necessarily represent in situ root zone salinity. Furthermore, there is significant uncertainty regarding how the plant integrates multiple stresses across the rooting zone and during its growing season, representing a significant knowledge gap [20]. (4) Improved understanding of the combined and interactive effects

of crop drought and salinity stress: Drought and salinity are the two most prevalent abiotic stressors in agricultural crops, and their simultaneous occurrence is relatively common in irrigated fields. Despite their simplicity, empirical reduction functions are useful tools for studying the impacts of drought and salinity stresses on large-scale hydrological models. Currently, detailed process-based approaches are available, which can be used to improve our understanding of how combined water and salinity stresses impact plant transpiration and growth [21,22]. (5) Effects of salinity and sodicity on soil physical properties: In many salt-affected regions where sodium salts are prevalent, salinity and sodicity are inter-related, yet they exert distinct effects on the soil. There is a paucity of research quantifying dynamic soil hydraulic properties, including soil water retention, hydraulic conductivity, solute transport, and soil aeration properties and processes, as influenced by changing soil salinity and sodicity. This is particularly evident when considering the complex nature of soil structure degradation, which is controlled by numerous additional soil properties beyond soil salinity and sodicity alone [23,24]. (6) Limitations and opportunities of using non-conventional water sources for irrigation: It is imperative that irrigated agriculture expands, and that new water sources, which were previously deemed “marginal” (e.g., saline, treated wastewaters, and desalinated water), are employed to meet the growing demands of the future. It is inevitable that the projected intensification of irrigated agriculture in areas utilizing marginal quality water will affect pre-existing fragile environments and threaten the overall sustainability and functionality of these agro-ecosystems [25]. The challenge for the future is to devise strategies that increase food production while simultaneously preserving soil ecological functionality, minimizing human health risks and promoting the sustainable use of our land and water resources for agricultural use [26].

The identification of knowledge gaps and priority needs in saline agriculture will facilitate the allocation of research funding for the advancement of knowledge and innovative solutions. Furthermore, it is our intention to encourage the scientific community to pursue new avenues of salinity research that address the gaps identified by our synthesis.

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Article

Effect of Different Fertilization Measures on Soil Salinity and Nutrients in Salt-Affected Soils

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Abstract: Saline soil from the coast is a valuable and readily available resource. It is also a valuable resource for reserving arable land. Adding organic fertilizers to salinized soils is an effective method of enhancement. However, saline soils cannot be improved using a single measure, and the effects of compound measures of organic fertilizers combined with mineral elements, such as humic acid, are significant and worthy of further examination. To explore the effects of various measures on the features of pH, electrical conductivity (EC), and nutrient changes in coastal salinized soils in Yancheng, Jiangsu Province, a ryegrass–alfalfa rotation with organic fertilizer and compound measures was designed. The findings indicated that the total nitrogen (TN) content of the soil increased and that all organic fertilizer composites decreased the electrical conductivity of the surface soil. However, the organic fertilizer with microbial fertilizer and humic acid was especially effective at regulating the pH and electrical conductivity of the surface soil when salts were prone to accumulation. In conclusion, our findings highlight new approaches to lowering salinity and boosting fertility in coastal saline soils: organic fertilizer with microbial fertilizers and humic acid, as well as organic fertilizer with attapulgitic clay.

Keywords: microbial fertilizer; humic acid; attapulgitic clay; soil fertility; soil salinity

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1. Introduction

Approximately 1 billion ha of the global land surface is currently salt-affected, representing about 7% of the earth's land surface. Whereas most of it results from natural geochemical processes, an estimated 30% of irrigated lands globally are salt-affected as a result of secondary human-induced salinization [1]. Although the net changes in soil salinity and the total area of salt-affected soils are highly variable, geographically speaking, the continents with the most salt-affected areas are Asia (particularly China, Kazakhstan, and Iran), Africa, and Australia [2]. One-third of the world's saline soils are located in China, where their total area is estimated to be 3.69 million hm² [3]. The greatest barrier to producing agricultural land in coastal beach reclamation zones in salinized coastal areas is soil salinity. Saline soils have a high concentration of soluble salts, poor soil physicochemical characteristics, low soil enzyme activity, and sluggish nutrient release, which impacts plant nutrient absorption and upsets the nutrient uptake balance mechanism, lowering crop production and quality [4–6]. Different technical methods, including physical, hydrological, chemical, biological, and integrated remediation strategies, can be used to regulate soil salinity [7]. The physical measures include no tillage, subsoiling, rotary and ridge tillage [8], subsurface drainage [9], etc.; the chemical measures include the application of chemical amendments or mineral fertilizers such as flue-gas desulfurization gypsum [10] and sulfur [11], etc.; and the biological measures include earthworm inoculation [12], plant planting [13,14], and the application of microbial fungicides [15].

It has been shown that adding soil amendments and inorganic or mineral additions can improve physical and chemical properties of saline soils [16]. Of these, biochemical measures involving the application of organic matter such as farmyard manure, straw, and gray manure are generally considered the most economical and effective measures, as they can increase soil porosity, reduce salt accumulation, and mitigate salt damage, and have a significant impact on the management of saline soils [17–20]. Saline soils are becoming increasingly problematic, and the long-term application of organic fertilizers leads to the accumulation of soil salts, so some organic materials are selected to be compounded with organic fertilizers to improve the physical and chemical properties of saline soils.

Attapulgite clay (ATP) is rod-shaped and fibrous, with pores running through its layers and a concave–convex appearance. It has a large specific surface area and high thermal stability, showing good adsorption and ion exchange properties [21,22]. Slow-release fertilizer with attapulgite clay was used as the core material for slow release and water retention [23]. It has been established that attapulgite clay reduced soluble Na ions in soil via electrostatic attraction and a cation exchange [24]. Polyacrylamide (PAM) improves soil structure, water content, pH, and organic matter stability when combined with other amendments [25]. Humic acid is the predominant component of soil organic matter and is a type of brown or black amorphous macromolecular colloidal complex generated following complex modifications in plant and animal wastes [26]. According to several investigations, humic acid combined with inorganic fertilizers lowered the soil pH in coastal saline soils [27]. Meanwhile, bio-fertilizers improve soil physical and chemical qualities [28]. One study [29] showed that humic acid application increases soil salinity in addition to increasing soil water content and wheat yield, and PAM [30] and attapulgite clay [24] application reduces soil salinity, but the effect of PAM and attapulgite clay in combination with other additives has not been thoroughly tested under field conditions. Additionally, organic fertilizers [31] can reduce soil salinity, so we selected these measures to better improve saline soils and provide greater economic benefits. To verify that comprehensive measures would be more advantageous for improving coastal saline soils, we conducted a one-year field trial of organic fertilizers in combination with multiple soil amendments in the Jiangsu Province to investigate the synergistic effects of various amendment materials and organic fertilizers on coastal saline soils and provide technical support for the improvement of coastal saline soil.

2. Materials and Methods

2.1. Overview of the Study Site

The field experiment was performed in the Dafeng District of Yancheng City, Jiangsu Province, China. The climate of the research region is subtropical, influenced by transitional, oceanic, and monsoon winds, with significant seasonal temperature and rainfall changes. The area's average year-round temperature is 14.4 °C, with 1066.7 mm of precipitation—almost 70% of which falls between June and September—and 2214.4 h of sunlight. Figure 1 depicts an overview map of the research area. Table 1 displays the basic soil parameters in the study region. Figure 2 depicts Dafeng's precipitation and mean temperature from November 2020 to December 2021. Precipitation and average temperature data were obtained from <https://www.tianqi24.com/dafeng/history2020.html> (accessed on 12 September 2023) and <https://www.tianqi24.com/dafeng/history2021.html> (accessed on 12 September 2023).

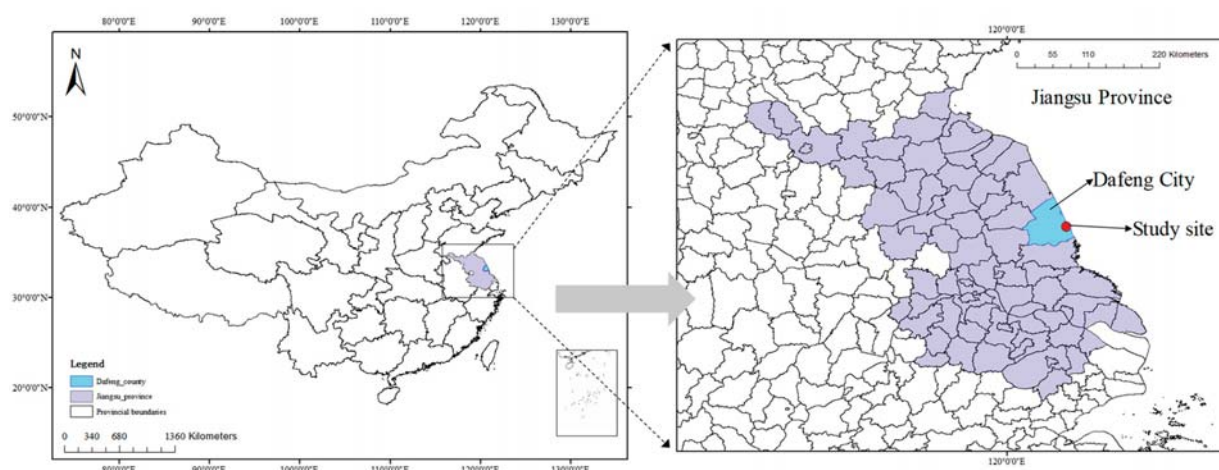


Figure 1. Overview map of the study area.

Table 1. Basic properties of the original topsoil (0–20 cm) used for the experiment.

	pH	EC ($\mu\text{S}/\text{cm}$)	SOM (%)	TN (g/kg)
CK	8.54	844.40	0.63	0.50
CK0	8.46	567.03	0.59	0.37
N	8.43	1037.33	0.64	0.38
NA	8.29	1166.00	0.68	0.57
NF	8.21	898.77	0.73	0.52
NP	8.44	774.53	1.05	0.58
NFE	8.43	861.63	0.79	0.64

Notes: EC—electrical conductivity; SOM—organic matter content; TN—total nitrogen. CK, CK0, N, NA, NF, NP, NFE are the different treatment labels, representing the no fertilizer treatments, conventional fertilizer, organic fertilizer, organic fertilizer + attapulgite clay treatment, organic fertilizer + humic acid treatment, organic fertilizer + PAM treatment, organic fertilizer + humic acid + ETS biofertilizer treatment.

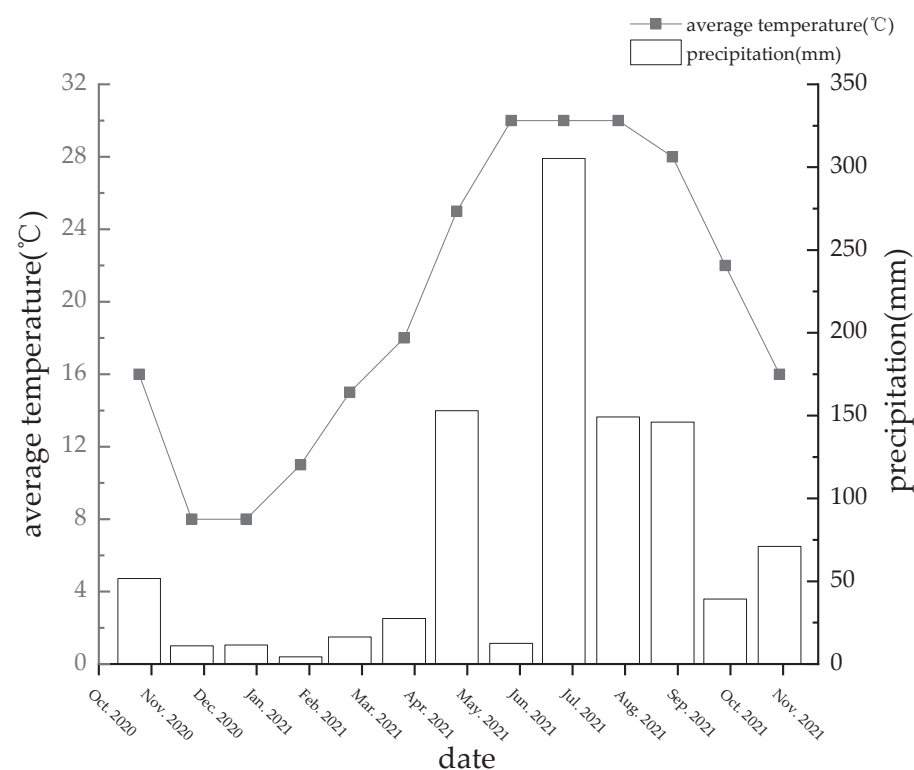


Figure 2. Monthly precipitation and average temperature in Dafeng.

2.2. Experimental Treatments and Sample Collection

This experiment involved seven treatments, each with three replications, for a total of 21 plots. The treatments were no fertilizer (CK), conventional fertilizer (CK0), organic fertilizer (N), organic fertilizer + attapulgite clay treatment (NA), organic fertilizer + humic acid treatment (NF), organic fertilizer + PAM treatment (NP), organic fertilizer + humic acid + ETS biofertilizer treatment (NFE). The area of each plot in this experiment was 20 m², and the NA treatment used 75 kg of attapulgite clay and 10 kg of organic fertilizer; the NF treatment used 100 kg of humic acid and 10 kg of organic fertilizer. For the NP treatment, 10 kg of organic fertilizer and 100 g of PAM were used. For the NFE treatment, 10 kg of organic fertilizer, 100 kg of humic acid, and 4.8 kg of biofertilizer were used. Exclusively commercial organic fertilizers were used in this experiment. Ryegrass was planted from November 2020 to June 2021, while alfalfa was planted from June 2021 to November 2021. Nitrogen was sprayed at a rate of 225 kg/hm² for each planting season, and each treatment (except for the control treatment—CK) was set up with a constant amount of nitrogen fertilizer based on its existing nitrogen content. Soil samples were taken from the 0–100 cm soil layer in November 2020, ryegrass was harvested and alfalfa was planted in June 2021, and soil samples were taken from the 0–100 cm soil layer in November 2021, then from the 0–20 cm soil layer in the remaining months. There are no irrigation systems accessible in the study region, which relies on precipitation to replenish water.

2.3. Soil Testing Methods

Soil electrical conductivity (EC) and pH were determined using a METTLER TOLEDO conductivity meter (Shanghai, China) and a METTLER TOLEDO pH meter (Shanghai, China) using 1:5 (*w/v*) soil: water suspensions. Soil moisture content was determined via the drying method. Organic matter (SOM) was evaluated by oxidizing the soil sample with potassium dichromate and heated using an external heating method, followed by titration with a ferrous sulfate reference solution. The total nitrogen was determined using an element analyzer (DeChem-Tech Company Fully Automated Intermittent Chemistry Analyser, Hamburg, Germany) [32].

2.4. Statistical Analysis

Data were processed using SPSS version 26.0 and subsequently presented as mean $\pm$ standard deviation. Any significant differences between treatments were determined via one-way analysis of variance (ANOVA). Post hoc tests were performed using Duncan's method with a significance level of $p < 0.05$.

3. Results

3.1. Effect of Different Fertilization Measures on Soil Salinity and Water Content

3.1.1. Effect of Different Fertilization Measures on Soil Salinity in the 0–20 cm Soil Layer

The electrical conductivity in different periods could reflect the trend of soil salinity [33]. Although the initial salinity values in the 0–20 cm soil layer differed significantly between treatments, the soil salinity tended to be similar in all treatments by November 2021. Treatments NFE, NP, NF, NA, and N all significantly reduced EC in the 0–20 cm soil layer compared to CK from November 2020 to November 2021, with treatment NA being the most successful, reducing EC by 56.6%, 39.3%, 64.9%, 124.3%, and 97.2%, respectively, compared to CK0. During this time period, all treatments showed an overall decline, most noticeably from November 2020 to December 2020, with treatment NA showing the most pronounced decrease with the exception of a tiny increase in April 2021 (Figure 3). The soil EC values of all treatments rapidly reduced in December 2020, and when compared to CK0, all composite treatments had better reduction efficiency, with treatment NA having the best reduction efficiency. Since less precipitation occurred from January 2021 to June 2021, the top layer of soil was more prone to salt formation, and NFE had a salt suppression impact compared to CK0 and other treatments during this time period. In summary, all treatments except for NF effectively declined soil EC in the 0–20 cm layer by June 2021. During the

process, NA showed the best reduction efficiency, followed by treatment NFE and N. From June 2021 to November 2021, salinity in all treatments was maintained within a relatively safe range when crop growth was not affected by salts.

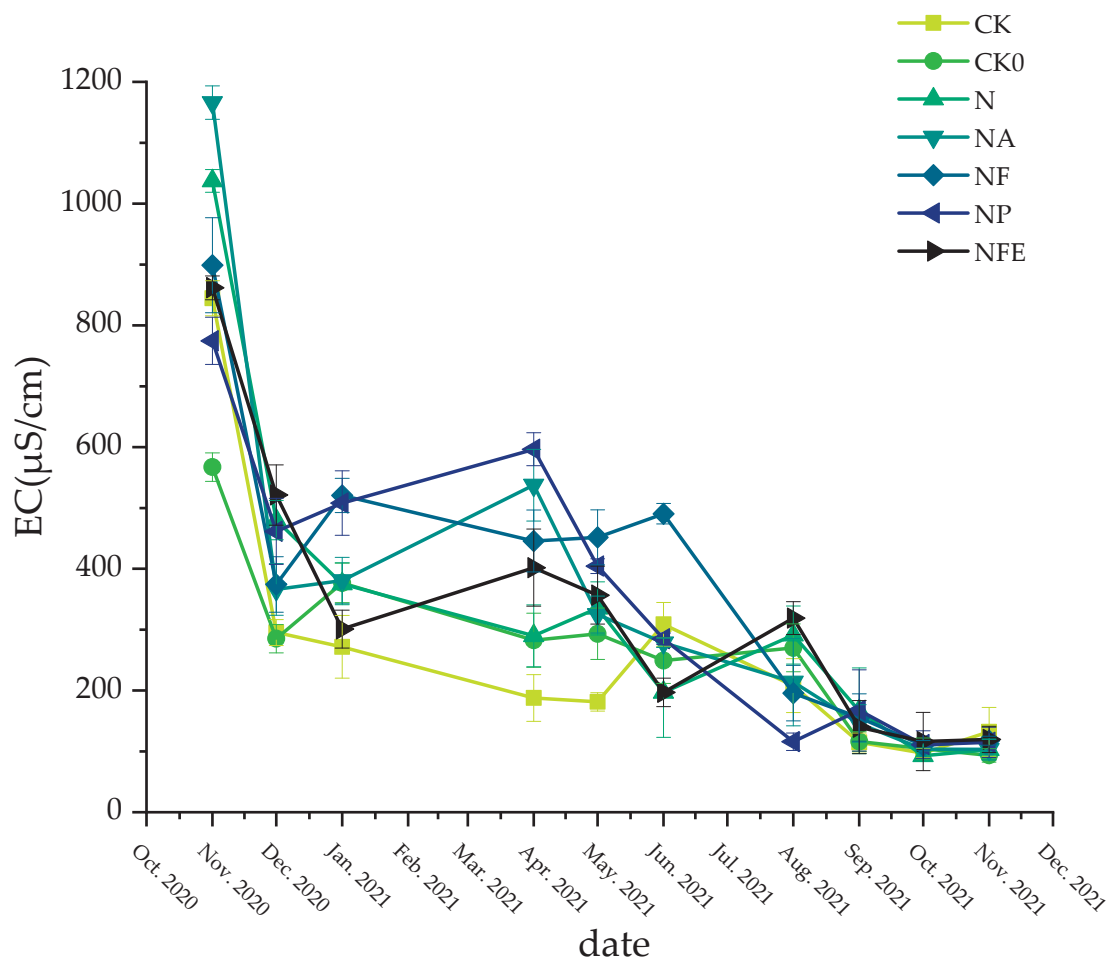


Figure 3. Effect of organic fertilizer compound treatments on EC in the 0–20 cm soil layer. Error bars indicate one standard deviation from the mean.

3.1.2. Effect of Different Fertilization Measures on Soil Salinity in the 20–40 cm Soil Layer

Treatments NP, NF, and N significantly reduced soil salt content in the 20–40 cm soil layer compared to CK0 from November 2020 to November 2021, with N having the most significant effect. However, in the 20–40 cm soil layer, all treatments reduced soil salinity by November 2021 (Figure 4). Compared to CK0, treatments NP, NF, and N significantly lowered the soil EC by 111.2%, 123.0%, and 235.6%, respectively. All treatments exhibited a considerable increase in soil salt content from November 2020 to December 2020, as salinity in the 0–20 cm soil layer decreased in December 2020, allowing salts to leach into the 20–40 cm soil layer. In June 2020, when precipitation was significantly lower than in May, treatment NF showed a decrease in May and an increase in June, which did not occur for the other treatments, indicating that treatment NF had no inhibitory effect on salinity during the period in which salts were prone to accumulate. There was an overall declining trend in the EC values of the treated NFE from January 2021 to June 2021, demonstrating the effect of salt suppression. In summary, the EC of all the treatments was controlled below 600 µS/cm except for NF treatment, for which crop growth could not be affected by salts. From June 2021 to November 2021, the salinity of all the treatments was reduced to very low values.

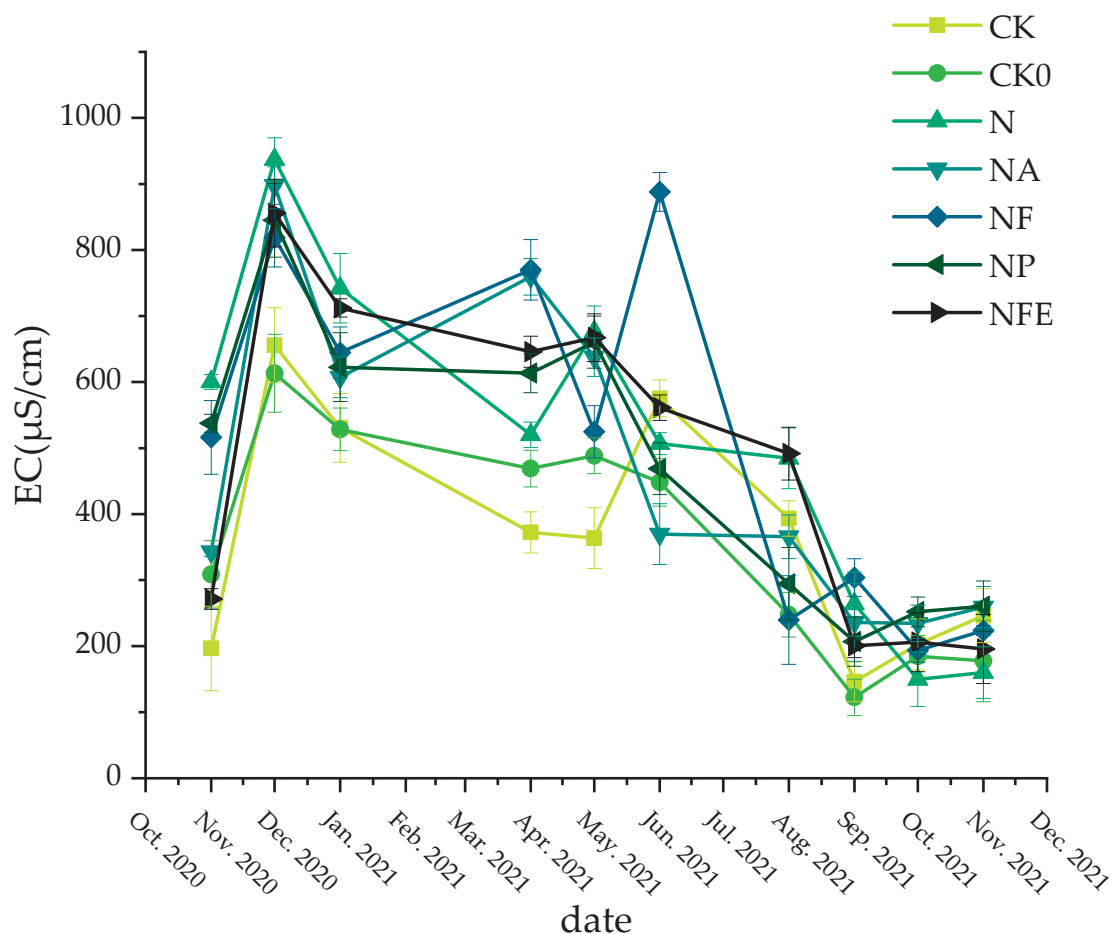


Figure 4. Effect of organic fertilizer complex treatments on EC in the 20–40 cm soil layer. Error bars indicate one standard deviation from the mean.

3.1.3. Effect of Different Fertilization Measures on Soil Salt Content in the 0–100 cm Soil Layer

The soil salinity in the 0–20 cm soil layer reduced significantly from November 2020 to November 2021, whereas the salinity in the 80–100 cm soil layer increased in all cases. Although there were some differences in the initial values of soil salinity in each treatment's 0–100 cm soil layer, the distribution of the soil salinity content was basically the same in November 2020 and June and November 2021. The soil EC in the 20–40 cm soil layer of each treatment in November 2020 exhibited a significant decrease compared to the soil salinity content in the 0–20 cm soil layer, followed by a significant decrease in the soil salinity content in the 0–20 cm soil layer. The soil EC of the 40–60 cm soil layer, the 60–80 cm soil layer, and the 80–100 cm soil layer reduced more slowly. In June 2021, the soil EC in the 20–40 cm soil layer of each treatment was greater than that in the 0–20 cm soil layer, and the soil salinity steadily declined as the soil depth increased. NP, NA, and NFE resulted in a gradual increase in salinity content in the 0–60 cm soil layer, while the soil salinity content in the 60–80 cm soil layer decreased. Meanwhile, CK, CK0, N, and NF led to a gradual increase in salinity content in the 0–80 cm soil layer and a decrease in salinity content in the 60–80 cm soil layer (Figure 5). NF treatments were ineffective with regard to controlling soil salinity in the profile by June 2021, and the remaining treatments successfully reduced the salinity in the 0–40 cm soil layer. By November 2021, the soil salinity was leached to the deeper layer, and the salinity of the upper soils was controlled in the lower values.

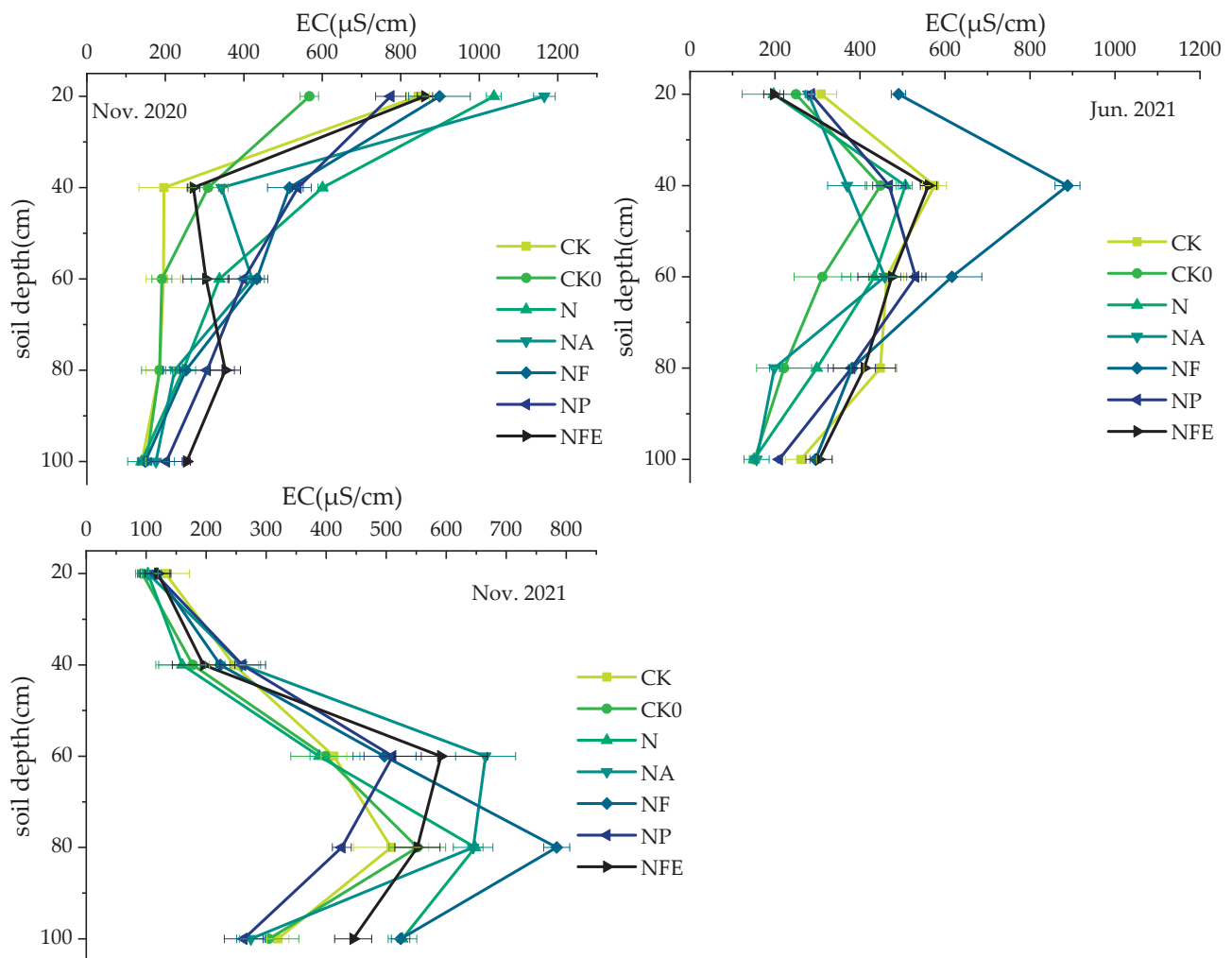


Figure 5. Effect of organic fertilizer compound treatment on EC in the 0–100 cm soil layer. Error bars indicate one standard deviation from the mean.

3.2. Effect of Different Fertilization Practices on Soil pH

3.2.1. Effect of Different Fertilizer Application Measures on pH in the 0–20 cm Soil Layer

The pH value of all treatments in the 0–20 cm soil layer increased slightly from November 2020 to November 2021, whereas treatment NA's pH increased dramatically. Throughout the trial period, the pH of all treatments fluctuated, but in September, October, and November 2021, the pH of all treatments decreased, then increased, and then decreased again. By October 2021, the pH of all treatments was over 9.00. The pH of treatments NFE, NP, and NA was considerably lower than that of CK0 from November 2020 to May 2021. Overall, the pH of treatments N, NP, and NFE increased less than that of the control treatment CK0. In December 2020, treatments N, NP, and NFE all exhibited a falling trend, while the remaining treatments showed a slight increase (Table 2). Treatments NA, NF, NP, and NFE had considerably lower pH than CK0 from December 2020 to November 2021. Overall, all the treatments improved the pH compared to its initial value, but it remained lower than the value resulting from the CK0 treatment.

Table 2. Effect of different organic fertilizer compound treatments on soil pH in the 0–20 cm soil layer.

Treatment	Sampling Date									
	November 2020	December 2020	January 2021	April 2021	May 2021	June 2021	August 2021	September 2021	October 2021	November 2021
CK	8.54 ± 0.06 a	8.85 ± 0.08 a	8.95 ± 0.02 a	9.42 ± 0.04 a	8.83 ± 0.02 a	9.15 ± 0.05 a	9.28 ± 0.03 b	8.96 ± 0.01 b	9.39 ± 0.02 a	8.64 ± 0.03 a
CK0	8.46 ± 0.02 b	8.68 ± 0.08 b	8.39 ± 0.05 c	8.6 ± 0.04 c	8.66 ± 0.04 bc	8.54 ± 0.05 c	9.37 ± 0.02 a	8.85 ± 0.04 c	9.38 ± 0.04 a	8.65 ± 0.03 a
N	8.43 ± 0.04 b	8.37 ± 0.05 d	8.73 ± 0.02 b	8.83 ± 0.03 b	8.57 ± 0.11 cd	8.85 ± 0.05 b	9.05 ± 0.05 d	8.72 ± 0.03 d	9.42 ± 0.04 a	8.52 ± 0.07 b
NA	8.29 ± 0.08 c	8.15 ± 0.03 e	8.32 ± 0.04 d	8.52 ± 0.02 c	8.40 ± 0.02 e	8.56 ± 0.03 c	9.10 ± 0.02 c	8.98 ± 0.03 b	9.15 ± 0.03 b	8.61 ± 0.02 a
NF	8.21 ± 0.04 c	8.55 ± 0.01 c	8.25 ± 0.02 e	8.28 ± 0.02 d	8.71 ± 0.03 b	8.86 ± 0.03 b	8.67 ± 0.01 e	8.65 ± 0.02 e	9.38 ± 0.05 a	8.47 ± 0.02 b
NP	8.44 ± 0.02 b	8.06 ± 0.03 e	8.16 ± 0.02 f	8.29 ± 0.02 d	8.55 ± 0.04 d	8.51 ± 0.04 c	9.38 ± 0.01 a	9.05 ± 0.02 a	9.21 ± 0.04 b	8.46 ± 0.04 b
NFE	8.43 ± 0.04 b	8.14 ± 0.05 e	8.27 ± 0.04 de	8.57 ± 0.11 c	7.99 ± 0.07 f	8.86 ± 0.02 b	9.07 ± 0.02 cd	8.83 ± 0.02 c	9.00 ± 0.04 c	8.52 ± 0.03 b

Note: Different letters in the same column indicate significant differences between the two groups ($p < 0.05$).

3.2.2. Effect of Different Fertilizer Applications on pH in the 20–40 cm Soil Layer

In all treatment groups except for the CK group, the pH of the 20–40 cm soil layer increased during the experiment, and the increase in pH for N, NA, NF, NP, and NFE was greater than that of CK0, with treatment NF showing the biggest increase in pH, followed by treatment N. In December 2020, the pH of all treatments decreased considerably. With the exception of January and April 2021, the pH of treatment NF was significantly lower than CK0 from October 2020 to October 2021, and the pH of treatment NP was significantly lower than CK0 (Table 3). Overall, all the treatments improved pH compared to the initial pH value, but all values remained lower than that of the CK0 treatment. By November 2021, the pH of treatment NP was at its lowest, followed by NA and NFE. In summation, treatment NP, NA, and NFE performed better in terms of soil pH reduction in the 20–40 cm soil layer.

Table 3. Effect of different organic fertilizer compound treatments on soil pH in the 20–40 cm soil layer.

Treatment	Sampling Date									
	November 2020	December 2020	January 2021	April 2021	May 2021	June 2021	August 2021	September 2021	October 2021	November 2021
CK	9.32 ± 0.03 a	8.37 ± 0.03 b	8.64 ± 0.05 a	9.17 ± 0.04 a	8.88 ± 0.02 a	8.72 ± 0.01 a	9.26 ± 0.02 a	9.57 ± 0.06 a	9.14 ± 0.03 bc	9.27 ± 0.01 a
CK0	8.94 ± 0.02 b	8.50 ± 0.04 a	8.29 ± 0.01 cd	8.23 ± 0.04 e	8.68 ± 0.03 b	8.53 ± 0.05 b	9.29 ± 0.04 a	9.28 ± 0.03 b	9.18 ± 0.02 b	9.07 ± 0.05 b
N	8.45 ± 0.04 d	8.23 ± 0.01 c	8.25 ± 0.02 de	8.74 ± 0.03 b	8.33 ± 0.06 f	8.73 ± 0.05 a	8.21 ± 0.04 c	8.74 ± 0.03 e	8.94 ± 0.02 d	9.08 ± 0.01 b
NA	8.39 ± 0.04 e	7.96 ± 0.03 e	8.47 ± 0.03 b	8.54 ± 0.03 c	8.56 ± 0.01 c	8.43 ± 0.03 c	9.16 ± 0.02 b	9.23 ± 0.04 b	9.36 ± 0.07 a	8.92 ± 0.07 c
NF	8.41 ± 0.04 de	8.16 ± 0.02 d	8.21 ± 0.04 e	8.05 ± 0.01 f	8.41 ± 0.03 de	8.45 ± 0.06 c	9.17 ± 0.05 b	8.75 ± 0.04 e	9.09 ± 0.05 c	9.11 ± 0.0 b
NP	8.36 ± 0.03 e	8.16 ± 0.03 d	8.35 ± 0.04 c	8.43 ± 0.03 d	8.35 ± 0.02 ef	8.25 ± 0.05 d	9.11 ± 0.01 b	8.95 ± 0.02 d	8.74 ± 0.02 e	8.74 ± 0.03 d
NFE	8.70 ± 0.04 c	8.13 ± 0.03 d	8.32 ± 0.02 c	8.45 ± 0.05 d	8.44 ± 0.04 d	8.44 ± 0.03 c	9.15 ± 0.04 b	9.15 ± 0.03 c	9.09 ± 0.04 c	9.04 ± 0.05 b

Note: Different letters in the same column indicate significant differences between the two groups ($p < 0.05$).

3.2.3. Effect of Different Fertilization Measures on Soil pH of 0–100 cm Soil Layer

The initial pH values in the 0–100 cm soil layer varied significantly between the treatments, with NF, NA, and N showing a similar trend of increasing pH as the soil layer deepened. NFE, CK0, and CK treatments led to a similar increase in pH in the 20–40 cm soil layer and a reduction in the pH as the soil layer deepened from 40 to 100 cm. NP induced a 20–40 cm soil layer decrease, and after the 40 cm soil layer, the pH after NP treatment was lower. For treatments combined with compound treatment of organic fertilizer, the pH in the 0–80 cm soil layer was less than that of CK0, whereas the pH in the 80–100 cm soil layer was greater than that of CK0. By June 2021, the trend in the pH variation in different soil layers for all treatments was basically the same, with pH falling and then increasing as the soil layer deepened. The pH values for treatments NA and NP were slightly higher than that of CK0 in the 80–100 cm soil layer but lower than CK0 in the 0–80 cm soil layer, whereas the pH values for treatments NF and NFE were higher than CK0 in the 0–20 cm soil layer but lower than CK0 in the 20–100 cm soil layer. In November 2021, the pH in the 0–100 cm soil layer for treatments NA, NP, and NFE was less than CK0, with the exception of treatment NP in the 20–40 cm soil layer. In summary, compound treatments of NP, NA, and NFE decreased the soil pH in the 0–80 cm soil layer (Figure 6).

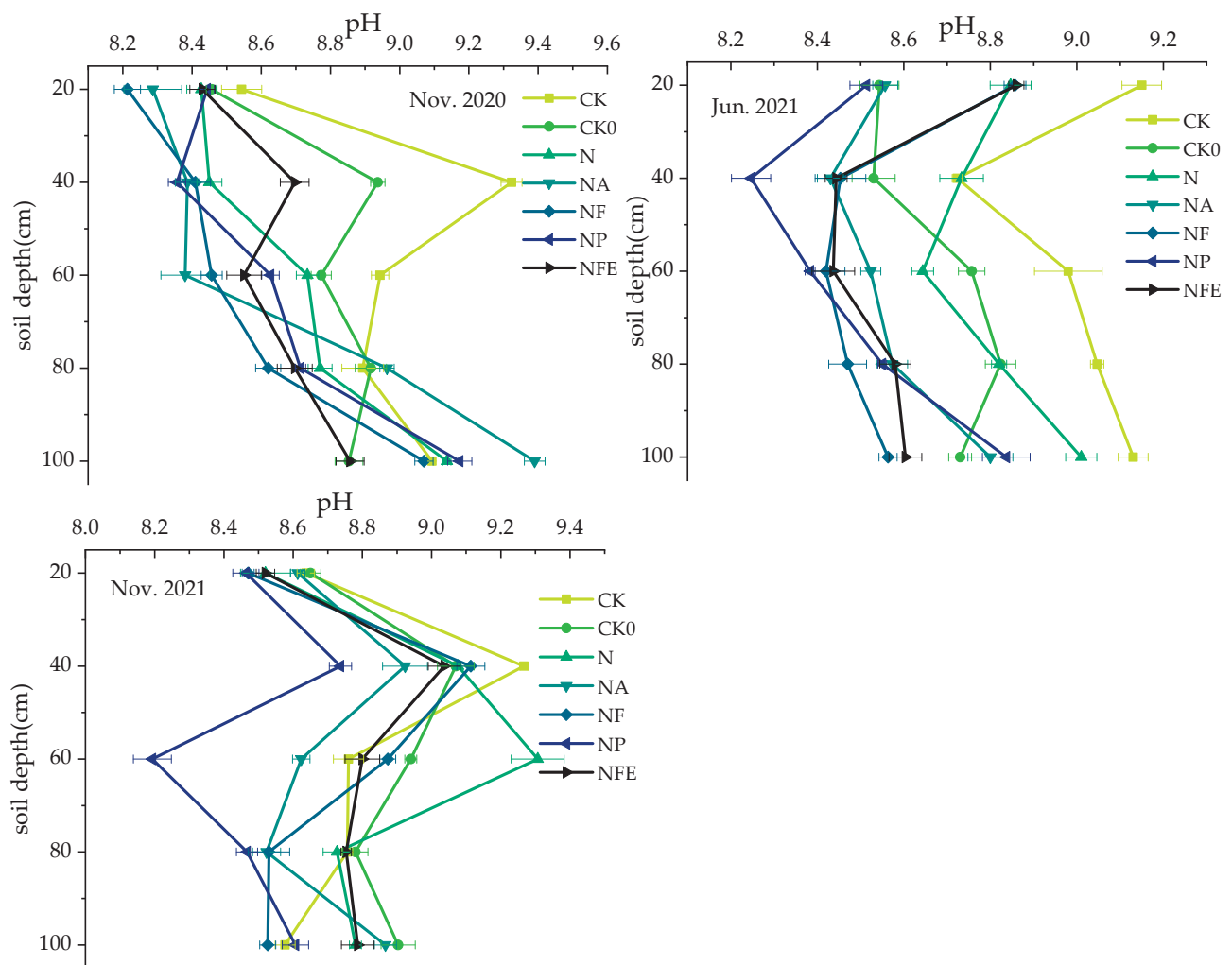


Figure 6. Effect of organic fertilizer compound treatment on pH in the 0–100 cm soil layer. Error lines indicate one standard deviation from the mean.

3.3. Effect of Different Fertilization Practices on Top Soil Moisture

After four months of testing, the soil water content after various treatments was not significantly different from that of CK0 in March 2021, but after nearly one year of testing, NA and NF treatments led to significantly higher soil water content than CK0 in September 2021, whereas N, NP, and NFE treatments resulted in no significant difference compared to CK0. Overall, treatments NA and NF retained the most water (Figure 7).

3.4. Effects of Different Fertilization Practices on Soil Nutrients

3.4.1. Effect of Different Fertilizer Application Measures on Soil Organic Matter

The initial value of soil organic matter (SOM) in all treatments showed no significant difference except for treatments of NP and NFE. By November 2021, the SOM of treatments of NA, NF, and NFE was much greater than that of CK0, while the SOM of NP treatment was significantly lower. The SOM following treatments with NA and NF increased by 34.4% and 148.1% compared with that of CK0, respectively, while the SOM after NFE treatment was lower (Figure 8). Compared to CK0, treatments NA and NF significantly increased soil SOM, while treatments N and NP decreased it, but the SOM of treatment NFE remained basically unchanged, ensuring the stability of the organic matter.

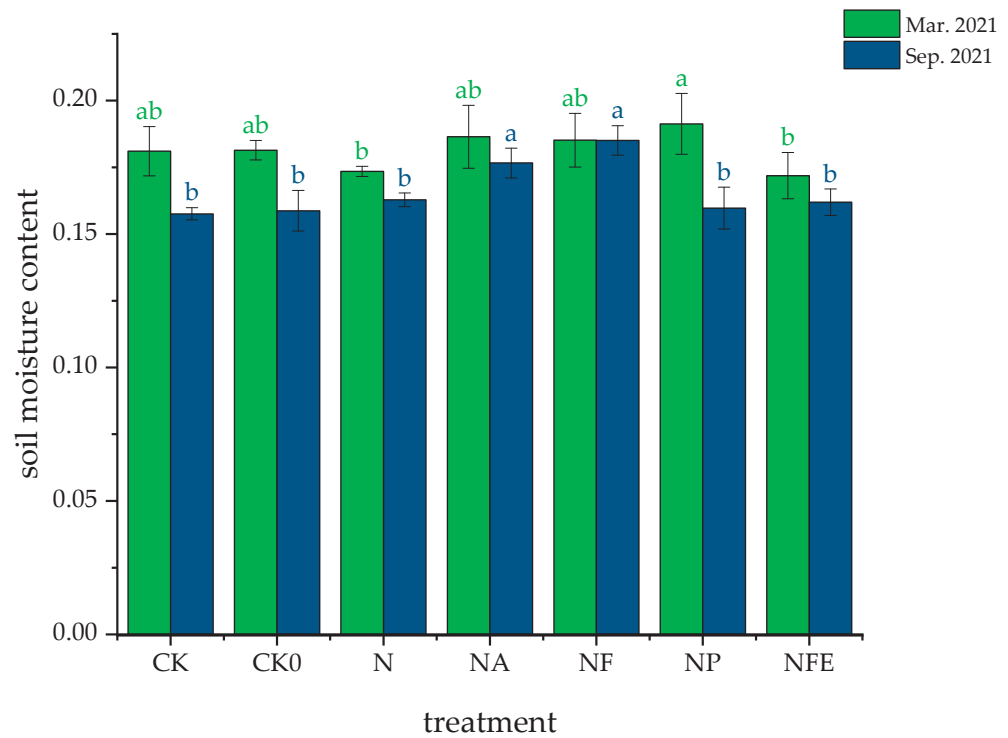


Figure 7. Effect of organic fertilizer compound treatments on soil water content of the 0–20 cm soil layer. Error bars indicate one standard deviation from the mean. Notes: The different colors represent various groups. Different letters of the same color indicate significant differences between treatments ($p < 0.05$).

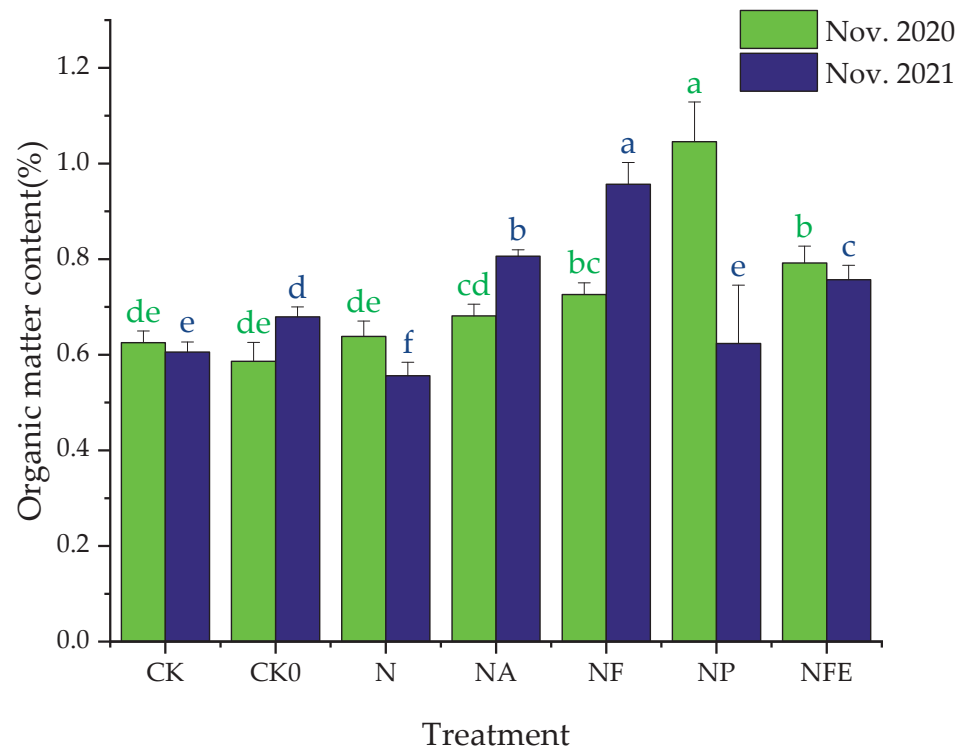


Figure 8. Effect of organic fertilizer compound treatments on the organic matter content of the 0–20 cm soil layer. Error bars indicate one standard deviation from the mean. Notes: The different colors represent various groups. Different letters of the same color indicate significant differences between treatments ($p < 0.05$).

3.4.2. Effect of Different Fertilization Measures on Soil Total Nitrogen

The pattern of change in SOM and TN content in the 0–20 cm soil layer was consistent across all treatments. In November 2021, the soil TN content increased significantly during all treatments, and the increase in TN in all composite treatments was noticeably higher than that of CK0, with treatment NA leading to a significantly greater increase than other treatments. Overall, the composite treatments greatly enhanced soil TN content, with the effect of the increase being $NA > NF > NFE > NP$ (Figure 9).

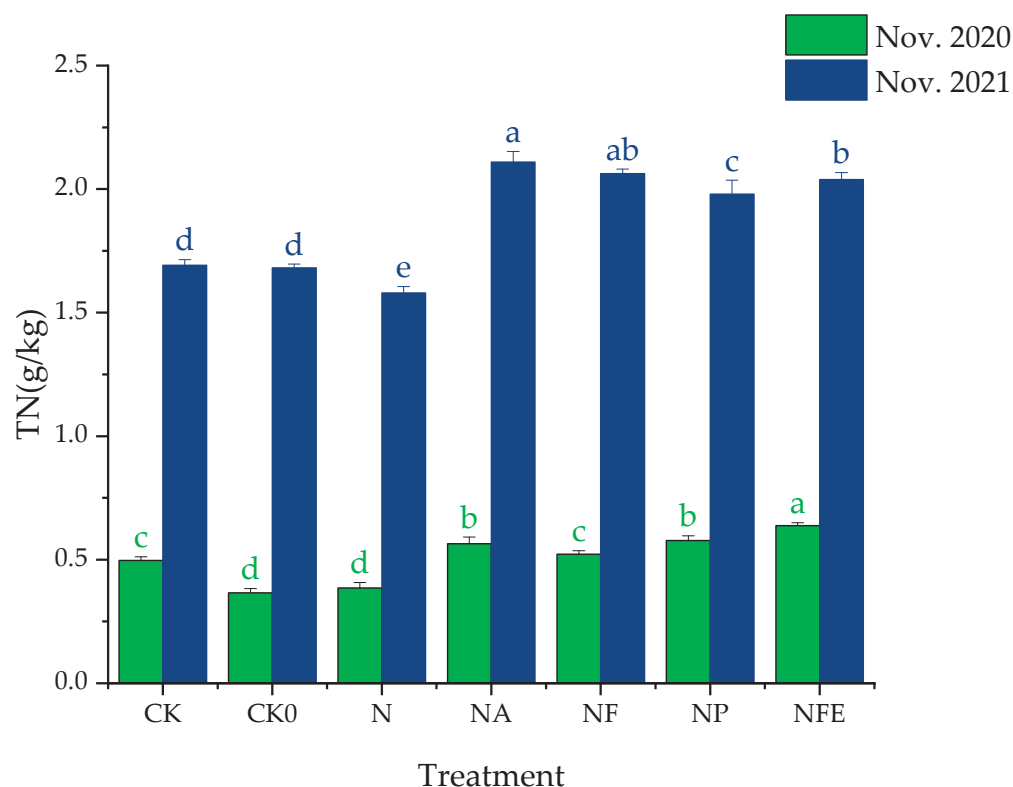


Figure 9. Effect of organic fertilizer complex treatments on the total nitrogen content of the 0–20 cm soil layer. Error bars indicate one standard deviation from the mean. Notes: the different colors represent various groups. Different letters of the same color indicate significant differences between treatments ($p < 0.05$).

4. Discussion

High salt concentrations can impede plant growth through nutritional imbalance, osmotic stress, and specific ion toxicity [34]. Soil salinity negatively affects crop yield and agricultural sustainability. Numerous studies have demonstrated that using organic fertilizers and chemical additions can not only reduce soil salinity but also increase saline soil fertility [35–37]. The field experiment described in this paper focused on how soil EC, pH, organic matter content, and total nitrogen content changed under the compound measures combined with organic fertilizer, humic acid, and other materials. Our findings contributed to the increasing amount of evidence indicating that the interaction of organic fertilizers with chemical additions altered the characteristics of saline soils and soil nutrients.

4.1. Effect of Different Fertilizer Applications on Soil Salt Content and pH

In this study, organic fertilizer and its compound measures effectively reduced the salt content in the 0–20 cm soil layer, with the organic fertilizer combined with attapulgite clay having the most noticeable impact. Organic fertilizer compounded with PAM and humic acid reduced the salt content of the soil's 20–40 cm layer; however, the effect of organic fertilizer compound treatment on reducing the salt content and pH of the deeper soil layer was not immediately obvious. Due to its excellent adsorption properties, attapulgite

clay [24] was also found to be suitable for lowering soil salinity. In the current study, an influence of Au-bearing rods on soil salt content was only identified in the 0–20 cm soil layer. This is largely because attapulgite clay can absorb Na^+ from the soil [24], reducing the salt concentration in the 0–20 cm soil layer considerably. Additionally, the attapulgite clay application increased the soil's ability to hold more water in the present study. In contrast with our findings, Zhao [38] showed that attapulgite clay significantly increased the pH value of the soil. This is most likely because the test area is significantly influenced by precipitation, and the application of attapulgite clay increased the soil's capacity to hold water. As a result, the application of attapulgite clay to the soil affects the pH value of the soil, particularly the pH value of the tillage layer.

According to research [30], the application of PAM can improve soil characteristics and decrease salinity. These findings are likely due to the fact that PAM not only improves soil surface particle cohesion, increases the content of soil aggregates >0.25 mm, improves soil stomatal structure and permeability, and inhibits the formation of soil crust [39], but also allows salts to percolate downwards and improves the water-holding capacity of the soil, reducing the salinity of the 0–40 cm soil layer. Liu [40] and Huang [29] discovered that humic acid can increase soil macroaggregates and reduce salinity in the soil tillage layer, which is consistent with the results of our experiment.

Humic acid lowered soil pH while increasing soil salinity [41–43], and the soil EC of organic fertilizer with humic acid slightly increased. Meanwhile, the pH of the treatment declined in the present study; a similar effect was observed in the previous study. However, when implemented together with biological fertilizer, the effect on EC and pH was affected, reducing the conductivity while regulating pH.

4.2. Effect of Different Fertilizer Application Measures on Soil Organic Matter

Soil organic matter is an important component and indicator of soil fertility [44]. Studies have shown that adding humic acid to salt-affected soils can significantly reduce salt stress and improve plant growth by improving nutrient availability and water retention, enhancing soil structure, and increasing microbial bioactivity [45,46]. Additionally, because humic acid is an important component of soil organic matter, the addition of humic acid in this study significantly increased the organic matter content of the soil. The use of attapulgite clay and organic fertilizer, on the other hand, can help to manage and improve the level of nutrients in the soil. Although attapulgite clay has not been proven to increase soil organic matter, organic fertilizer compounded with attapulgite clay increased soil organic matter significantly in this study, and I believe that attapulgite clay can accelerate the release of nutrients from organic fertilizer and fix nutrients in the soil, enhancing organic matter in the soil after ryegrass harvesting and alfalfa planting. Biofertilizer has also been shown to improve soil nutrients and increase soil organic matter [47,48], but the effect was less pronounced in this study—likely due to an antagonistic effect between biofertilizer and humic acid—and the two could not increase the soil organic matter when used together.

4.3. Effect of Different Fertilization Measures on Soil Total Nitrogen Content

Total soil nitrogen is another significant nutritional indicator. It has been demonstrated that humic acid increases total soil nitrogen [42], which is in agreement with our findings. Attapulgite clay treatment enhanced total soil N, and its application with organic material boosted total soil N considerably. The use of attapulgite clay increased soil agglomeration and created a protective coating, reducing the contact between the soil surface and air and, subsequently, reducing N loss [49]. I believe this to be the main contributor to the increase in total N content of the soil caused by the application of organic fertilizer that includes attapulgite clay. Organic fertilizer combined with microbial fertilizer and humic acid boosted total soil N in this experiment. Ma [50] found that biofertilizers had no discernible effect on total soil N, whereas some studies [44,45] found that biofertilizers could boost soil nutrients. I believe that biofertilizer with humic acid hastened the breakdown of organic

matter, which increased soil nutrients and the overall soil N content; this concurs with the results of this study.

5. Conclusions

This experiment demonstrated that organic fertilizer and other techniques may reduce the salinity of coastal saline soils, but they were still dependent on precipitation. Thus, composite measures effectively improved coastal saline soil due to the abundant precipitation in the coastal region of the Jiangsu Province. The study has shown that organic fertilizer containing attapulgite clay can reduce the salinity of coastal saline soil, increase soil nutrients, and control soil pH. Humic acid and microbial fertilizer implementation, together with organic fertilizer, can enhance soil total nitrogen and organic matter while lowering soil salinity and controlling the pH of the soil surface layer. In conclusion, the suggested compound measures of NA and NFE can regulate the salinity and pH of coastal saline soil while also improving soil fertility in the coastal saline soil. To deepen our understanding of the interaction between microbial fertilizers and humic acids, the processes by which humic acids affect the microorganisms in the fertilizers and the microorganisms in the soil are in need of further investigation. The current experiment was conducted over a one-year period, which is insufficient time to fully determine the influence of different organic fertilizer blending procedures on soil salinity and nutrients in land areas, and there are some limitations. This study was technical, lacked research on mechanisms, and did not consider nitrogen loss from saline soils. Future research will focus on nitrogen leaching and effective nitrogen use from saline soils, as well as on the mechanisms of the effects of fertilization measures on salinity and nutrients in saline soils.

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Conflicts of Interest: The authors declare no conflict of interest.

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Article

Effect of Straw Mulching and Deep Burial Mode on Water and Salt Transport Regularity in Saline Soils

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Abstract: To examine the impacts of various straw mulching techniques, this study used the indoor soil column test as the primary research method and the field test as the validation test on the salinity dynamics of saline and alkaline soils. The experiment in this study was designed with five treatments: SC means for straw covered on the soil surface; DB means for straw buried 40 cm below the soil surface; S1D1, S2D1, and S1D2 represent the ratio of soil surface cover to the amount of straw buried 40 cm below the soil surface as 1:1, 2:1, and 1:2, respectively. The results of the indoor soil column test showed that all kinds of straw mulching techniques could effectively reduce soil moisture evaporation, and the straw mulching and deep burial mode was more effective: after 45 days of evaporation, compared with that of CK, the cumulative evaporation of soil moisture were reduced by 29.61%, 27.49%, 37.87%, 65.85%, and 54.58% for SC, DB, S1D1, S2D1, and S1D2, respectively; the straw mulching and deep burial mode could reduce the soil evaporation intensity more effectively than the single-layer straw mulching mode: the mean soil evaporation rates of CK, SC, DB, S1D1, S2D1 and S1D2 after 45 days of evaporation were 1.27 mm/day, 0.90 mm/day, 0.92 mm/day, 0.80 mm/day, 0.43 mm/day, and 0.58 mm/day; various straw mulching techniques could inhibit the accumulation of salts in the surface soil and effectively regulate the distribution of salts in the soil profile, among which the straw mulching and deep burial mode had the best effect of salinity suppression: after 30 days of evaporation, the re-salinization levels of the 0–40 cm soil layer of SC, DB, S1D1, S2D1, and S1D2 were reduced by 66.78%, 43.08%, 33.95%, 92.04% and 45.94% compared with that in the CK, respectively; there was a significant positive correlation between cumulative evaporation of soil moisture and cumulative soil salinity, which implied that cumulative soil salinity increased with the increase in cumulative evaporation of soil moisture. The results of the field experiment justified the results of the indoor soil column test: after four months of evaporation, the field moisture contents of CK, SC, DB, S1D1, S2D1, and S1D2 in the 0–20 cm soil layer were 14.77%, 3.51%, 15.10%, 15.26%, 18.73%, and 2.94%, respectively; during the experimental period, the salt inhibition rate of SC, DB, S1D1, S2D1 and S1D2 in 0–20 cm soil layer were 35.46%, 44.76%, 50.98%, 54.80% and 37.30%, respectively. Therefore, in a comprehensive view, S2D1 treatment had the best effect of salt and vapor suppression on saline soil. This study is of great significance for the resource utilization of straw waste, the improvement of water utilization and efficiency, and the management of soil salinization.

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Keywords: straw; mulching and deep burial; soil evaporation; resalinization rate; desalinization rate

1. Introduction

Soil salinity is a major challenge to land resource utilization and agricultural productivity worldwide [1]. It is estimated that approximately 1.1×10^9 hectares (ha) of land

globally suffer from soil salinity [2], posing a significant threat to agricultural output, soil health, and food security [3]. Particularly in China, there are over 3.6×10^7 ha of salty soils that, with the right amelioration, have a substantial potential for use in agriculture. China has up to 1.01×10^6 ha of coastal saline soils, with the Yellow River Delta serving as a representative area. This region constitutes a relatively concentrated zone of saline soils in the country, encompassing 254,200 ha and accounting for about 42.3% of the total available area within the delta [4,5]. In this area, coastal saline land comprises more than 70% of the total landmass [6]. As soil salinization advances, it poses a growing threat to ecological balance and hampers sustainable development. The detrimental effects of soil salinization include diminished fertility, decreased microbial activity, and compromised soil structure, all of which significantly impede food production and agricultural progress [7]. According to the basic tenet that “salt follows water and water follows salt”, water-salt transfer in soil generally follows these two directions; therefore, a variety of factors, such as precipitation, soil texture, groundwater, and temperature, can affect how salty a soil is [8]. Therefore, it is crucial to properly manage soil water evaporation, reduce salt accumulation, and improve the soil’s physical and chemical qualities in order to increase soil water usage in the salty soils of the Yellow River Delta.

Artificial capillary barriers are natural barriers to soil water movement under unsaturated conditions and, when properly designed and installed, can improve crop water use efficiency [9]. It has been demonstrated that mulching with various materials can decrease soil water evaporation, increase the amount of stored soil water that is available for plants, and reduce salt buildup in the soil [10]. According to Yin et al. [11], ground cover can effectively reduce soil water evaporation while concurrently impeding salt accumulation on the surface. Straw is the most common organic mulch material in almost all climatic zones [12] and, when applied in the field, can improve soil water utilization by reducing soil evaporation and keeping soil temperatures in the right range for crop growth [13]. Carson et al. [14] discovered that mulching with crop residues resulted in a 10–20% increase in water use efficiency. A study conducted by Zhou et al. [15] revealed that straw mulching not only improved soil moisture retention and soil structure but also suppressed weed growth. According to a study written by Yang et al. [16] the utilization of 4–6 t/ha of straw mulch has been found to significantly improve soil physical conditions in tropical regions. This includes the protection of the topsoil. Based on field experiments, Huang et al. [17] found that straw mulch placed on the soil surface provides shade, reduces nonproductive water evaporation, and increases available water capacity. This efficiently prevents soil water evaporation and salt surface aggregation, which enhances the physical and chemical characteristics of the soil and increases the efficiency of soil water usage [18].

Deep incorporation of straw into the soil can enhance soil organic matter content, water holding capacity, and agroecological water use efficiency, thus ensuring stable crop yield while optimizing water and salt distribution in the tillage layer and promoting salt leaching [19]. Zhong et al. [20] demonstrated that the cumulative evaporation from the straw-amended treatment was only 36.9% to 49.79% of that from the homogeneous soils during soil evaporation. The distribution of soil moisture and salinity is substantially impacted by the way straw is incorporated. According to Wanfeng Zhan et al. [21], placing the straw layer at a depth of 35–40 cm increased soil water retention capacity by 17.1% and salt leaching rate by 7.6% on average. Based on field study results, Zhao et al. [22] added a straw layer improved salt leaching and reduced salt buildup around crop roots. Additional advantages of using deep straw include lowering soil pH, reducing particle density, and improving plant emergence, according to other researchers [23]. Furthermore, the thorough integration of straw into the soil can enhance the content of soil organic matter, thereby ensuring consistent crop yields [24]. This practice also facilitates the deceleration of water infiltration, as well as the optimization of water and salt distribution and soil structure within the tillage layer [25]. The integration of straw mulching and deep incorporation of soil strata substantially enhanced soil moisture at a depth of 0–40 cm and markedly

diminished salinity in the surface layer (0–20 cm). This amalgamation could potentially exemplify the optimal field management approach for crop cultivation on saline soils.

Although the effects of surface straw mulching and deep burial of straw layers on soil water content and salinity have been widely studied, there is little information on the interactive effects of these factors. Based on previous studies, this study proposed the straw mulching and deep burial model as a method for saline soils improvement, aiming to make the effect of evapotranspiration and salinity suppression on saline soils better, in order to improve the efficiency of saline soils improvement by returning straw to the field. The impacts of various straw mulching techniques on water and salt dynamics in saline soils were examined through laboratory soil column simulation experiments. Additionally, this study analyzed soil water and salt transport patterns under different treatments during the soil leaching and evaporation phases. The research further aimed to identify the most effective straw mulching methods for reducing evapotranspiration and suppressing salinity, ultimately enhancing water use efficiency and promoting the implementation of straw mulching technology for the improvement of saline lands.

2. Materials and Methods

2.1. The Soil Column Test

2.1.1. Test Materials

The soils for this experiment came from the Bohai Farm (37°79' N, 118°63' E) in Dongying Province, China. According to Kottek et al. [26], the region has a warm-temperate continental monsoon climate with mean annual evapotranspiration, precipitation, and air temperature readings of approximately 1982 mm, 552 mm, and 12 °C, respectively. Table 1 lists the major physicochemical characteristics of the soil before the experiment.

Table 1. Basic properties of soils used in the experiment.

Soil Type	TN (g/kg)	AP (mg/kg)	AK (mg/kg)	SOM (g/kg)	pH	EC ($\mu\text{s}/\text{cm}$)	SAR ($\text{mmol}_\text{c} \text{ L}^{-1}$) ^{0.5}	Total Salt (g/kg)	Bulk Densit (g/cm^3)
salted tidal soil	0.93	34.14	110.87	9.67	8.14	1735.5	13.1	6.4	1.39

Note: TN, total nitrogen; AP, available phosphorus; AK, available potassium; SOM, soil organic matter; EC, electrical conductivity; SAR, sodium adsorption ratio.

2.1.2. Test Setup

The experiment was conducted at the experimental station of the College of Resources and Environment, Shandong Agricultural University. This study utilized polyvinyl chloride (PVC) pipes to establish a 100 cm soil column with a 30 cm diameter for analyzing soil ecological processes. In order to ensure smooth infiltration of the soil water flow, a 10 cm layer of fine sand was first positioned at the bottom of the column. Subsequently, the bottom of the soil column was sealed with gauze and positioned in a plastic basin containing a 10 g/L saline solution to simulate the groundwater environment. Finally, based on the soil density of the test soil of about 1400 kg/m³, fill the soil layer by layer and tamp it down, each time filling about 5 kg, tamping about 5 cm thickness, the previous tamping and then filling the next layer until the top. The detailed experimental setup is illustrated in Figure 1.

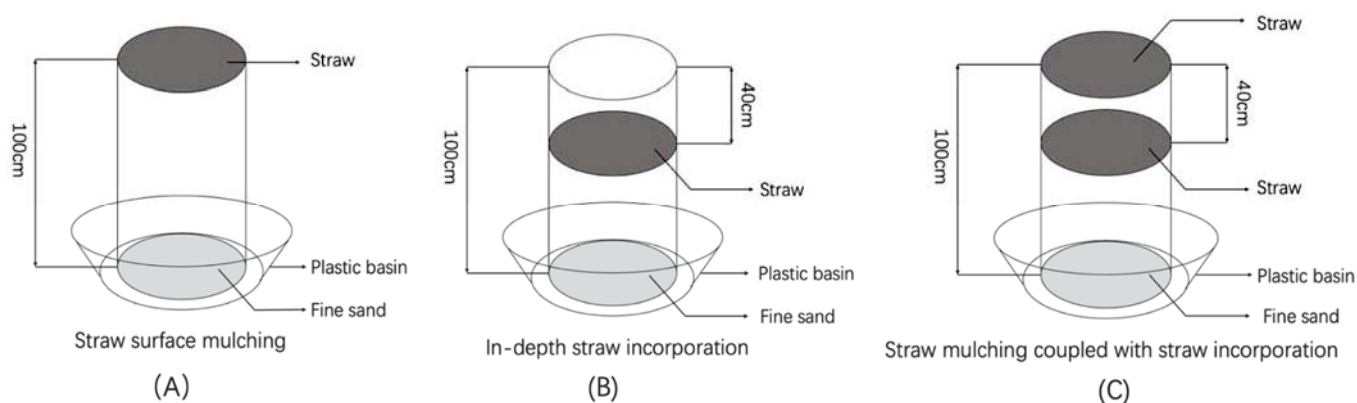


Figure 1. Testing device for different straw mulching treatments.

2.1.3. Treatments

The maize straw used in this study was gathered from cornfields, dried by air, and then chopped into 2–3 cm lengths. The collected straw was then mixed with saline-alkali soil and loaded into soil columns for analysis as illustrated in Figure 1. The experimental design consisted of six treatments: surface-covered straw (SC), straw buried at 40 cm below soil surface (DB), a 1:1 ratio of soil surface cover to the amount of straw buried 40 cm below the soil surface (S1D1), a 2:1 ratio of soil surface cover to the amount of straw buried 40 cm below the soil surface (S2D1), a 1:2 ratio of soil surface cover to the amount of straw buried 40 cm below the soil surface (S1D2), and a control group without straw mulching (CK). The amount of straw mulched was 1800 g/m^2 , and each treatment was replicated three times.

To minimize the impact of external factors such as rainfall on the experiment, the soil columns were placed inside a greenhouse. To ensure a stable brackish groundwater environment at the bottom of the soil column, a solution containing 10 g/L of brackish was introduced into the plastic basin placed at the base of the column during the entire duration of the experiment.

2.1.4. Sample Collection and Determination

At the commencement of the experiment, a total of 200 mm of distilled water was employed to leach the salt at a constant rate. Subsequently, once all the water had infiltrated, soil samples were collected auger from the soil column's surface at four distinct depths: 0–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm. These were then analyzed to determine the soil's salt content. After the beginning of the test, the empty PVC pipe was set as a control to synchronize the determination of the evaporation intensity of the water surface during the test, and the soil column was weighed every 5 days, and the difference between the two times before and after was used to calculate the evaporation of soil moisture; at the same time, samples were taken from the soil column every 10 days, and the sampling positions were 0–20 cm; 20–40 cm, 40–60 cm, and 60–80 cm from the soil surface for the determination of the soil Salinity. During the experiment, a saline solution with a concentration of 10 g/L was periodically introduced into the plastic basin placed at the base of the soil column. This was done to ensure a consistently stable saline environment at the lower section of the soil column.

Determination of Soil Moisture Content (Drying Method)

Fresh soil samples were placed in aluminum boxes and weighed using an analytical balance with a precision of 0.01 g . The boxes were then opened and placed in an oven at 105°C for 12 h. After removal from the oven, the boxes were covered and allowed to cool to room temperature in a desiccator, which took approximately 30 min. The samples were then weighed immediately.

The moisture content of the soil samples was calculated using the following formula:
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$$\text{Moisture content (\%)} = \frac{(\text{mass of aluminum box and soil sample before drying} - \text{mass of aluminum box and soil sample after drying})}{(\text{mass of aluminum box and soil sample after drying} - \text{mass of drying empty aluminum box})} \times 100$$

Determination of Soil Salinity (Residue Drying-Mass Method)

The soil samples were air-dried, ground, and sieved through a 2 mm sieve. The soil solution was then leached using a soil-water ratio of 1:5. A certain amount of the soil leachate was drawn into a porcelain evaporating dish and evaporated on a water bath. The organic matter was oxidized using hydrogen peroxide and then dried in an oven at a temperature of 105–110 °C. The dried residue was weighed to determine its mass.

The soil salt content was calculated using the following formula:

2.2. The Microzone Test

2.2.1. Study Area and Site Characterization

From February 2023 to June 2023, the field experiment was carried out at the Bohai Farm in Dongying Province, China (37°79' N, 118°63' E). Warm-temperate continental monsoon is the classification for the climate in the region. The four seasons in a year are also distinguished clearly in the area. Approximately 1982 mm, 552 mm, and 12 °C, respectively, are its mean annual evapotranspiration, precipitation, and temperature. The three main crops are cotton (*Gossypium hirsutum*), wheat (*Triticum aestivum*), and maize (*Zea mays* L.). Tidal soil that had been salted served as the experimental soil, and Table 2 displays typical soil characteristics.

$$\text{Soil salt content} \left(\frac{\text{g}}{\text{kg}} \right) = \frac{\text{drying residue mass}}{\text{drying soil sample mass}} \times 1000$$

Table 2. Basic properties of the field soil at the beginning of the experiment.

Soil Depth	TN (g/kg)	AP (mg/kg)	AK (mg/kg)	SOM (g/kg)	pH	EC (μs/cm)	SAR (mmol _c L ^{−1}) ^{0.5}	Total Salt (g/kg)	Bulk Densit (g/cm ³)
0–20 cm	0.67	37.4	118.3	10.41	8.39	1764.3	13.5	6.13	1.31
20–40 cm	0.53	30.2	83.47	7.18	8.36	1699.5	12.8	6.57	1.41
40–60 cm	0.41	21.2	51.15	6.17	8.37	1652.3	12.1	6.11	1.46
60–80 cm	0.49	22.8	52.55	6.77	8.39	1667.7	12.3	6.29	1.43

Note: TN, total nitrogen; AP, available phosphorus; AK, available potassium; SOM, soil organic matter; EC, electrical conductivity; SAR, sodium adsorption ratio.

2.2.2. Treatments

The experiment was designed with six treatments: surface-covered straw (SC), straw buried at 40 cm below soil surface (DB), a 1:1 ratio of soil surface cover to the amount of straw buried 40 cm below the soil surface (S1D1), a 2:1 ratio of soil surface cover to the amount of straw buried 40 cm below the soil surface (S2D1), a 1:2 ratio of soil surface cover to the amount of straw buried 40 cm below the soil surface (S1D2), and the control (CK) was covered with straw, the amount of straw returned to the field was 18 t/hm², and each treatment was replicated three times. The micro-areas were constructed in February 2023, with each plot measuring 2 m × 2 m = 4 m², for a total of 18 plots. The plots were firstly trenching and deep excavation around the plots to 1 m from the ground surface, and then blocked with a double-layer plastic sheet to ensure the independence between the micro-areas, and the intermediate gaps were filled with soil. Before burying the straw, the soil in the micro-area was first taken out with a shovel according to the soil layers of 0–20 cm and 20–40 cm in turn, and placed separately, and then the threshed and broken rice straw was evenly laid at a depth of 40 cm from the soil surface, and finally the excavated soil was backfilled layer by layer according to the original level and compacted. The straw

compartment treatment was completed in one go and no further operations were carried out thereafter. In order to ensure the consistency of the test base, the soil layer 0–40 cm of the CK treatment was also dug out and backfilled.

2.2.3. Sample Collection and Determination

To initiate the soil samples were collected during the months of March, April, May, and June 2023 at depths ranging 20 cm, 20 to 40 cm, 40 to 60 cm, and 60 to 80 cm. The soil moisture content was promptly determined upon the samples' retrieval to the laboratory, followed by the subsequent drying of the soil to evaluate its salinity. The calculation procedure remains consistent with that outlined in Section 2.1.4.

2.3. Data Analysis

In this study, data were systematically organized and compiled using Microsoft Excel for further analysis. Subsequently, the data were processed and evaluated using the statistical software, SPSS version 22.0 (SPSS Inc., Chicago, IL, USA), to investigate the relationship between soil water evaporation and soil salinity. Furthermore, Origin 2019b (Origin Lab, Northampton, MA, USA) was employed for graphical representation of the correlation and to examine the fitting parameters of cumulative soil evaporation as a function of time. The comprehensive analysis of the data allowed for a deeper understanding of the soil evaporation processes and their connection with soil salinity, contributing to the field of soil ecology.

3. Results

3.1. Effect of Different Treatments on Soil Water and Salt Transport in Soil Columns

3.1.1. Soil Water Evaporation Analysis

Figure 2 illustrates the temporal variation in mean daily soil evaporation under distinct straw mulching treatments. The daily evaporation rates of soil moisture for the five different straw mulching techniques (SC, DB, S1D1, S2D1, and S1D2) and the control treatment (CK) exhibited a decreasing trend over time, with varying magnitudes. Within 5 days after the initiation of the experiment, evaporation from the soil surface was primarily facilitated by the lower layer of water through capillary conductive water. The control treatment exhibited a larger and significantly higher average daily evaporation compared to the other treatments, be attributed to the exposed soil surface in the control treatment, which led to a faster exchange between the soil surface and atmosphere, resulting in increased daily evaporation. However, this larger daily evaporation also caused a significant issue of salinity epimetry, leading to the formation of a salt crust on the soil surface. Consequently, the evaporation of water was inhibited, causing a decrease in the average daily evaporation of the control treatment over time. Nevertheless, it remained significantly higher than that of the other treatments. Among these treatments, all five demonstrated varying levels of reduction in evaporation compared to CK. The suppressive effect of each treatment on soil moisture evaporation became apparent on the fifth day post-application, with the mean daily soil evaporation rates of SC, DB, S1D1, S2D1, and S1D2 decreasing by 27.82%, 56.39%, 60.53%, 70.68%, and 63.91% relative to CK, respectively. The average daily evaporation of SC treatment was less than that of CK treatment in the first 5 days of the experiment, probably because the soil capillary of SC treatment was continuous, and the water could rise to the soil surface with the help of the capillary force, but the capillary barrier formed by covering the soil surface with straw was effective in attenuating the vertical evaporation of the soil water. The average daily evapotranspiration of the DB treatment was 56.39% lower than that of the CK treatment because the buried straw layer under the soil surface cut off the continuity of soil capillaries, formed an upward obstacle to soil capillary water, and weakened evapotranspiration capacity. The S1D1, S2D1, and S1D2 treatments had the most obvious effect of inhibiting soil moisture evaporation due to the dual effect of straw surface mulching and burying the straw layer. The minimum average daily evaporation

rate (0.31 mm) was observed in the S2D1 treatment on the 45th day of the experiment, representing a 67.02% reduction compared to the CK treatment at the same timepoint.

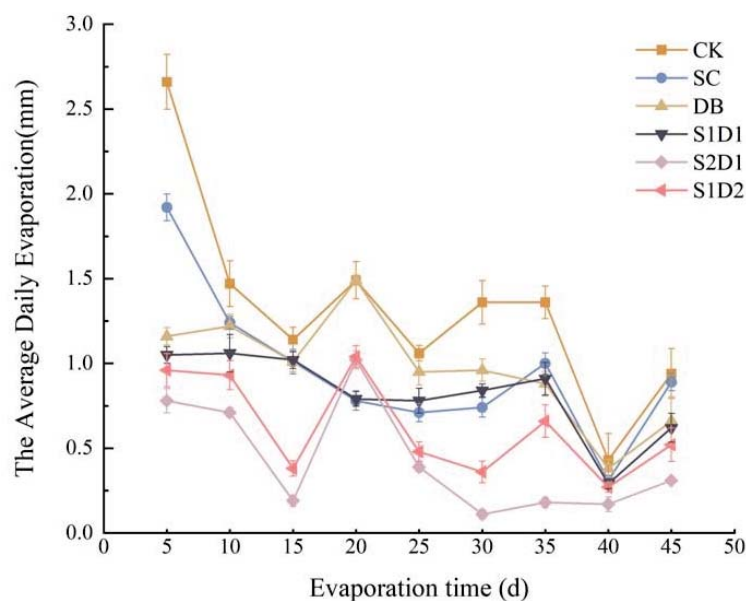


Figure 2. Diurnal variation in daily evapotranspiration of different straw mulching methods.

Figure 3 illustrates the effect of various straw mulching strategies on the cumulative evaporation of soil moisture based on experimental results. According to the investigation, the cumulative soil moisture evaporation under several straw mulching techniques (SC, DB, S1D1, S2D1, and S1D2) showed a trend toward rising over time. When compared to the cumulative evaporation measured using the five mulching techniques, the cumulative evaporation of the control (CK) was much higher. After 45 days of continuous evaporation, the cumulative evaporation from the soil columns of SC, DB, S1D1, S2D1, and S1D2 were 40.28 mm, 41.48 mm, 35.55 mm, 19.54 mm, and 25.99 mm, respectively. These values correspond to a reduction in cumulative evaporation by 29.61%, 27.49%, 37.87%, 65.85%, and 54.58% compared to the control treatment. This implies that the straw mulching and deep burial treatments (S1D1, S2D1, and S1D2) were more effective in inhibiting soil water evaporation than the single-layer straw mulching treatments (SC, DB), with S2D1 exhibiting the strongest inhibition. Nonetheless, during the initial phase of the experiment, the cumulative evapotranspiration observed in the DB soil column was found to be lower than in SC soil column. As time progressed, the cumulative evapotranspiration in the DB soil column gradually exceeded that of the SC soil column. This may be due to the fact that during the evaporation process, water gradually starts to be stored inside the straw, and some of the water in it diffuses upward in the form of water vapor, while the water available for recharge to the evaporated soil surface from the subsoil layer of the SC soil column is relatively low.

Figure 4 presents the evapotranspiration (ET) inhibition rates of various straw mulching patterns after 45 days. The single-layer straw mulching treatments (SC and DB) exhibited soil moisture evaporation inhibition rates of 29.61% and 27.49%, respectively, indicating that the depth of straw placement had a minimal effect on soil moisture evaporation inhibition rate. In contrast, the straw mulching and deep burial model showed varying results: S2D1 had the highest evaporation inhibition effect (65.85%), followed by S1D2 (54.58%), while S1D1 had a relatively weak effect (37.87%). The lowest inhibition effect observed in S1D1 was still 27.89% higher than that of SC, demonstrating that straw mulching and deep burial model is more effective in reducing soil evaporation compared to single-layer mulching. The data also suggest that when the amount of surface straw mulch remains constant, a greater amount of deep straw mulch leads to a higher evaporation inhibition rate and

improved inhibition effect. Conversely, when the amount of deep straw mulch is kept the same, increasing the quantity of surface straw mulch results in a higher evaporation inhibition rate and enhanced inhibition effect.

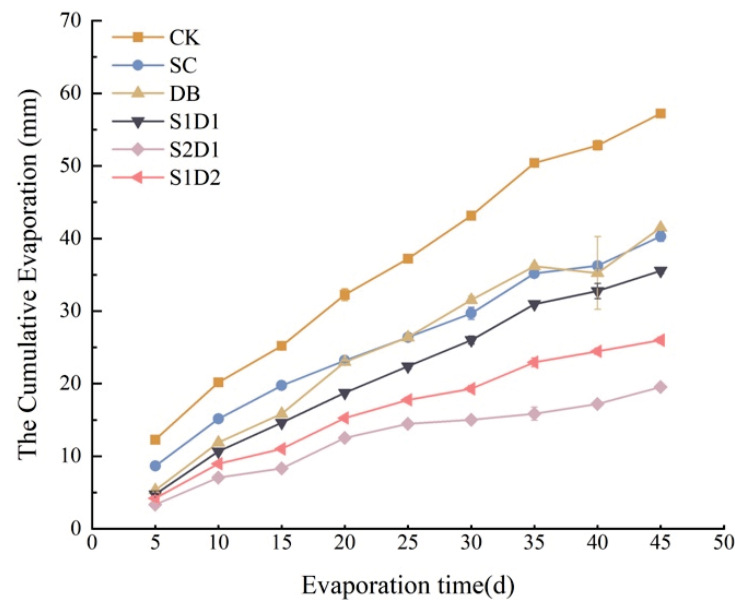


Figure 3. Variation in cumulative evaporation with time in different straw mulching.

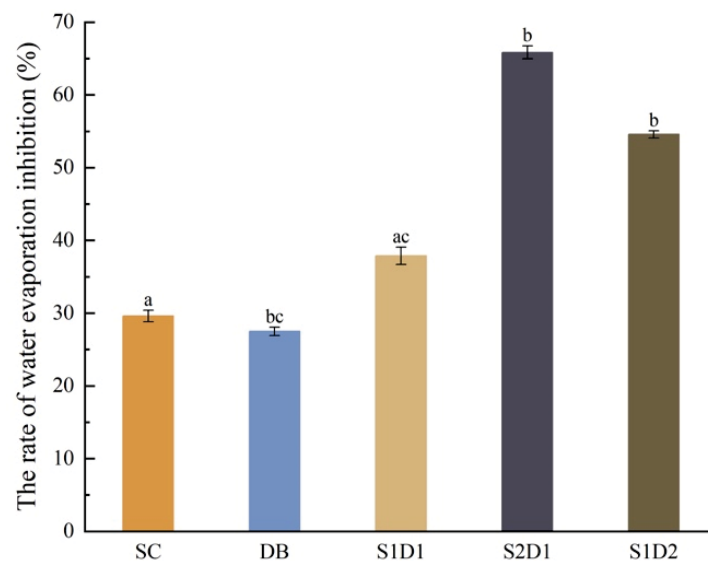


Figure 4. The rate of water evaporation inhibition under different straw covering modes. **Note:** Different lowercase letters indicate that values are significantly different from each other at $p \leq 0.05$.

Figure 5 presents the mean soil evaporation rates of various straw mulching treatments after a 45-day evaporation period. Based on the data in Figure 5, the soil evaporation rates for CK, SC, DB, S1D1, S2D1, and S1D2 treatments were 1.27 mm/day, 0.90 mm/day, 0.92 mm/day, 0.80 mm/day, 0.43 mm/day, and 0.58 mm/day, respectively, throughout the evaporation process. All straw mulching treatments had lower soil evaporation rates than the control (CK). Notably, the S2D1 treatment exhibited the lowest soil evaporation rate, which was 66.14% lower than that of the CK treatment. According to this finding, the S2D1 treatment appeared to have the most inhibitory impact on soil water evaporation, making it more suited to improving soil water utilization.

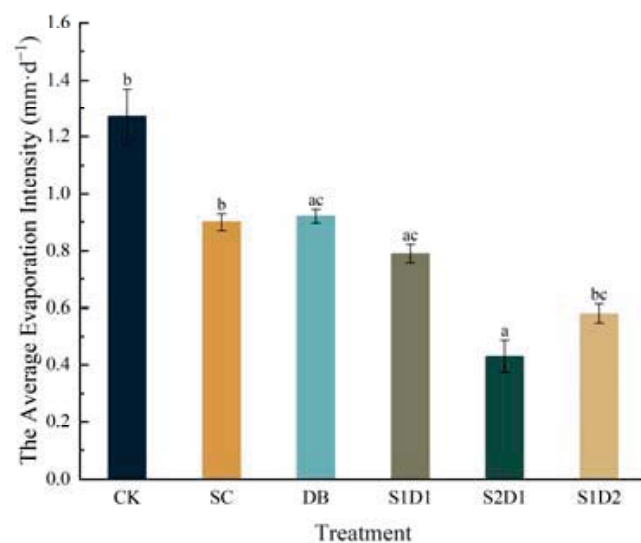


Figure 5. The average evaporation intensity under different straw covering modes. **Note:** Different lowercase letters indicate that values are significantly different from each other at $p \leq 0.05$.

3.1.2. Changes in Salt Dynamics

Figure 6 illustrates the impact of various straw mulching techniques on the salinity levels within the soil profile at distinct time intervals. As depicted in Figure 6, an initial application of 200 mm of fresh water was introduced to the soil column at the commencement of the experiment. Consequently, the salts present in the surface layer of the soil were leached into the sublayer following the irrigation process. Before and after the drenching, the soil salinity content of different treatments changed significantly, especially on the soil salinity in the 0–40 cm soil layer of each treatment. As demonstrated in Figure 6, the salts in the soil transitioned from the upper stratum to the lower stratum post-leaching across all experimental treatments. However, discrepancies were observed in both the transport rates and content between the treatments. To gain insight into the specific alterations in salt concentrations before and after leaching for each soil treatment, the leaching efficiency within the 0–40 cm soil layer was computed for each treatment. The leaching efficiency values were found to be 68.45%, 70.22%, 55.98%, 83.31%, 68.46%, and 76.30% for the CK, SC, DB, S1D1, S2D1, and S1D2 treatments, respectively. The leaching efficiency of the SC and S2D1 soil columns were nearly identical to that of the CK, while the leaching efficiency of the DB soil column exhibited a 18.21% reduction relative to the CK. Conversely, the leaching efficiency of the S1D1 and S1D2 soil columns increased by 21.71% and 11.47% compared to the CK, respectively. The S1D1 treatment exhibited highest desalination rate, indicating its superiority in improving water utilization. Additionally, Figure 6 illustrates ability of various treatments to suppress salt accumulation on the soil surface. As time elapses, the distinct impacts of different straw mul techniques on soil salt accumulation become increasingly apparent. After 30 days of evaporation, the re-salinization levels of each 0–40 cm soil column were 225.67%, 74.98%, 128.45%, 149.06%, 17.96%, and 121.99%, respectively. The salt reversion rates of single-layer straw mulch treatment (SC, DB) and straw mulching and deep burial treatments (S1D1, S2D1, and S1D2) were lower than that of the CK, indicating that straw mulching is advantageous for promoting soil salt management, salt suppression, and enhancing water utilization in the soil. The salt reversion rate of the S2D1 soil column was the lowest, at 92.04% less than that of CK, signifying that it is the most effective treatment for inhibiting soil salt reversion. This is because the soil in the straw compartment retains more water during evaporation, resulting a lower concentration of dissolved salts. The evaporation of water within the compartment increases the water potential difference between compartment and the soil layer, thereby inhibiting the upward movement of water and salts. This mechanism helps reduce salt accumulation on the soil surface. Additionally, the straw covering the soil surface effectively suppresses vertical

evaporation of soil moisture, leading to better inhibition of soil moisture evaporation and salt accumulation.

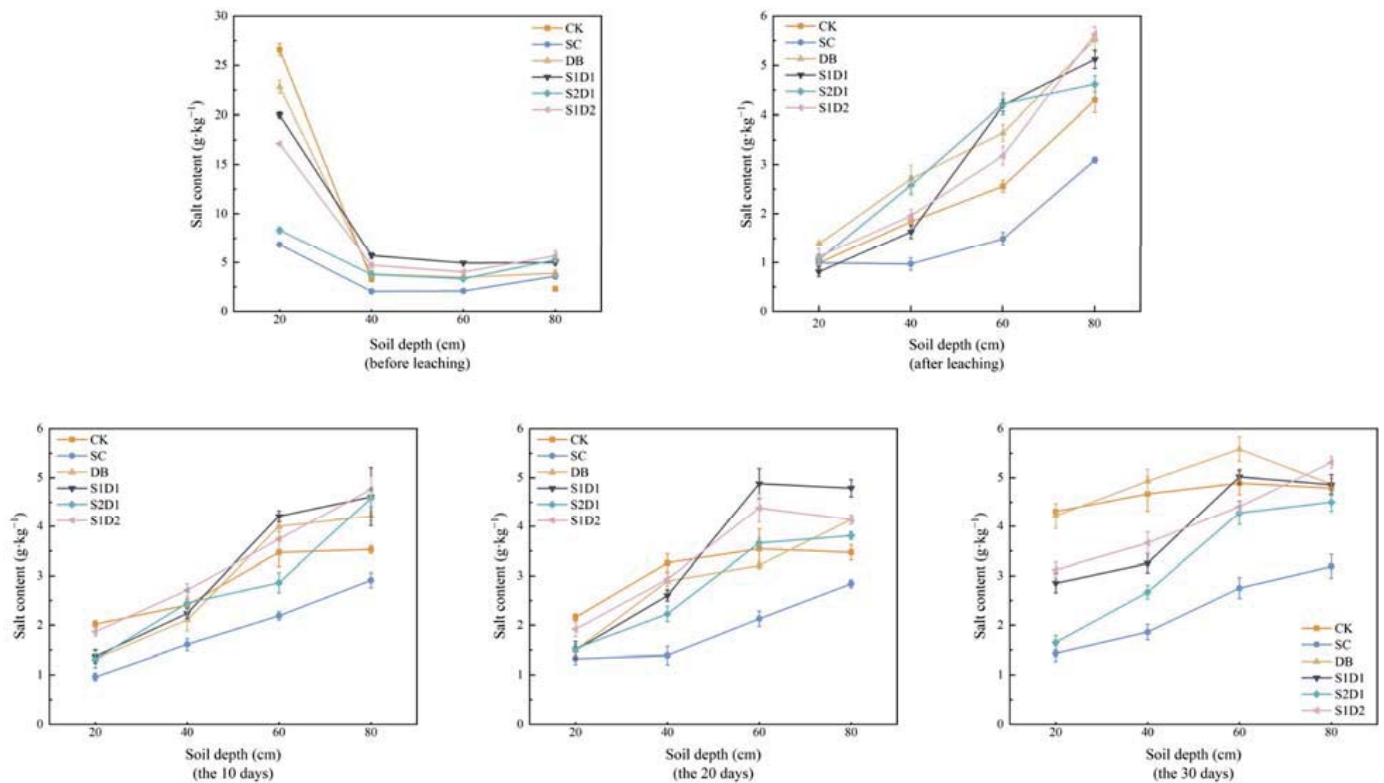


Figure 6. Different straw mulching on soil salt content in the section effects.

3.1.3. Correlation Analysis

The movement of water and salt in soil exhibits distinct patterns and characteristics, with water movement exerting a predominant and determining influence. In this study, an analysis was conducted to examine the correlation between the cumulative evapotranspiration of soil moisture and soil salinity during the experimental period. The results of this analysis are presented in Table 3. As indicated in Table 3, the correlation coefficient between cumulative evaporation of soil moisture and cumulative soil salinity is 0.848, signifying a strong positive correlation. This suggests that an increase in the evaporation of soil moisture is associated with a corresponding increase in cumulative soil salinity.

Table 3. Water and salt related analysis.

		Cumulative Evaporation (mm)	Cumulative Salt Content (g/kg)
Cumulative evaporation	Pearson correlation	1	0.848 *
	Significance (bilateral)		0.033
	The sum of square and fork product	481.1	120.8
	Covariance	96.22	24.16
	N	6	6
Cumulative salt content	Pearson correlation	0.848 *	1
	Significance (bilateral)	0.033	
	The sum of square and fork product	120.8	42.18
	Covariance	24.16	8.436
	N	6	6

Note: Significant correlation at the 0.05 level. * represents a sig value of less than 0.05

3.2. Effects of Different Treatments on Water-Salt Distribution in Agricultural Soils

3.2.1. Moisture Distribution Characteristics

During the experimental period, soil moisture content was mainly affected by straw treatment, rainfall, evaporation and temperature, and the distribution of soil moisture in the farmland was complicated. Figure 7 shows the changes in soil profile moisture content in different periods of each treatment. The graphic illustrates the stark changes in soil profile moisture content between various treatments as a result of various moisture retention effects. On 8 March 2023, the soil layers of different treatments exhibited no significant differences, which can be attributed to the influence of rainfall factors. The DB treatment potentially enhanced soil moisture content within the 20–80 cm soil layer, while the SC treatment demonstrated a relatively higher soil moisture content in the 0–40 cm soil layer in comparison to CK. Both S1D1 and S2D1 treatments contributed to an increase in soil moisture content across all soil horizons, with the S2D1 treatment displaying a higher moisture content in all soil horizons. In contrast, the soil moisture content in all soil horizons of the S1D2 treatment did not exhibit a significant deviation from that of CK. On 11 April 2023, the soil surface moisture content demonstrated considerable variation among treatments due to a decrease in rainfall. The SC treatment raised soil moisture content in the 0–20 cm soil layer by 16% as compared to CK, and all other soil layers had greater moisture contents than CK but no appreciable difference. The DB and S1D1 treatments increased soil moisture content in all soil layers, but none of them had significant differences. The S2D1 treatment also increased soil moisture content in all soil layers, especially in the 40–80 cm layer, which had significant differences compared to CK. The S1D2 treatment exhibited no significant deviation from the control (CK) concerning soil moisture content across all soil horizons. On 4 May 2023, the SC treatment led to an increase soil moisture content within the 0–20 cm soil layer, albeit without a significant difference. In comparison to CK, the DB treatment demonstrated a relatively higher soil moisture content in the 0–20 cm soil layer, while the moisture content in the 20–80 cm layer was lower than that of CK. Both the S1D1 and S1D2 treatments showed no significant disparities in soil moisture content across all layers when compared to CK. The S2D1 treatment exhibited the most effective water retention, displaying higher water content in all soil layers. On 9 June 2023, a significant difference was observed in the soil moisture content of each treatment within the 0–20 cm soil layer. The S2D1 treatment possessed the highest moisture content, which was 17.4% greater than that of CK. No other displayed a significant difference from CK in the remaining soil layers.

It is clear that the various treatments can each have a certain effect on water retention. The S2D1 treatment has the best effect on water and moisture retention and can significantly inhibit the evaporation and dissipation of soil moisture, which is consistent with the findings of the indoor soil column test.

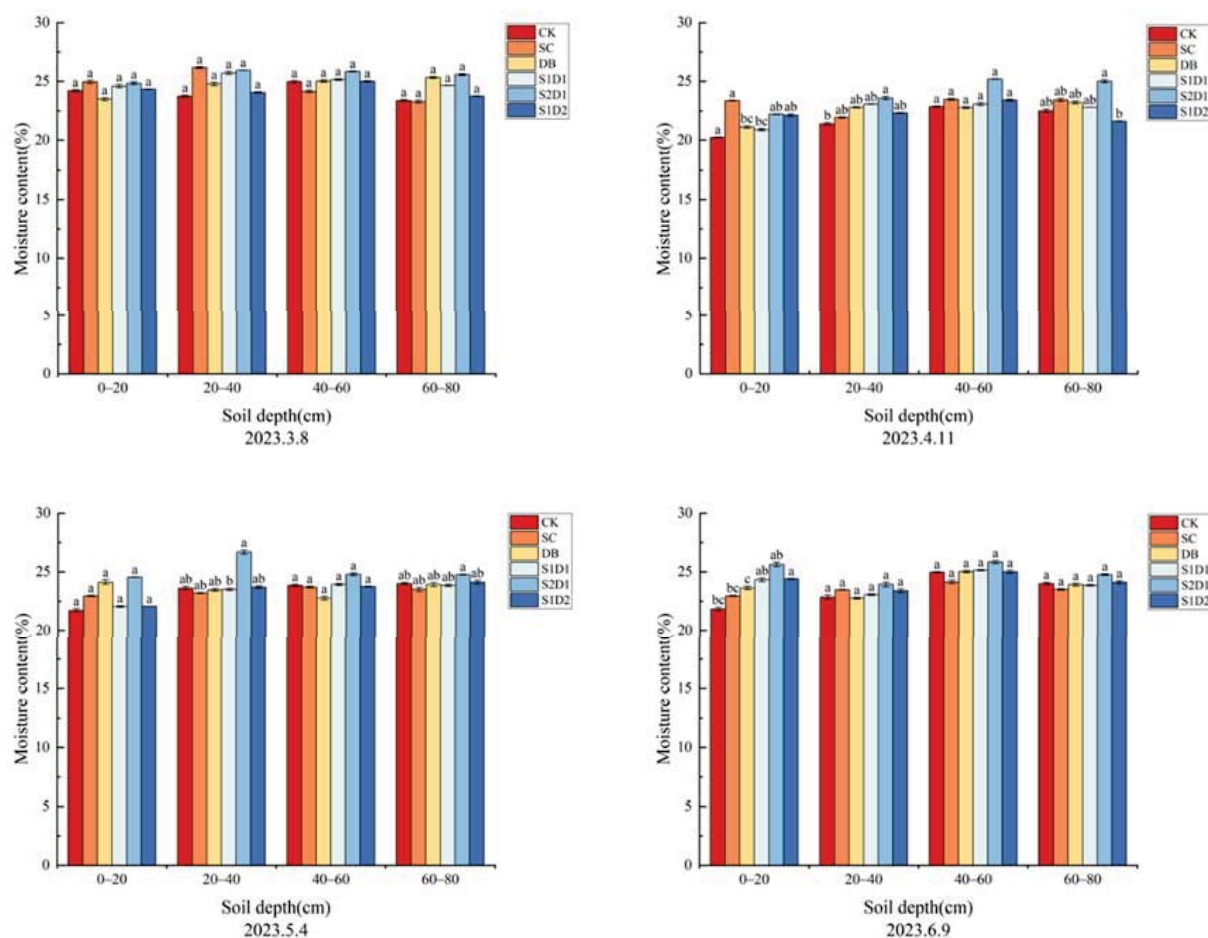


Figure 7. Soil water content for different treatments in different periods. **Notes:** Different lowercase letters indicate that values are significantly different from each other at $p \leq 0.05$.

3.2.2. Salt Distribution Characteristics

Figure 8 depicts the average soil salinity distribution across the various experimental treatments. since can be seen in the image, there was a clear salt epimerization phenomenon since all treatments exhibited greater salinity in the 0–20 cm soil layer. The S1D2 had the lowest salinity, indicating that it had the best impact of blocking the return of salts to the soil top layer. Among them, the soil salinity of CK was the most noticeable, and the average soil salinity reached 12.82 g/kg. The soil salinity in the 20–40 cm soil layer was found to be the lowest among all treatments, with the average soil salinity of S2D1 being the lowest at 4.07 g/kg. This suggests that S2D1 effectively mitigated soil salinity in the till layer. Subsequently, the average soil salinity of each treatment increased in the 40–80 cm soil layer, although it remained lower than the salinity observed in the 0–20 cm soil layer. The lowest soil salinity was found in DB, although there was no discernible difference between it and S2D1, showing that both of them could successfully prevent salt from returning to the deep soil.

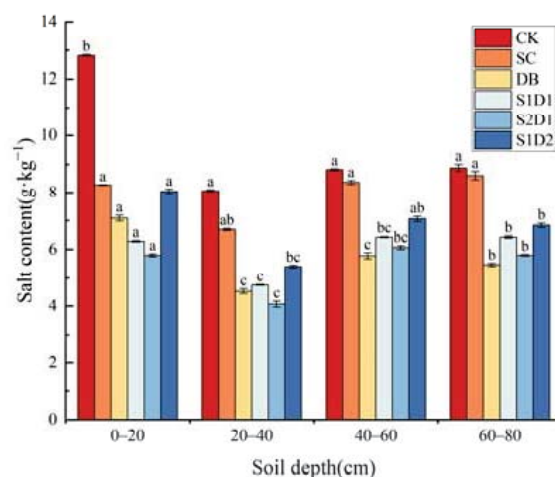


Figure 8. Distribution of soil salinity in different treatments. **Notes:** Different lowercase letters indicate that values are significantly different from each other at $p \leq 0.05$.

Table 4 shows the salt inhibition rate of different treatments compared with CK during the experimental period. According to the table, there are notable differences between the salt suppression effects of various treatments in various soil layers, and the overall pattern is that as soil layers deepen, the salt inhibition rates of the treatments gradually drop and the salt suppression effects weaken. In the 0–20 cm soil layer, the salt suppression effect of each treatment was the best, and the salt inhibition rate of SC, DB, S1D1, S2D1, and S1D2 were 35.46%, 44.76%, 50.98%, 54.80%, and 37.30%, respectively, of which the salt inhibition rate of S2D1 was the highest, which indicated that the S2D1 could effectively inhibit the return of salt to the surface layer of the soil. In the soil layer of 20–40 cm, the salt inhibition rate of S2D1 remained the highest at 49.47%, suggesting that S2D1 can substantially decrease the salt content in the soil tillage layer and mitigate the detrimental impact of saline soil on crops. In the 40–80 cm soil layer, the salt inhibition rate of DB was the highest, followed by the salt suppression effect of straw mulching combined with deep burial treatments (S1D1, S2D1, and S1D2). However, there was no significant difference in the salt suppression effect of SC when compared with CK. This indicates that deep buried straw can significantly inhibit the salt return to the deep soil layer, and surface mulched straw can only inhibit the salt return to the surface layer of the soil, and the inhibition effect on the deep soil salinity is poor.

Table 4. Salt rate of different treatment inhibition during the test period.

Soil Depth	Salt Inhibition Rate (%)				
	SC	DB	S1D1	S2D1	S1D2
0–20 cm	35.46	44.76	50.98	54.80	37.30
20–40 cm	17.14	43.79	41.03	49.47	33.11
40–60 cm	5.064	34.52	27.04	31.23	19.85
60–80 cm	3.047	38.53	27.51	34.73	22.97

In conclusion, the different treatments had the effect of salt control and salt suppression on all soil layers, among which the salt suppression effect of S2D1 treatment on 0–40 cm soil layer was particularly significant, which was consistent with the results of the soil column test. In the 40–80 cm soil layer, the salt inhibition rate of each treatment decreased, among which DB treatment had the best salt suppression effect on deep soil, and the salt inhibition rate of S2D1 treatment was lower than that of DB but there was no significant difference.

4. Discussion

4.1. Effect on Soil Water Evaporation

Soil moisture evaporation is the main pathway for water vapor to enter the atmosphere from the soil surface and an important cause of inefficient soil moisture loss. In soil, the capillary barrier effect refers to the retardation of water flow within soil pores, which can be attributed to intermolecular forces between liquid and solid particles. This phenomenon can be observed when the ground surface is covered with straw or when straw is deeply, resulting in the formation of a capillary barrier that slows the rate of water evaporation from the soil. Straw mulching has been recognized as an effective soil moisture conservation technique. Studies conducted by Yusefi et al. [27,28] have demonstrated that straw mulching can increase the water content of the topsoil layer (0–5 cm) regardless of soil type, and that the rate of evapotranspiration from straw mulched treated soil was reduced by 26% as compared to bare soil. Straw as a surface mulch blocked the direct communication between soil moisture and the atmosphere, which acted as a capillary barrier to the upward movement of soil surface water, and also increased light reflectance and heat transfer, which lowered the temperature of the soil surface layer, and consequently reduced the evaporation of soil water [29]. The cumulative evapotranspiration of SC in this study was reduced by 29.61% compared with CK after 45 days of evapotranspiration, which was consistent with the experimental results of Liu et al. [30] and Chen et al. [31]. Considering the restricted impact of surface straw mulch on the transport of water in deep soil, several scholars have suggested suppressing soil water evaporation by incorporating the straw layer at a greater depth, thereby enhancing the overall utilization of soil water. Rasool et al. [32] demonstrated that by positioning a straw layer at a depth of 25 cm beneath the soil surface, the water storage efficiency within the 0–25 cm soil stratum could reach 89–91% after a period of six days. of water into the soil is predominantly associated with the configuration of soil pores. Notably, the pore structure within the straw layer exhibits non-homogeneity, which contrasts with the characteristics of homogeneous soil [33]. The discontinuity between straw and soil causes it to become more difficult for soil moisture to reach the heat required for evaporation, and the rate of evaporative loss of soil moisture is consequently slowed down. In this experiment, it was discovered that burying a layer of straw 40 cm below the surface might considerably improve the soil's ability to store water, and similar results were confirmed by Lu et al. [34]. Different straw mulching or deep burial techniques can inhibit soil water evaporation to different degrees. The implementation of the straw mulching and deep burial method, which entails deep burying and surface straw mulching, has been proposed by several studies as a way to considerably improve the soil water content and water storage at the conclusion of infiltration. Zhou et al. [35] showed that the effect of straw mulching and deep burial mode was better than that of single-layer straw mulching, and there was a certain correlation between straw mulching and deep burial treatment and soil water evaporation, and the most advantageous method to inhibit the evaporation of soil water was to bury the upper layer at a depth of 80 mm, and to bury the lower layer at a depth of 300 mm. This technique not only prevents the evaporation of water from the deeper soil layers, but also decreases the loss of water from the surface layers, increasing the amount of water present in all soil levels. The technique not only mitigates water evaporation from deeper soil layers but also reduces water loss from surface layers, thereby enhancing the water content across all soil strata. The soil column experiments conducted in this study revealed that after 45 days of evapotranspiration, the soil moisture evapotranspiration inhibition rates for SC, DB, S1D1, S2D1, and S1D2 treatments were 29.3%, 27.82%, 37.46%, 65.89%, and 54.54%, respectively. These findings suggest that the straw mulching and deep burial treatment is more effective in curbing soil water evaporation compared to single-layer straw mulching. Among the treatments, the S2D1 treatment (a 2:1 ratio of soil surface cover to the amount of straw buried 40 cm below the soil surface) exhibited the most efficient suppression of evapotranspiration, which corroborated the results of the field experiment. Consequently, it can be inferred that the straw mulching and deep burial model significantly enhances soil water retention and

evaporation inhibition, thereby contributing to improved soil water use efficiency within the soil ecology framework.

4.2. *Effect Soil Salinity Dynamics*

Soil moisture movement is the main driver of soil salt movement, soil moisture is at the same time an important carrier in the process of salt migration, soil salts move with soil moisture movement [36]. The experimental findings of Yang et al. [37] demonstrated that incorporating straw, biochar, and peat as salt-blocking materials could influence the distribution of water salts in coastal saline soils. Among these materials, the straw layer exhibited the most effective control of salt accumulation. Guo et al. [38] revealed that soil tillage salinity was higher when the straw layer was buried 25 cm below the surface compared to when the soil tillage was covered with surface straw. This suggests that the deep straw burial treatment's capacity to inhibit salinity was less efficient than that of the surface straw mulching treatment. This was also confirmed in the present study where after 30 days of evapotranspiration, the soil salinity in SC tillage decreased by 60.17% compared to CK, whereas the soil salinity in DB tillage increased by 5.57% compared to CK. Based on this phenomenon, Li [39] pointed out that while deep straw mulching attenuated the upward movement of soil salts below the compartment, it did not inhibit the aggregation of soil salts above the straw layer to the soil surface, and that the accumulation of soil salts in the surface layer was probably due to the surface aggregation of salts in the soil above the compartment and not to the supply of water from the capillary support at the bottom. Zhang et al. [40] found that deep straw compartments with a mulch cover were more effective in reducing soil salinity and had a long-lasting effect. However, surface mulching is prone to pollute the soil, so double-layer mulching with straw may be a better way to improve saline soil. Based on the aforementioned observations, a novel approach involving straw mulching combined with deep burial was proposed. By placing straw beneath the soil surface and incorporating surface mulching, this method can effectively mitigate salt accumulation. Specifically, it can impede the upward movement of salts from deeper soil layers and prevent the concentration of salts in the upper soil strata, thereby significantly reducing the overall salt content within the tillage layer.

In the present research, a combination of surface mulching and deep burial methodologies was utilized to alleviate the transportation of salts from the deeper soil strata to the upper layers, as well as to diminish the accumulation of salts on the soil surface. Our experimental results revealed that during the leaching and infiltration stage, the leaching rates in the 0–40 cm soil layer for CK, SC, DB, S1D1, S2D1, and S1D2 treatments were 68.45%, 70.22%, 55.98%, 83.31%, 68.46%, and 76.30%, respectively. Compared to the CK, the SC treatment (surface-covered straw) did not show significant changes, while the straw mulching and deep burial treatments (S1D1, S2D1, and S1D2) were more effective in enhancing soil dewatering and desalination rates. Among these treatments, S1D1 treatment (a 1:1 ratio of soil surface cover to the amount of straw buried 40 cm below the soil surface) exhibited the highest desalinization rate, with a 14.83% increase in soil desalinization compared to the CK. During the water evaporation phase, the soil resalinization rate at 0–40 cm depth in the S2D1 treatment (a 2:1 ratio of soil surface cover to the amount of straw buried 40 cm below the soil surface) was 207.71% lower than that in the CK. In the field experiment, the S2D1 treatment had the best effect on controlling salinity in the soil surface layer and soil tillage layer, with salt suppression rates of 54.80% and 49.47% in the 0–20 cm and 20–40 cm soil layers. This result indicates that S2D1 treatment is more effective at inhibiting soil resalinization and promoting soil salinity control and salt suppression. Consequently, employing straw mulching and deep burial model may prove to be a superior method for improving saline soils.

4.3. *Soil Water and Salt Transport Patterns*

In accordance with the principle of “Salt comes with water, salt goes with water”, the migration of soil salinity is closely associated with water movement. As soil water

evaporates, the salts within the soil progressively migrate to the surface, leading to a continuous build-up of salinity in each soil layer, a phenomenon referred to as salt return. Throughout the evaporation process, salts originating from deeper soil strata migrate towards the surface in conjunction with soil moisture. Subsequently, upon evaporation, these salts accumulate on the soil surface. Conversely, during precipitation or irrigation events, water infiltration facilitates the downward transportation of salts to the deeper soil layers [41]. In the present research, the association between soil moisture and salinity under straw mulch treatments was investigated by establishing a correlation between the cumulative evaporation of soil moisture and the cumulative salinity of the soil. The findings demonstrated a strong correlation between the migration of soil salinity and moisture movement. Both water and salt transport exhibit distinct characteristics and follow specific patterns, with the accumulation of soil salts increasing as soil water evaporation escalates. Given that water serves as a natural solvent for soil salts, dissolving and carrying various mineral salts during transport, water movement plays a pivotal role in the soil water-salt transport process. These results suggest that implementing straw mulching as a means to suppress soil water evaporation is a viable strategy for reducing salt accumulation in the soil.

5. Conclusions

The effects of different straw mulching methods on soil evapotranspiration properties and salt distribution were preliminarily investigated through indoor soil column simulation tests. The primary findings of these investigations are summarized below.

- (1) Straw mulching has been demonstrated to be efficient in mitigating soil water evaporation, with varying degrees of effectiveness observed in different treatment methods. The hierarchy of evaporation suppression, in descending order of efficacy, is as follows: S2D1 > S1D2 > S1D1 > SC > DB. Straw mulching and deep burial model exhibits superior performance in reducing soil water evaporation compared to single-layer straw mulching. Specifically, S2D1 treatment (a 2:1 ratio of soil surface cover to the amount of straw buried 40 cm below the soil surface) had the most obvious effect and the cumulative evaporation of soil moisture was 65.85% lower than that of CK (the control treatment), which had the best effect of inhibiting evaporation.
- (2) In the drenching and infiltration stage, S1D1 treatment (a 1:1 ratio of soil surface cover to the amount of straw buried 40 cm below the soil surface) had the best drenching effect and the highest desalination rate. In the evaporation phase, S2D1 treatment had much lower salt levels than CK, indicating that the S2D1 treatment had the best inhibition effect on soil salinity reversal.
- (3) There was a significant positive correlation between the cumulative evaporation of soil water and cumulative soil salinity, which meant that the cumulative soil salinity increased with the cumulative evaporation of soil water.

The effects of different straw mulching methods on soil water and salt transport in agricultural soils were investigated through a microzone test as a validation test, and the results were consistent with the soil column test, with specific conclusions as follows.

- (1) Different treatments could reduce the evaporation of soil moisture, but the moisture retention effect and duration were different. Among them, the S2D1 treatment maintained high soil water content in all soil layers during all periods of the experiment, which could obviously inhibit the evaporation and dissipation of soil moisture.
- (2) Different treatments can inhibit soil salinity return to a certain extent in all soil layers. All treatments could keep the soil salinity in the 0–40 cm soil layer at a lower level, among which the S2D1 treatment had the best effect on salt suppression in the surface soil. In the 40–80 cm soil layer, the best soil salinity suppression was DB treatment (straw buried at 40 cm below soil surface).

Author Contributions: M.L. and W.W. curated the data, analyzed the results, and wrote the original draft; W.C. and E.C. conceived the experiment, administrated the project, and carried out supervision; M.L., C.Y., W.C., Y.W., Z.W., X.W. and W.Z. conducted the experiment. All authors reviewed the final manuscript. All authors have read and agreed to the published version of the manuscript.

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Article

Effect of Ridging Shapes on the Water–Salt Spatial Distribution of Coastal Saline Soil

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Abstract: The Yellow River Delta, located in China, experiences prevalent soil salinization and serves as a crucial ecological management zone within the Yellow River Basin. The shallow groundwater depth and high mineralization contribute to salt accumulation in the soil, which has a negative impact on crop growth. The sustainable use of saline land in the Yellow River Delta hinges on managing the soil salinity within the crop root zone. This study investigated the spatial distribution of soil salinity in coastal saline soil in the Yellow River Delta under various ridging configurations: triangular, arch, and trapezoidal, using flat land as a control. It also examined the impact of evaporation on soil salinity migration. The findings revealed that the ridge–furrow system successfully caused salt to accumulate in the superficial layer of the ridge. Among the three ridge shapes, the triangular ridge was the most effective at concentrating salt on the ridge surface, with 54.04% of the salt mass accumulation in the ridge’s top layer (0–1 cm) and with the furrow bottom achieving a maximum desalination rate of 93.07%. The results implied that the triangular ridge fostered a favorable soil environment for crop growth by minimizing the salt content in the furrow. This research provides a theoretical foundation for the sustainable advancement of saline–alkali agriculture in the Yellow River Delta, which can lead to higher crop yields and better land management practices.

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1. Introduction

Soil is an important natural resource for human survival and reproduction, and soil quality directly determines the carrying capacity of land resources, which plays a vital role in human survival and development. Soil salinization has become one of the major problems threatening land resources and food security, and about 7.6×10^7 hm² of land worldwide is affected by soil salinization [1]. Therefore, paying attention to the dynamics of salinized soil and taking active countermeasures to prevent the continuous intensification of salinization is an important way to carry out the protective development and utilization of global land reserve resources.

The Yellow River Delta has important ecological value for the global ecosystem, with more than 50% of the total area of salinized soil due to natural conditions [2]. In recent years, due to the shortage of freshwater resources and irrational irrigation, coupled with the shallow groundwater table depth, the salt cannot be discharged for a long time after entering the soil profile, which aggravates soil salinization and seriously restricts the sustainable and high-quality development of the local ecology and agriculture [3–5]. Therefore, appropriate technical measures to control the salt in the soil or accelerate the discharge of salt in the soil profile should be carried out to prevent and control soil salinization.

Overall, it is difficult to improve plant growth or reduce soil salinity in semi-arid areas of China due to water shortages [6]. Ridging is one of the traditional farming methods that improve soil permeability through artificially constructed differences in the ground surface height and has been used for several decades. A previous study suggested that

ridge–furrow plastic mulching brought about a yield increase comparable to irrigated crops but used 24% less water in comparison with irrigation due primarily to a noteworthy water use efficiency and better maintenance of soil water [7]. Studies showed that surface elevations affect spatial soil water and salt distribution, and the soil surface salt content tends to increase with elevation, while water content is the opposite [8–10]. A field study suggested that paired-row planting and furrow irrigation had an increased pod yield, saved water, and enhanced the WUE of groundnut under hot sub-humid conditions, where the ridge and furrow and paired-row methods decreased the ET by 13 and 21%, respectively, and increased the crop WUE by 32.6 and 48%, respectively, over a flatbed [11].

In rain-fed agricultural areas, to solve the problem of irrigation water shortage, furrow sowing is often used, and mulching on the ridge can collect rainfall and provide a suitable water environment for the crops in the trench [12,13]. This method uses the principle of soil water and salt transport to construct a relatively low-salt environment, which has high efficiency, is economically friendly, and has been widely used in practice. A study showed that the concentration of surface soil solution with ridge mulching combined with drip irrigation measures is reduced by 41.25–74.92% compared with flat sowing [14]. Li et al. [15] pointed out that ridge-mulched furrow-sown winter wheat can increase the yield by 25.4% compared with flat land. Sun et al. [16] pointed out that ridge mulching changes the micro-topography of the soil surface, thereby enhancing the water storage capacity of the soil, which can increase the yield by 37–196.4% compared with the control group. Studies showed that in the case of an irrigation water shortage, the yield of furrow-sown winter wheat is significantly higher than that of ridge sowing and has a higher water tolerance threshold, with 7.5 dS/m vs. 5 dS/m, respectively [17]. Trench sowing increased the water content of 0–200 cm soil by 11–15%, and the cereal yield increased by 75% under precipitation conditions of 230–340 mm. Two years of field experiments showed that ridge and furrow mulching technology can significantly improve the water use efficiency and yield of maize [18]. The trench sowing technique effectively reduces soil temperature and prolongs the water supply time during the growing season of winter wheat [19].

These studies showed that soil water and salt are significantly affected by the ridge–furrow planting system. At present, relevant studies mainly study the soil water–salt transport process in the form of ridge cropping from the perspective of the leaching process or the combination of evaporation and leaching, while there are few studies that have considered soil water–salt transport under evaporation alone; when it comes to the geometric characteristic of the ridges, both width and height were studied in the previous research [20–22], though there are few studies involving the influence of ridge shapes on water–salt migration, and the influence of ridge shapes (cross-sectional shapes) on soil water–salt transport and its redistribution pattern is still unclear. Therefore, this study intended to analyze and study the influence of ridges on the spatial distribution of water and salt in the soil profile by constructing different ridge shapes artificially through indoor experiments to explore the regulatory effect of the ridge shape on the spatial distribution of soil water and salt in coastal saline soil to find the suitable ridge shape for creating a low-salinity environment as a supplement to the ridge cropping theory, which has reference significance for the formulation of the “salt avoidance tillage” system in salinized areas.

2. Materials and Methods

2.1. Soil Sample

The experimental soil was collected from the Base of Modern Agriculture High-Quality Development of Modern Agriculture in Dongying (37.66° N, 118.92° E), and the depth of the soil was 0–60 cm. After the soil sample was dried, it was sieved (2 mm) for reserve, and its physical and chemical properties are shown in Table 1.

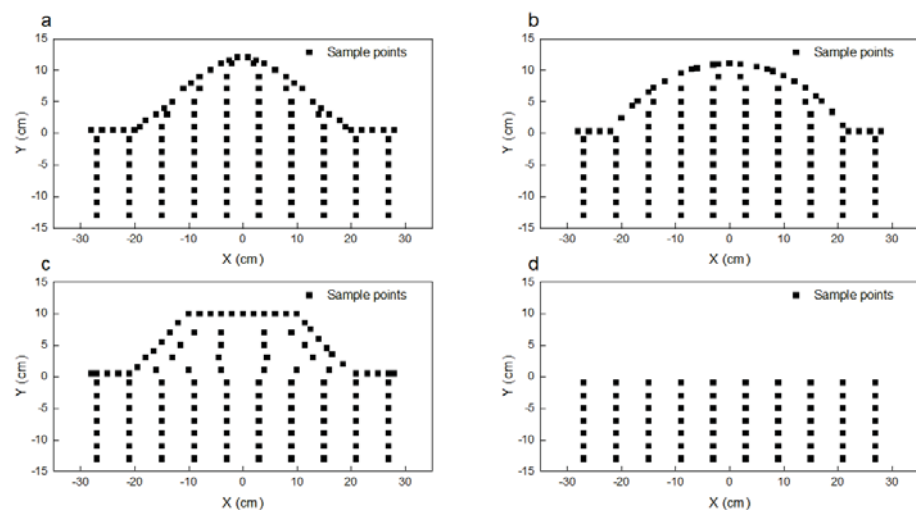
Table 1. Basic physical and chemical properties of the experimental soil samples.

Indicators	Soil Particle Size Composition (%)			Nitrogen	Salt Content	pH	Soil Texture
	Sand	Silt	Clay	(g/kg)	(g/kg)		
Measured values	81.73	10.76	7.51	0.47	9.56	7.9	Sandy loam

2.2. Experimental Setup

The experiments were carried out in the Laboratory of Regional Soil and Water Resources and Agricultural Utilization of Ludong University, and the designed shapes of the ridge profiles were triangular, arched, and trapezoidal, denoted as T1, T2, and T3, respectively, using flat surface (CK) as the control. The experimental setup consisted of transparent cylindrical plexiglas tanks (8 mm thick) with a size of $60 \times 10 \times 30 \text{ cm}^3$ and Mariotte bottles. A water inlet pipe and water level control pipe were provided in the lower part of the clay tank to create a groundwater environment and control the groundwater table depth. To create uniform groundwater conditions and ensure good water permeability, 2 cm thick quartz sand was poured into the bottom of the soil tank and covered with clean and pollution-free filter paper to separate the quartz sand from the experimental soil, where the bulk density of the loaded soil was 1.35 g/cm^3 . After reaching 13 cm, an artificial ridge treatment was constructed using subsequent soil, and the maximum height of the three ridge shapes was about 15 cm.

After the soil tank was filled, under the condition that the Mariotte bottle did not leak and the distilled water was sufficient, the Mariotte bottle was connected to the water supply pipe at the bottom of the organic glass soil tank with a rubber hose to maintain a fixed water head to form a fixed water supply condition. When the water level of the soil tank reached the highest point of the ridge, the water supply was stopped, and the soil tank was placed indoors without direct sunlight to create a natural evaporation condition. The experimental soil samples were collected 90 days after the end of the water supply, and soil samples were taken every 2 cm of soil with a depth of 1 cm along the surface to study the distribution of salt along the ridge surface, where the sampling volume was $2 \times 10 \times 1 \text{ cm}^3$. The sampling volume of the $2 < d \leq 16 \text{ cm}$ depth profile soil was $5 \times 10 \times 2 \text{ cm}^3$. Samples were collected with a sharp soil dressing knife to a given size, where the center coordinate of each soil sample was recorded as the sample coordinate. The sample point coordinates were drawn in a two-dimensional Cartesian coordinate system and are shown in Figure 1. The soil water content was determined immediately after sampling, and the rest of the samples were placed in a ziplock bag after drying, grinding, and passing through a 2 mm sieve for testing.

**Figure 1.** Distribution of the sample points; (a–d) represents T1, T2, T3, and CK, respectively.

2.3. Test Items

The moisture content of the soil samples (105 °C, 8 h) was determined using the oven drying method. The conductivity of the soil sample leachate (5:1 water–soil ratio) was determined using a DDS-12A conductivity meter. The Cl^- content in the soil samples was determined using the silver nitrate titration method. The Na^+ content in the soil samples was determined using the flame photometer method, where the operating procedure was based on *Soil Agricultural Chemistry Analysis* [23].

2.4. Data Analysis

The desalination rate (D) is an important indicator used to characterize soil salinity changes, and the formula is

$$D = (T - E) / T \quad (1)$$

where D is the desalination rate and T is the initial soil salinity content, E is the existing salt content of the soil, $D > 0$ indicates the soil desalination, and $D < 0$ indicates the soil salt accumulation.

The coefficient of variation, which reflects the degree of spatial variation of soil physical and chemical indexes, is calculated using the following equation:

$$C_v = SD / \bar{X} \quad (2)$$

where SD is the standard deviation of the sample and $\bar{X}$ is the mean of the sample. $C_v < 10\%$ indicates a weak variation, $10\% \leq C_v \leq 100\%$ indicates a moderate variation, and $C_v > 100\%$ is a strong variation [3].

3. Results

3.1. Spatial Distribution of the Soil Water Content in Different Ridge Shapes

The soil water content is an important carrier of salt, where in the process of water absorption and infiltration, water carries salt in the soil profile, and after the water reaches the surface, it is lost due to evaporation to form water vapor and the salt is retained in the soil.

3.1.1. Soil Water Content (0–1 cm)

Figure 2 shows the water content of the topsoil with different ridge treatments at the end of the experiment. The differences in surface soil water content between the ridges and furrows can be seen. The water content of the furrow surface of the three ridge forms was higher than that of the ridge surface, the water content showed a decreasing trend from the furrow to the ridge, and the water content was lower at the convex or inflection point of the ridge, where these latter locations also had the most salt accumulation. According to the experimental data, the average moisture content of the surface layer at the furrow of T1 was 14.09%, the average moisture content of the ridge surface layer was 12.33%, the average moisture content of the surface layer of T2 furrow was 14.66%, the average moisture content of the ridge surface layer was 12.45%, the average moisture content of the surface layer of T3 furrow was 13.21%, the average moisture content of the ridge surface layer was 12.42%, and the average moisture content of CK surface layer was 12.85%. The average water content of the surface layer of the three ridge forms was higher than that of the flat surface, which can provide better water conditions for plant growth and salt leaching.

It can be seen from Figure 2 and Table 2 that the surface 0–1 cm soil water content fluctuated after ridging, and the average soil water content of the surface layer (0–1 cm) of the furrow was higher than that of the soil water content at the ridge surface layer (0–1 cm), and the surface soil water content showed a trend of reduction to some extent during the transition from a furrow to a ridge in each treatment. After evaporation, the surface water contents of the T1, T2, and T3 ridges were 4.07%, 3.18%, and 13.18% lower than that of the CK surface, respectively, and the average water content of the T3 ridge was 11.16%, which

was lower than those of T1, T2, and CK with 12.33%, 12.45%, and 12.85%, indicating that the surface of the trapezoidal-shaped ridge had greater evaporation strength. The surface water contents of T1, T2, and T3 were higher than that of CK, and were 9.65%, 14.03%, and 2.76% higher, respectively.

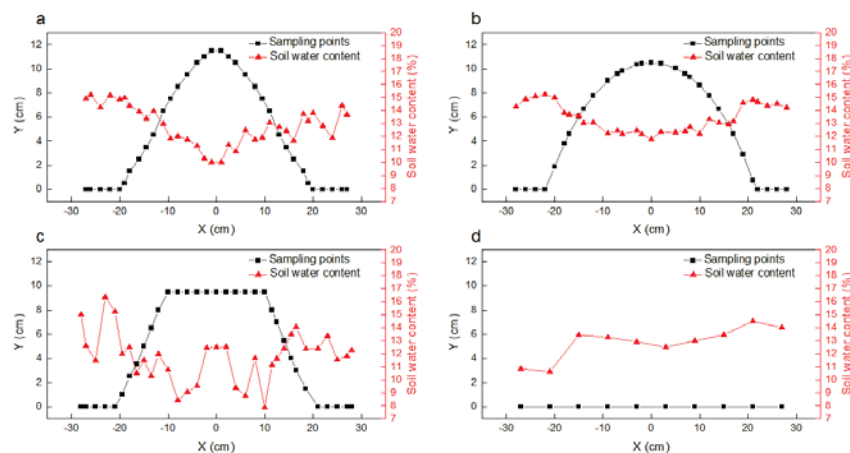


Figure 2. Variation in soil water content in the superficial layer (0–1 cm) under different treatments; (a–d) represents T1, T2, T3, and CK, respectively.

Table 2. Statistical results of soil indicators of 0–1 cm soil in the lower layer of different treatments.

Treatments	Parameters	Positions	Maximum	Minimum	Average	STD	Coefficient of Variation (%)
T1	Water content (%)	Ridge	14.97	10.02	12.33	1.35	10.93
		Furrow	15.2	11.89	14.09	1.08	7.66
	Salinity (g/kg)	Ridge	135.94	5.62	48.78	38.66	79.25
		Furrow	16.83	7.26	12.92	2.83	21.86
T2	Water content (%)	Ridge	15	3.09	12.45	2.31	18.58
		Furrow	15.25	14.22	14.66	0.38	2.59
	Salinity (g/kg)	Ridge	109.35	26.61	72.68	26.87	36.98
		Furrow	42.34	22.65	33.79	6.51	19.25
T3	Water content (%)	Ridge	14.05	7.85	11.16	1.68	15.01
		Furrow	16.36	11.5	13.21	1.73	13.09
	Salinity (g/kg)	Ridge	179.64	42.13	92.68	32.23	34.77
		Furrow	107.19	37.92	53.56	19.98	34.31
CK	Water content (%)		14.5	10.61	12.85	1.25	9.76
	Salinity (g/kg)		46.86	31.6	40.74	4.22	6.68

Note: T1, T2, T3, and CK represent triangular, arched, trapezoidal, and flat, respectively.

By calculating the coefficient of variation of the ridge and furrow surface of different treatments, the influence of ridging and the shapes of ridges on the fluctuation of soil surface water content were analyzed (Table 2). It can be seen from Table 2 that after the evaporation, the water content of the surface layers of the T1, T2, and T3 ridges all showed medium variations, and the coefficients of variation were 10.93%, 18.58%, and 15.01%, respectively, which were higher than the coefficient of variation of 9.76% in the surface layer of CK; furthermore, T2 was the largest, indicating that the ridge changed the redistribution of soil surface water after evaporation, and the arch-shaped ridge led to more obvious water fluctuations.

3.1.2. Distribution of the Water Content in the Soil Profiles

Figure 3 shows the soil water content of the ridge and furrow soil profile after evaporation, and Figure 4 shows the contour diagram of the soil profile water distribution after evaporation. It can be seen from Figures 3 and 4 that the surface water content of each treatment was the smallest, and with the increase in depth, the soil water content showed an increasing trend and then tended to be flatter. The water contents of T3 and CK increased first and then decreased with the increase in depth, and the highest water content of CK was 15.01% at a depth of 5 cm. The highest water content of the T3 ridge was 16.79% at a depth of 13 cm, and the maximum water content at a depth of 5 cm in the furrow profile was 16.45%. It can be seen from Figure 3a that the soil water content increased below 0–1 cm in the ridge surface layer, and the soil water content of the top layer of different treatments showed a trend of $T1 < T3 < T2 < CK$, i.e., 10.02%, 10.26%, 12.10%, and 12.85%, respectively.

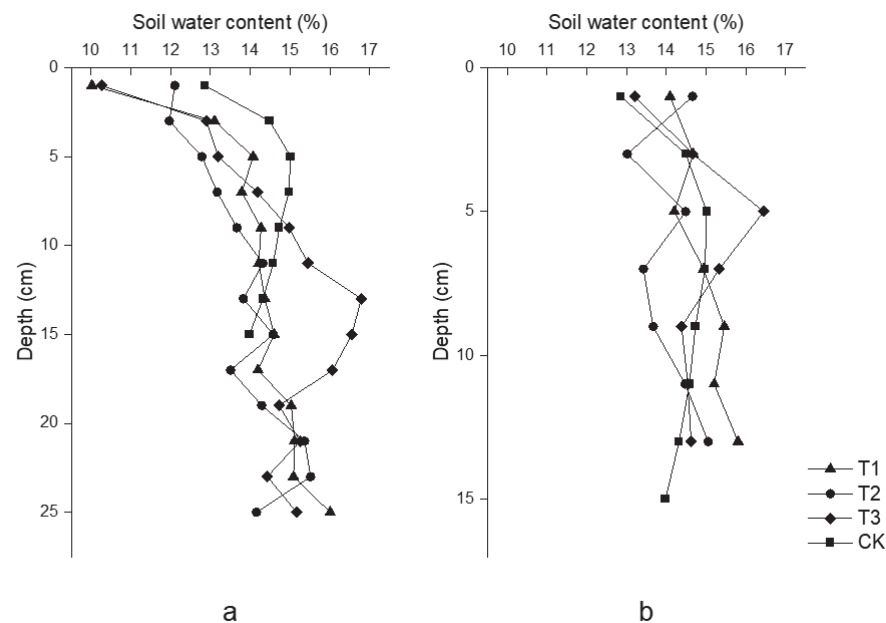


Figure 3. Trends of the soil water content in different ridge and furrow profiles, where (a,b) represent ridge and furrow profiles, respectively.

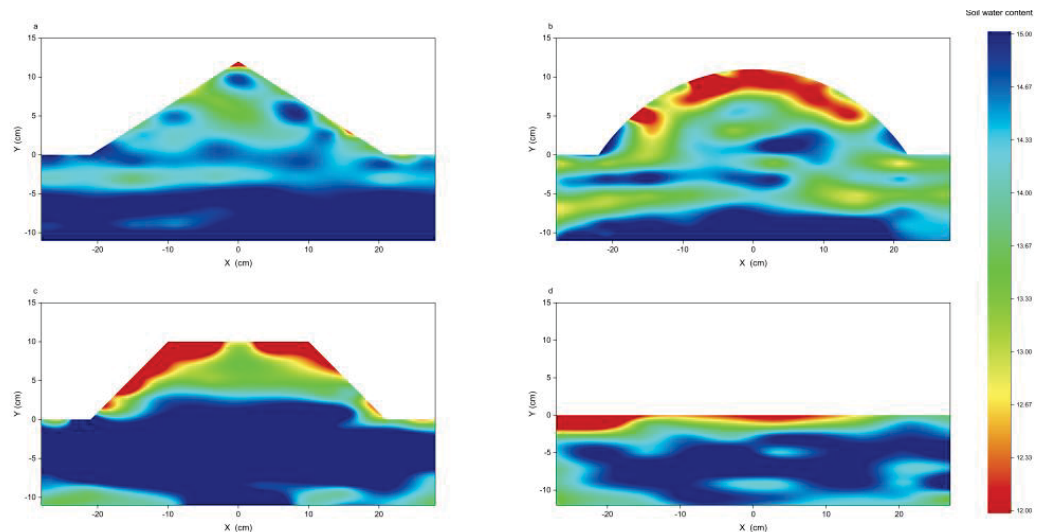


Figure 4. Spatial distribution of water content in the soil profile under different treatments, where (a–d) represents T1, T2, T3, and CK, respectively.

In contrast, the water content of the subsoil was opposite to that of the surface layer, and the soil water content was ranked $CK < T2 < T3 < T1$, i.e., 13.98%, 14.16%, 15.16%, and 16.01%, respectively. At a depth of 5 cm, the water content of ridge soil was ranked $T2 < T3 < T1 < CK$, i.e., 12.78%, 13.20%, 14.07%, and 15.01%, respectively. Within the depths of 0–10 cm, the water contents of T1, T2, and T3 were higher than that of CK, and gradually became consistent below the 10 cm soil layer, indicating that the ridge part had a greater evaporation strength. As shown in Figure 3b, the water content of the soil profile of the furrow increased with the increase in depth. Overall, the water content of the furrow was higher than that of the ridge, indicating that the ridge was conducive to maintaining the soil water. The vertical coefficient of variation of the ridge water content was 7.95–11.90%, while that of the furrow was 4.2–6.67% compared with the 4.86% of CK.

3.2. Spatial Distribution of the Soil Salinity in Different Planting Ridge Shapes

Creating a low-salinity growth environment for crops in areas affected by salinization is of critical importance. The main purpose of this study was to use the ridge furrow treatment to create salt accumulation in some parts of the soil profile and a desalination situation in other parts to form a low-salt area to facilitate plant growth and development. Furthermore, for the salt in the high-concentration area, salt removal can be carried out artificially to reduce the overall salt content of the profile.

3.2.1. Spatial Distribution of the 0–1 cm Soil Salinity

After the experiment, the salt in the soil was redistributed, where 60.01%, 40.46%, 47.81%, and 38.62% of the total salt mass were concentrated in the soil surface layer of T1, T2, T3, and CK in 0–1 cm, respectively. The accumulation ratio of the surface salt in the T1 ridge was the largest at 54.04%, while the total surface salt content under the same projection area of soil without ridge accounted for only 23.46% of all salt in the soil tank, which was much lower than that of other treatments. Figure 5 shows the trend of 0–1 cm soil salinity in the surface layer after evaporation. It can be seen from the figure that the surface soil was in a state of salt accumulation; from the furrow to the ridge, the salt content of the surface soil showed the opposite trend to the water content, that is, the salt content of the surface soil gradually increased, and especially the changing trend in salt content on the triangular-shaped ridge was the most obvious. After a statistical analysis of the soil water and salt content, the results are presented in Table 2. It can be seen that the average salt content of the ridge surface soil was ranked $T3 > T2 > T1$, i.e., 92.68, 72.68, and 48.78 g/kg, respectively, and the salt content of furrow surface soil was ranked the same with 53.56, 33.79, and 12.92 g/kg, respectively. The average salt content of the surface layer of the T3 ridge was the highest, and the difference between the ridge and furrow was the largest, indicating that the trapezoidal ridge had the most obvious effect on the salt aggregation, among which the average salt contents of the T1 and T2 furrows were lower than that of CK (40.74 g/kg), and T1 was the lowest. After the construction of the ridge furrow system, a relatively low-salt environment could be created for the furrow to a certain extent, among which from the current situation, the effect of the triangular ridge is better.

From the experimental results, ridge raising made the salt change of the ridge more drastic, which was reflected in the extremely high soil salt content at the geometric inflection point of the ridge. The analysis of the coefficient of variation of soil salinity content in the surface layer of ridges and furrows showed that the spatial variability of soil salinity after evaporation was moderate on the surface. The maximum coefficient of variation of the surface layer of the T1 ridge was 79.25%, which was higher than that of the 36.98% of T2 and 34.77% of T3, indicating that the salt content of the triangular ridge layer fluctuated the most. The lowest position of the ridge salt content in Figure 5b was due to an obvious crack during the drying process, resulting in sudden changes in the soil salt content. The trapezoidal ridge (Figure 5c) also showed an abnormal salt content measurement result due to cracks at the right inflection point.

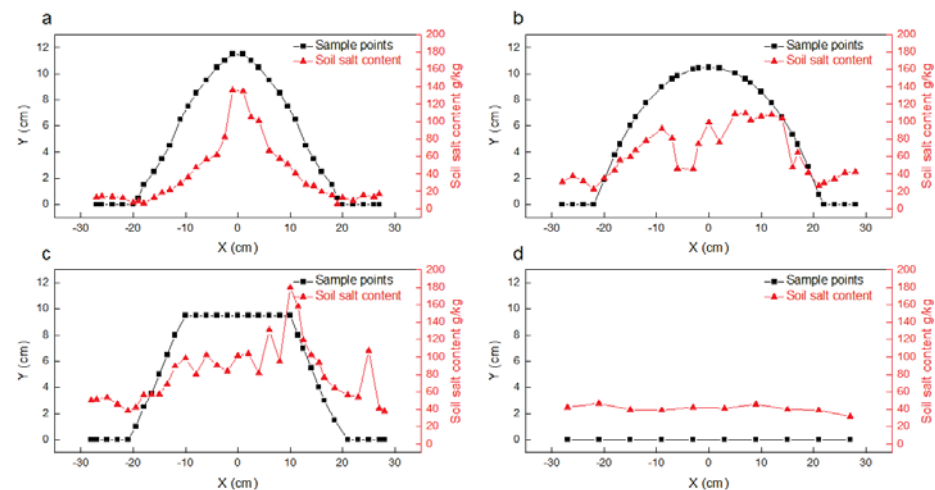


Figure 5. Variation in the soil salinity in the superficial layer (0–1 cm) under different treatments, where (a–d) represents T1, T2, T3, and CK, respectively.

3.2.2. Spatial Distribution of the Salinity in the Soil Profiles

Figures 6 and 7 show the vertical variation and spatial distribution of the salt in the soil profiles under different treatments, and it can be seen from the figures that the soil salinity accumulated on the surface layer of the ridge after evaporation. The proportion of salt in the ridge to the total salt content was ranked $T1 > T2 > T3$, i.e., 81.77%, 80.26% and 73.11%, respectively, and the salt aggregation effect was the best with the T1 treatment. As shown in Figure 6a, in the range of 0–5 cm, the salt content of each treatment decreased rapidly with increased depth, where T1, T2, T3, and CK decreased by 124.6, 63.3, 80.35 and 29.51 g/kg, respectively, and the soil salt content was ranked $T2 > T3 > CK > T1$ at a depth of 5 cm, indicating that the salt content of the triangular ridge decreased fast with depth. Below the depth of 5 cm, the soil salt content under the T1, T2, and T3 ridges continued decreasing, and the final bottom salt content was ranked $T2 > T3 > T1$, i.e., 2.18, 0.81, and 0.50 g/kg, respectively. The salt content of CK remained basically unchanged until the bottom salt content, which was 9.44 g/kg. The ridges of T1, T2, and T3 showed desalination from depths of 7, 9, and 11 cm, respectively, and the desalination rates were 60.85%, 89.22%, and 58.90%, respectively. With the increase in depth, the desalination rate also increased gradually, and the maximum desalination rates reached 94.76%, 93.82%, and 91.98%, respectively, and the triangular-shaped ridge system had the best desalination efficiency.

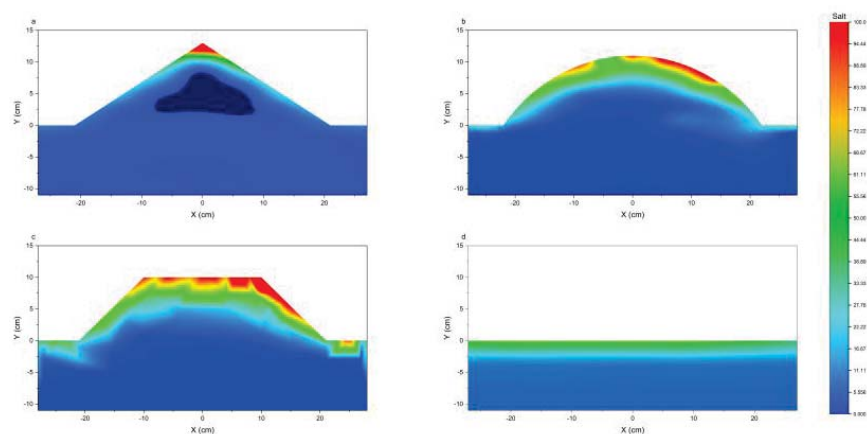


Figure 6. Spatial salt distribution in the soil profile with different treatments, where (a–d) represents T1, T2, T3, and CK, respectively.

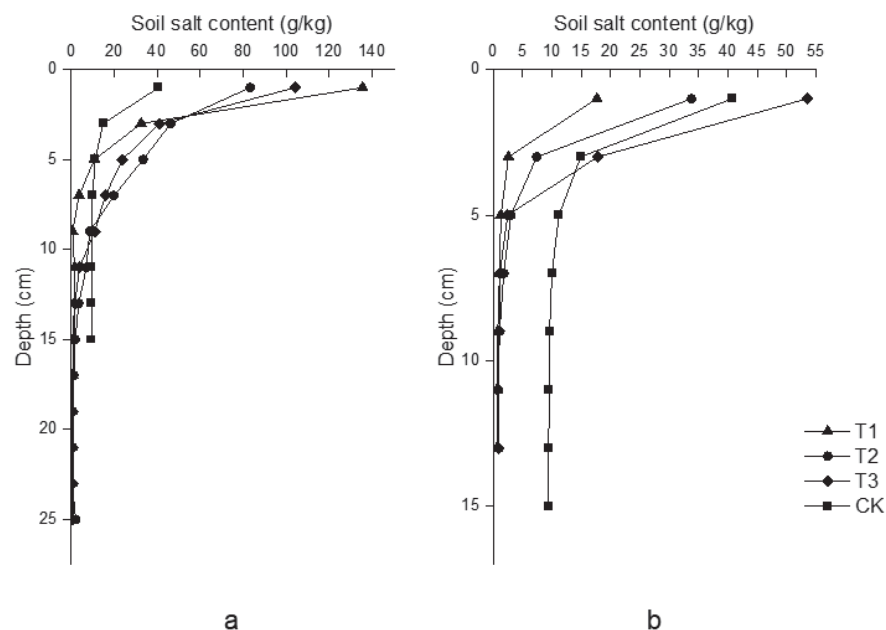


Figure 7. Trends of the soil salinity in different ridge and furrow profiles, where (a,b) are ridge and furrow profiles, respectively.

As shown in Figure 6b, the changes in soil salinity of furrows under different ridge–furrow systems were similar to those of the ridges, and the soil salinity decreased rapidly in the range of the 0–5 cm soil layer, where T1, T2, and T3 decreased by 16.36%, 30.29%, and 6.74%, respectively. At the depth of 3 cm, the soil desalination rates were ranked $T1 > T2 > CK > T3$, i.e., 72.69%, 22.38%, −56.22%, and −86.54%, respectively. At the depth of 5 cm, the salinity of the T3 furrow decreased rapidly, and the soil desalination rates were ranked $T1 > T3 > T2 > CK$, i.e., 86.30%, 74.10%, 68.09%, and −17.50%, respectively. The desalination rate did not change much below 5 cm, where T1 maintained a high desalination rate in each treatment, and the maximum desalination rates of T1 and T2 appeared at the bottom (15 cm), which were 93.07% and 91.63%, respectively. On top of that, T3 and CK had desalination rates of 92.01% and 0.96% in the 13 cm deep soil layer, respectively, indicating that the ridge–furrow patterns were conducive to desalination, among which the triangular ridge had the largest desalination rate, indicating that the desalination efficiency of this type of ridge–furrow system was the best, followed by the trapezoidal ridge, and the round arch ridge was the worst.

Na^+ and Cl^- are the key ions that hinder crop growth. It can be seen from the data that Na^+ and Cl^- were concentrated at the ridge, and their distribution patterns in the surface layer were similar to the salt content. The average contents of Na^+ in the T1, T2, and T3 ridges were higher than that on the surface of CK, and the average content of Na^+ in the T3 ridges was the highest at 9.25 g/kg. The average soil Na^+ content at the furrows was ranked $T2 > T3 > CK > T1$, indicating that the average content of Na^+ in the surface layer of the T1 furrow was the lowest in each treatment and was 1.46 g/kg. The average Cl^- contents of the soil in the CK and T1, T2, and T3 ridges were 42.40, 38.83, 90.01, and 46.46 cmol/kg, respectively, among which T2 was the highest, indicating that the trapezoidal-shaped ridge had the best effect on Cl^- aggregation. The average Cl^- contents in the surface soils of T1, T2, and T3 were 10.58, 30.48, and 43.87 cmol/kg, respectively, of which T1 was the lowest, indicating that the triangular-shaped ridge was more likely to create an environment with lower harmful ion levels in the furrows.

4. Discussion

Soil salinization occurs due to the movement of water through a porous material, which brings salt to the surface. As the water evaporates, the salts accumulate on the exterior surfaces or within the top layer of soil [24–26]. Theoretically, reducing water evap-

oration can reduce the degree of soil salinization and improve the growing environment of crops. Furrow planting is commonly used in agricultural production and is widely used around the world. In this study, after ridging, due to its lower positions, the airflow speed on the furrow surface was slower, and thus, the evaporation intensity was low, resulting in water gathering in the ridge and evaporation loss through the ridge surface, and the water content at the ridge and furrow was improved compared with the flat treatment, which was consistent with the results of Sun Chitao et al. [14]. The average annual evaporation in the Yellow River Delta is about four times the average annual precipitation, 70% of the precipitation occurs in summer, and has a shallow groundwater table depth, resulting in upward accumulation of soil salinity in spring and autumn rather than downward leaching [27,28]. After ridge lifting, the salt is transported to the ridge due to its strong evaporation strength, which reduces the soil salinity at the furrow [29,30]. Naturally, the salt at the surface of the furrow is dissolved and transported downward due to the heavy precipitation in summer, which further reduces the soil salt content at the ridge and furrow [31]. The soil surface evaporation was uniform under flat cropping, and there was no significant difference in the soil surface water content and salt content.

This study found that the migration of water and salt in the soil profile was also affected by the ridge shape, and the low soil water content and high salinity often appeared at the geometric inflection point of the ridge top, which may be caused by a large airflow velocity and high evaporation intensity at this position [29,30]. Taking the trapezoidal-shaped ridge as an example, our hypothesis was that in the process of water salt migrating up to the ridge, when passing through the geometric inflection point of “convexity”, a part of the water first evaporated and left the salt here; due to the effect of the matrix potential and solute potential, water salt was more easily caught at this point. Furthermore, different from the geometric inflection point on the ridge, the geometric inflection point of the “inner concave” of the ridge and furrow had no obvious salt accumulation due to the small evaporation intensity and limited water and salt reserves in the lower part. The surface layer of the triangular ridge had the highest salinity, which may have been due to the influence of the resultant force when the soil with salt was moved up; therefore, in the process of salt evaporation migration, there was both matrix potential traction from above and matrix potential traction from the soil surface (microtopographic edge), resulting in the gradual accumulation of surface salt all the way up through the slope, and the highest salt concentration happened at the superficial layer of the top, which also indicated that the strength of salt accumulation was related to the elevation of the point [9]. Through our study, 47.81%~60.01% of the total salt mass of each treatment was found concentrated at the superficial layer of the soil, which was higher than in the CK (38.62%), indicating a better salt accumulation effect on the ridge. The results provided observational evidence of salt migration through capillary rise [32].

The high concentration of Na^+ outside the cells of saline-alkali plants and the negative membrane potential in the plasma membrane constitute a transmembrane electrochemical potential difference, which promotes the excessive accumulation of Na^+ in the cell, causing an imbalance of intracellular ion metabolism and ion toxicity [33]. After ridge lifting, the soil Na^+ showed a similar distribution pattern with salt, when the ridge shape was triangular, the ridge and furrow soil Na^+ was the lowest, as well as the salt content, indicating that the effect of the triangular ridge was better for both salt and Na^+ removal, which may have been because of the flat and unobstructed triangular ridge slope, which made it possible to gather it on the surface. Meanwhile, due to the limited size of indoor experimental devices, the effect of the ridge shape on soil water and salt transport in fields still needs to be further explored.

5. Conclusions

Following the ridging creation, the soil's micro-topography resulted in variations in both soil water and salt distribution. The distribution of water and salt in different ridge patterns can serve as a guide to understanding capillary rise, which implies a potential

mechanism for the upward movement of salt in the ridge–furrow planting pattern. The ridge and furrow surface layer had a higher water content than the ridge, while salt was concentrated on the ridge, with the highest salt content at the geometric inflection point. The overall salinity in the ridge and furrow areas decreased, creating favorable conditions for plant growth. Notably, the soil within the 0–1 cm range of the triangular ridge’s surface layer accumulated 54.01% of the entire soil profile’s salt content. The average content of Na^+ and Cl^- of the surface layer of the T1 furrow was the lowest. Furthermore, the maximum desalination rate at the furrow bottom was the highest, reaching 93.07%, suggesting that the triangular ridge’s desalination efficiency outperformed other treatments. This study offers a scientific basis for the continual improvement of saline–alkali farming in the Yellow River Delta, a progression that can result in increased crop production and more effective land stewardship techniques.

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Article

Effect of Nitrogen Application and Microbial Fertilizer on Nitrogen Conversion Processes in Saline Farmland

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Abstract: The nutrient utilization rate of salinized farmland soils is low, the nitrogen loss is high, and soil salinity inhibits the hydrolysis of urea and the release of nutrients. In this work, the effect of microbial fertilizer on the nitrogen transformation characteristics and nitrogen morphology of salinized soils was studied using indoor constant temperature incubation tests with different nitrogen application rates—without (A0) and with microbial fertilizer application (A1 (15 t/ha)) or nitrogen application (N) of 0 kg/ha (N0), 97.5 kg/ha (N1), or 195 kg/ha (N2). The results show the following: (i) When no microbial fertilizer was applied, an increased nitrogen application promoted nitrogen fertilizer's ammonification and nitrification reactions. Furthermore, the maximum net nitrification rate with the high nitrogen fertilizer application decreased; the apparent ammonification rate and net ammonification rate A0N2 increased by 26.1% and 24.6%, respectively, compared with A0N1 on the first day of incubation; the maximum net nitrification rate of A0N1 was more than that of A0N2; and A0N1 > A0N2 on day 3, while A0N2 > A0N1 on days 3 to 15. At 3 d, the nitrogen conversion process of A0N1 was dominated by the nitrification reaction, while the ammonification reaction dominated in A0N2. (ii) Microbial fertilizers significantly increased the ammonification and nitrification rates under the low N fertilizer application. The intensity of ammonification and nitrification under the low N fertilizer application was greater than that under the high N fertilizer application. The apparent ammonification rate and net ammonification rate of A1N1 increased by 60.9% and 52.6% compared with A0N1 and 21.9% and 21.7% compared with A1N2 on the first day of incubation, and the peak net nitrification rates of A1N1 and A1N2 (28.19 mg/kg d and 11.02 mg/kg d, respectively) and net nitrification rates of A1N1 and A1N2 were 113.7% higher than those of A0N1. The net nitrification rates of A1N1 and A1N2 were 82.3% and 58.6% lower than the maximum net nitrification rates on the 15th day of incubation, respectively. (iii) In saline soils, low-nitrogen microbial fertilizers led to more ammonium nitrogen in the soil, and the high-nitrogen fertilizer application resulted in higher nitrate nitrogen in the soil, leading to nitrogen leaching. Therefore, when applying microbial fertilizer, choosing the most suitable period for reduced chasing is important for the efficient use of fertilizers, the alternative role of biofertilizers, and the study of environmental pollution.

Keywords: soil salinization; culture trials; microbial fertilizer; nitrogen application; nitrogen conversion

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1. Introduction

Nitrogen is one of the essential nutrients for plant growth and development. Nitrogen in soil is transformed into two forms, NH_4^+ and NO_3^- , which are mainly absorbed by plants through mineralization, nitrification, and denitrification promoted by soil microorganisms. However, NO_3^- is the main cause of N leaching [1,2]. To reduce N leaching, it is imperative

to regulate the process of N conversion. The amount of nitrogen applied is one of the main factors affecting the transformation of nitrogen by nitrogen fertilizers, which affects the rate and process of transformation in the soil. In general, adding exogenous nitrogen fertilizer can increase the soil urease and protease activities and promote mineralization to form ammonium nitrogen, thus increasing the net nitrogen mineralization [3]. Wang et al. [4] found that net soil ammonification was significantly higher in red loam soils under nitrogen application than in non-nitrogen treatments, and high nitrogen application inhibited soil nitrification. Tian et al. [5] showed that adding 250 mg/kg of exogenous N significantly increased the net N mineralization of purple tillage soils. Luo et al. [6] reported that low N treatment did not affect organic N mineralization in grassland soils, and high N treatment significantly promoted the net nitrification, ammonification, and mineralization rates. Nitrogen fertilizer increases the abundance and activity of soil *ammonia-oxidizing archaea* (AOA) and *ammonia-oxidizing bacteria* (AOB), resulting in a significant increase in the net nitrification rate with increasing nitrogen application; however, too much nitrogen fertilizer inhibits nitrification [7]. Zhu [8] analyzed the trend characteristics of N fertilizer on farmland in China, stating that ammonia volatilization losses accounted for 11% of applied N, nitrification–denitrification losses accounted for 34% of applied N, and runoff and leaching losses accounted for 7% of applied N. The losses were greater than crop uptake. It has also been reported that high N addition increases the risk of leaching losses of nitrate N and pollution of the environment [9]. Taken together, this suggests that the response of nitrogen transformation processes to N application may vary depending on soil type and N application level and that high N additions may not positively affect soil N supply capacity.

Soil salinity, an abiotic factor that affects crop yield, exerts a substantial influence on the efficiency of nitrogen utilization in crops through alterations in nitrogen transformations within saline soils. The process of salinization affects the cycling of nitrogen nutrients and the presence of inorganic nitrogen in the soil by modifying its physicochemical properties and microbial distribution [10]. Various scholars have investigated the impact of salinity on nitrogen transformations in soils, such as Wen [11], who analyzed the effects of salinity on soil mineralization and nitrification through soil incubation experiments, showing that a salinity at 2.9 g/kg significantly inhibited soil mineralization and nitrification processes, while a salinity below 1.9 g/kg did not significantly inhibit soil mineralization and nitrification processes. Reddy et al. [12] discovered that the mineralization of soil nitrogen was increasingly inhibited with rising salinity levels. Similarly, Li et al. [13] concluded that low salinity favors soil nitrogen transformations, whereas high salinity hampers it, with the inhibition becoming more pronounced as salinity increases. Previous studies demonstrate that salinization significantly affects soil nitrogen migration, transformation, and uptake, with the degree of inhibition being closely tied to soil salinity levels.

The beneficial microorganisms in microbial fertilizer promote mineral absorption through their own metabolism, enhance nitrogen fixation, improve the living environment of crops, and reduce their dependence on chemical fertilizers [14,15]. Regarding microbial fertilizers' impact on salinity, they perform remarkably well in saline farmland by reducing water evaporation from the soil surface layer and inhibiting salt accumulation in the shallow soil layer affected by water flow. Consequently, this fosters a reduction in soil salinity [16]. The selected microbial fertilizer in this study possesses an organic matter content exceeding 60%, which enhances nutrient absorption and utilization by crops while improving soil structure [17]. Duan et al. found that the application of different microbial fertilizers could lower soil salinity and increase the nutrient content in the soil. The effect of microbial fertilizers on nitrogen conversion was studied; applying *Bacillus subtilis* biofertilizers reduced ammonia volatilization by 44% in alkaline soils, reduced the conversion of nitrogen fertilizers to ammonium nitrogen, and accelerated the nitrification process [18]. Using *nitrogen-fixing cyanobacterial* biofertilizers reduced ammonia volatilization in red soil rice fields, increased the total soil nitrogen content, and increased the residence time of nitrogen in the soil, thus increasing the efficiency of nitrogen fertilizer

utilization [19]. The feasibility of replacing some nitrogen fertilizers with biofertilizers has been noted in existing studies [20–22]. Xuan et al. also confirmed this in a study on the effect of microbial fertilizers on the application of nitrogen fertilizer to sunflowers [15]. Previous studies have focused on the effects of biofertilizers on nitrogen fertilizer utilization and loss in non-saline soils and the effects of nitrogen application on nitrogen conversion in soils. This paper focuses on the effects of compound microbial fertilizers and different nitrogen application rates on soil nitrogen conversion processes in moderately saline soils to provide theoretical support for efficiently utilizing nutrients and reducing nitrogen loss in saline farmland soils.

2. Materials and Methods

2.1. Overview of the Area Where the Soil Samples Are Located

The test soil was taken from Sandaoqiao Town, Hangjinhou Banner, Bayannur City. The test area is located in the Loop Plain, a typical cold and arid area with an average annual precipitation of 135.9 mm, decreasing from southeast to northwest, with the most abundant precipitation in July and August. The local average annual temperature is 8.7 °C, evaporation is 1984.3 mm, the frost-free period is about 152 d, annual sunshine hours are over 3220 h, the cumulative temperature is over 3520 °C, and the sunshine rate is 73%. The saline soils contain mainly chloride and sulphate, the surface soil (0–20 cm) is sandy loam in texture, and the deep soil is mostly clay loam. The soil salinity ion composition is mainly Na^+ , Cl^- , and SO_4^{2-} .

2.2. Test Materials

The test chemical nitrogen fertilizer was urea, with a N content of 46%. The test commercial compound microbial fertilizer was *Eubacterium 1* (Paul Timken Biotechnology Ltd., Weifang, China); the main strains include *mycorrhizal fungi* 5%, *nitrogen fixing bacteria* 20%, *Bacillus megaterium* 10%, *Bacillus subtilis* 10%, *Bacillus coli* 15%, *Bacillus licheniformis* 5%, *Streptomyces jingdaoensis* 5%, beneficial live bacteria $\geq 5 \times 10^8$ CFU/g (actual bacteria content 1×10^9 CFU/g), and organic matter $\geq 60\%$. The physical and chemical indexes of the test soil are shown in Table 1.

Table 1. Soil physical and chemical indicators.

Bulk Density/ kg/cm ³	pH	Conductivity/ dS/m	Organic Matter g/kg	Total N g/kg	Available Phosphorus mg/kg	Nitrate Nitrogen/ mg/kg	Ammonium Nitrogen/ mg/kg	Inorganic Nitrogen/ mg/kg
1.45	8.0	2.40	17.2	0.78	21.35	18.88	13.79	32.67

2.3. Experiment Design

The experiment was conducted on moderately saline soils, using an indoor constant temperature culture. The experiment was set up with two factors: microbial fertilizer (without (A0), with (A1 (15 t/ha)) and nitrogen fertilizer (0 kg/ha (N0), 97.5 kg/ha (N1) (pure N), and 195 kg/ha (N2) (pure N)). The experiment was set up with six treatments, each replicated 18 times, for a total of 108 treatments.

The test was carried out in 250 mL plastic cups; 150 g of soil and microbial fertilizer were added to each cup, and the nitrogen fertilizer was added as an aqueous solution. The tops of the cups were sealed with cling film, and 20 small holes were evenly made in the cling film for ventilation, then the cups were placed in a constant temperature incubator at 25 °C. The soil was weighed and replenished daily to maintain the soil moisture content at 50–60% of the field water holding capacity. The soil's physical and chemical indicators were sampled at 1, 3, 5, 15, 25, and 35 d. Three replicates of each treatment were randomly taken at each time, and samples were taken at the end of the experiment to determine soil nitrogen patterns.

2.4. Measurement Methods and Calculations

The soil EC and pH were determined by the potentiometric method. The soil ammonium nitrogen ($\text{NH}_4^+\text{-N}$) content was determined using a 2 mol/L KCl leaching-indophenol blue colorimetric method [23]; the soil nitrate nitrogen ($\text{NO}_3^-\text{-N}$) content was determined using a dual wavelength UV spectrophotometer method; the soil total nitrogen content was determined using the semi-trace Kjeldahl method [24]; the soil organic matter was determined by the potassium dichromate volumetric external heating method [25]; and the available phosphorus in the soil was determined by the 0.5 mol/L NaHCO_3 method [26].

The following equations were used to calculate each index [27,28]:

$$\text{Inorganic N content (mg/kg)} = \text{NH}_4^+ - N_{t_n} + \text{NO}_3^- - N_{t_n}$$

$$\text{Apparent ammonification rate (mg/(kg}\cdot\text{d))} = (\text{bn NH}_4^+ - N_{t_{n+1}} - \text{bn NH}_4^+ - N_{t_n}) / (t_{n+1} - t_n)$$

$$\text{Net ammonification rate (mg/(kg}\cdot\text{d))} = [\text{bn (NH}_4^+ - N_{t_{n+1}} - \text{NH}_4^+ - N_{t_n}) - \text{CK (NH}_4^+ - N_{t_{n+1}} - \text{NH}_4^+ - N_{t_n})] / (t_{n+1} - t_n)$$

$$\text{Apparent nitrification Rate (mg/(kg}\cdot\text{d))} = (\text{bn NO}_3^- - N_{t_{n+1}} - \text{bn NO}_3^- - N_{t_n}) / (t_{n+1} - t_n)$$

$$\text{Net nitrification rate (mg/(kg}\cdot\text{d))} = [\text{bn (NO}_3^- - N_{t_{n+1}} - \text{NO}_3^- - N_{t_n}) - \text{CK (NO}_3^- - N_{t_{n+1}} - \text{NO}_3^- - N_{t_n})] / (t_{n+1} - t_n)$$

Note: $\text{NH}_4^+\text{-N}$, soil ammonium nitrogen content; $\text{NO}_3^-\text{-N}$, soil nitrate nitrogen content; bn, microbial fertilizer and nitrogen fertilizer dosage; CK, no fertilizer control; t_n , previous sample; t_{n+1} , latter sample.

2.5. Data Analysis Method

Microsoft Excel 2016 was used for data calculation; Origin 2022 software was used for plotting; SPSS 19.0 was used for statistical analysis; and Duncan's method was used for multiple comparisons.

3. Results

3.1. Effect of Microbial Fertilizer and Different Nitrogen Applications on the Ammonification Process of Nitrogen Fertilizer

As seen from Table 2, the ammonification rates of both the microbial fertilizer and the different nitrogen application treatments peaked on the first day of incubation and then declined rapidly after reaching the peak, with the most apparent decrease in the net ammonification rate from 1 to 3 d. Under the condition of no microbial fertilizer, the apparent and net ammonification rates of A0N2 were more than those of A0N1 on the first day of incubation; A0N2 increased by 26.1% and 24.6%, respectively, compared with A0N1. On the third day of incubation, the nitrogen conversion process of A0N1 was dominated by nitrification, while A0N2 was dominated by ammonification. Under the conditions of microbial fertilizer application, A1N1 had the maximum apparent ammonification rate and net ammonification rate, which were 21.9% and 21.7% higher than A1N2, respectively. The nitrification reaction in A1N1 was dominant on the third day of incubation, while the ammonification reaction in A1N2 remained dominant on the seventh day. The apparent ammonification and net ammonification rates of the fertilization treatments at d 1 were $\text{A1N1} > \text{A1N2} > \text{A0N2} > \text{A0N1}$. The apparent ammonification rate and net ammonification rate of A1N1 increased by 60.9% and 52.6% compared to A0N1, and A1N2 increased by 4.6% and 0.6% compared to A0N2.

Table 2. Rates of soil ammonification by microbial fertilizers and different nitrogen application treatments (mg/(kg·d)).

Indicator	Incubation Time (d)	A0N1	A0N2	A1N1	A1N2
Apparent ammonification rate	1	132.18	166.74	212.71	174.44
	3	−22.16	4.93	−23.59	6.85
	7	−11.20	−10.85	−16.92	1.58
	15	−6.64	−8.63	−10.70	−8.48
	25	−0.23	−7.41	−2.51	−13.89
	35	−0.12	−0.35	−0.09	−0.15
Net ammonification rate	1	140.62	175.18	214.54	176.27
	3	−20.99	6.10	−21.46	8.99
	7	−10.54	−10.19	−16.50	2.01
	15	−6.63	−8.61	−10.24	−8.03
	25	−0.50	−7.68	−2.32	−13.71
	35	−0.05	−0.28	−0.05	−0.11

3.2. Effect of Microbial Fertilizers and Different Nitrogen Applications on the Nitrification Rate of Nitrogen Fertilizers

As seen from Table 3, the apparent nitrification rates for the microbial fertilizer and different nitrogen application treatments peaked at d 1 and then declined rapidly, while the net nitrification rates were very low or even negative, indicating that denitrification was predominant at this time. In the absence of microbial fertilizer, the net nitrification rates of A0N1 and A0N2 peaked at 10.85 mg/kg d and 8.96 mg/kg d at d 7 and 2.14 mg/kg d and 2.76 mg/kg d at d 15, a decrease of 80.3% and 69.2%, respectively, compared to d 7. Under the conditions of microbial fertilizer application, the net nitrification rate of A1N1 and A1N2 peaked at 28.19 mg/kg d and 11.02 mg/kg d on the third and seventh day of incubation, respectively. The net nitrification rates of A1N1 and A1N2 peaked at 23.19 mg/kg d and 11.02 mg/kg d at d3 and d7, respectively, and were 4.11 mg/kg d and 4.56 mg/kg d at d15 of incubation. A1N1 and A1N2 decreased by 82.3% and 58.6%, respectively, compared to the maximum net nitrification rates, and the nitrification reaction process of A1N1 was nearly complete. When comparing the soil net nitrification rates, the peak of A1 treatment was higher than that of A0 treatment, and the peak size of the net nitrification rate was A1N1 > A1N2 > A0N1 > A0N2. A1N1 increased by 113.7% and A1N2 increased by 23.0% compared with A0N1.

Table 3. Microbial fertilizers and nitrification rates in soils treated with different nitrogen application rates (mg/(kg·d)).

Indicator	Incubation Time (d)	A0N1	A0N2	A1N1	A1N2
Apparent nitrification rate	1	81.81	79.07	83.44	97.32
	3	3.97	10.32	18.74	3.37
	7	8.91	7.01	2.74	8.99
	15	3.57	4.19	2.82	3.26
	25	−0.62	−0.92	−0.46	−1.44
	35	−0.82	−1.19	−1.03	−0.48
Net nitrification rate	1	−19.55	−22.28	−52.03	−38.15
	3	1.67	8.02	23.19	7.82
	7	10.85	8.96	4.77	11.02
	15	2.14	2.76	4.11	4.56
	25	−1.94	−2.25	−0.05	1.03
	35	−0.05	−0.42	0.16	0.71

3.3. Changes in Nitrogen Content of Salinized Farmland Soils as a Result of Microbial Fertilizers and Different Nitrogen Applications

3.3.1. Effect of Microbial Fertilizer and Different Application Rates of Nitrogen on the Change in Ammonium Nitrogen Content in Salinized Farmland Soils

As seen in Figure 1, the ammonium nitrogen content of the N1 application peaked on the first day of incubation and then decreased rapidly. At the same time, the ammonium nitrogen content of the N2 application showed a trend of increasing and then decreasing. The soil ammonium nitrogen content of all the nitrogen fertilizer treatments decreased to the lowest from 25 to 35 d with no difference from the control treatment. Under the condition of no microbial fertilizer application, the ammonium nitrogen content of A0N1 treatment peaked on the first day of incubation, and A0N2 peaked on the third day of incubation. The ammonium nitrogen content of all nitrogen treatments in saline soil was significantly higher than the A0N0 treatment. Under the conditions of microbial fertilizer application, the ammonium nitrogen content of A1N1 reached its peak on the first day of incubation, A1N2 reached its peak on the seventh day of incubation, and the ammonium nitrogen content of all the nitrogen fertilizer treatments was significantly higher than that of A1N0. On d 1, the trend in soil ammonium nitrogen content was A1N1 > A1N2 > A1N0, and on d 3–15, the trend in soil ammonium nitrogen content was A1N2 > A1N1 > A1N0. On balance, the A1 treatment had a higher ammonium nitrogen content than the A0 treatment from d 1–25 with the same amount of nitrogen fertilizer. By d 15 of incubation, the nitrogen contents of A0N1 and A1N1 were 97.5% and 89.0% lower than their respective maximum ammonium nitrogen content, and the nitrogen contents of A0N2 and A1N2 were 62.4% and 32.6% lower than their respective maximum ammonium nitrogen content, with the N1 treatment dropping to the lowest ammonium nitrogen content and the N2 treatment maintaining a higher content. Comparing the maximum ammonium nitrogen content of the applied nitrogen treatments, A1N1 had the maximum ammonium nitrogen content of 236.50 mg/kg, which was 62.0%, 14.0%, and 13.6% higher than A0N1, A0N2, and A1N2, respectively, and A1N2 increased by 9.4% compared to A0N2.

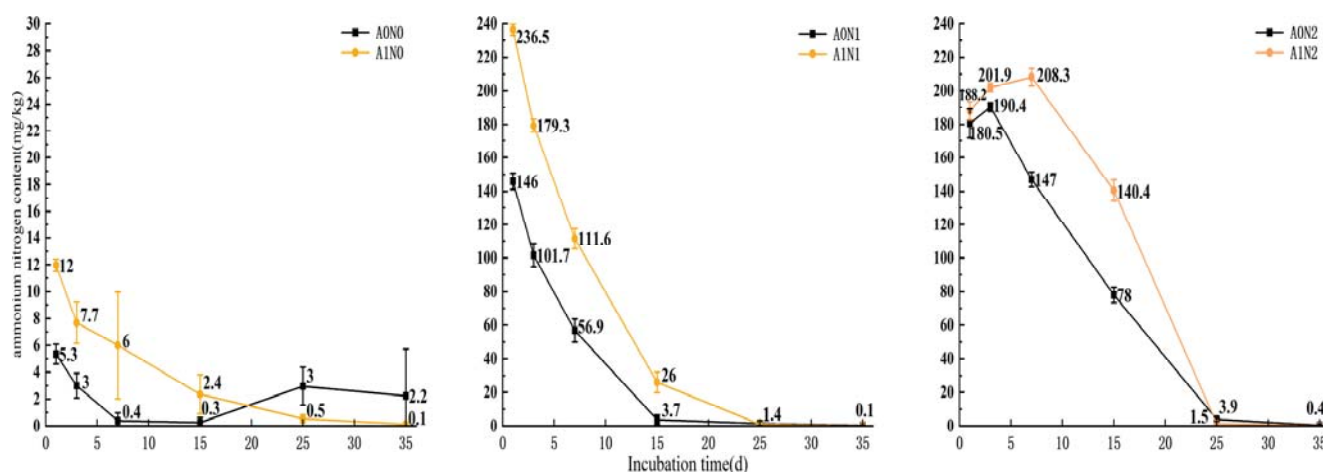


Figure 1. Changes in ammonium nitrogen content in saline soil during cultivation.

The results of an ANOVA between microbial fertilizer and nitrogen application on the soil ammonium nitrogen content are shown in Table 4. The interaction between microbial fertilizer and N application significantly affected the soil ammonium N content from 1 to 15 d of incubation.

Table 4. Variance analysis of the effect of microbial fertilizer and N application on soil ammonium N content.

Treatment	1 d		3 d		7 d		15 d		25 d		35 d	
	F	<i>p</i>	F	<i>p</i>	F	<i>p</i>	F	<i>p</i>	F	<i>p</i>	F	<i>p</i>
A	191.001	<0.001 *	338.419	<0.001 *	306.779	<0.001 *	209.350	<0.001 *	15.421	0.002 *	1.611	0.228
N	2650.629	<0.001 *	4438.005	<0.001 *	1886.159	<0.001 *	1154.125	<0.001 *	3.923	0.049 *	0.981	0.403
A × N	114.332	<0.001 *	187.127	<0.001 *	57.575	<0.001 *	78.798	<0.001 *	2.113	0.164	0.815	0.466

Note(s): * indicates a significant linear correlation in soil nitrogen content at the $p < 0.05$ level.

3.3.2. Effect of Microbial Fertilizers and Different N Application Rates on Changes in Nitrate N Content of Saline Farmland Soils

As shown in Figure 2, the nitrate–nitrogen content of the nitrogen fertilizer treatments showed a higher level with treatment A1 than A0 during the 35 days of incubation. When no microbial fertilizer was applied, the nitrate–nitrogen content of the soil in each nitrogen application treatment increased with increasing incubation time, reaching peaks of 144.24 (A0N1) and 180.21 (A0N2) on the 15th day of incubation, respectively, while the nitrate–nitrogen content of salinized soil in the A0N0, A0N1, and A0N2 treatments was 134.10 mg/kg, 158.50 mg/kg, and 159.08 mg/kg on the 35th day of incubation, respectively. Under the conditions of microbial fertilizer application, the nitrate–nitrogen content of the soil in each nitrogen application treatment increased with increasing incubation time, reaching peaks of 173.33 (A1N1) and 185.00 (A1N2) on the 15th day of incubation, and the trends in nitrate–nitrogen content of the saline soil on the first day of incubation was A1N0 > A1N2 > A1N1, on the third day of incubation it was A1N0 > A1N1 > A1N2, and in the remainder of the incubation time it was A1N0 > A1N2. A1N1 > A1N2. The rest of the time, the trend in soil nitrate nitrogen content was A1N2 > A1N1 > A1N0.

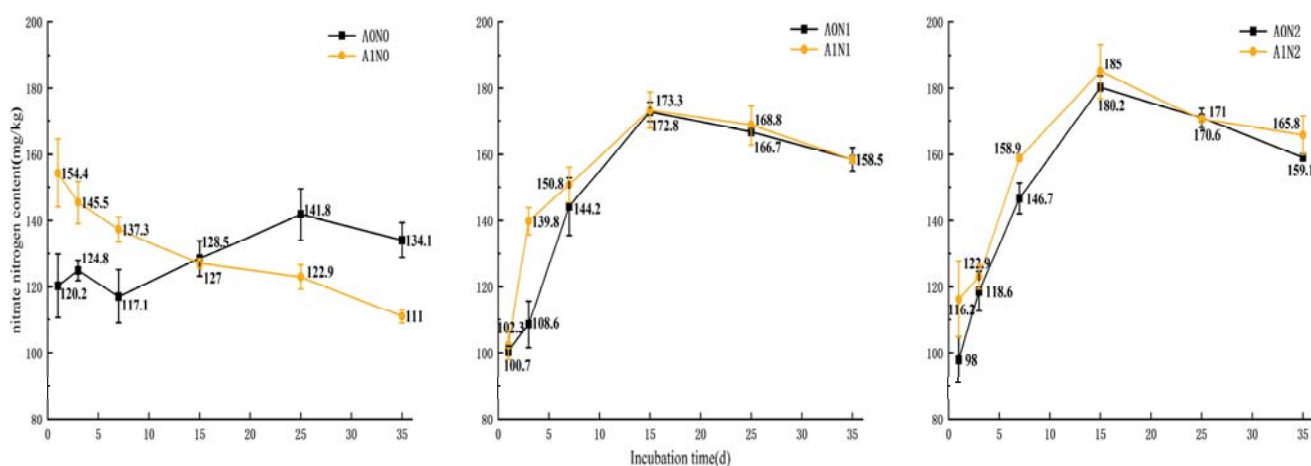
**Figure 2.** Dynamic changes in nitrate–nitrogen content in saline soil during cultivation.

Table 5 shows the significance of microbial fertilizer and nitrogen application on the soil nitrate–nitrogen content. The results show that nitrogen application had a significant effect on the soil nitrate–nitrogen content at 35 d of incubation ($p < 0.05$), and the addition of microbial fertilizer had no significant effect on the soil nitrate–nitrogen content at 1 d and 15 d of incubation ($p > 0.05$), and a significant effect at 3–7 d and 25–35 d ($p < 0.05$). The interaction between microbial fertilizer and nitrogen application significantly affected the soil nitrate–nitrogen content on 3 d and between 25 and 35 d.

Table 5. Variance analysis of the effect of microbial fertilizer and nitrogen application on soil nitrate nitrogen content.

Treatment	1 d		3 d		7 d		15 d		25 d		35 d	
	F	p	F	p	F	p	F	p	F	p	F	p
A	0.289	0.600	56.671	<0.001 *	22.332	<0.001 *	0.289	0.600	7.392	0.019 *	10.245	0.008 *
N	208.775	<0.001 *	12.525	0.001 *	32.013	<0.001 *	208.775	<0.001 *	137.461	<0.001 *	219.571	<0.001 *
A × N	0.631	0.549	10.248	0.003 *	2.091	0.166	0.631	0.549	9.886	0.003 *	27.776	<0.001 *

Note(s): * indicates a significant linear correlation in soil nitrogen content at the $p < 0.05$ level.

3.3.3. Effect of Microbial Fertilizers and Different N Applications on Changes in the Inorganic N Content of Saline Farmland Soils

From Figure 3, the inorganic N content of the soil under the N1 fertilizer dosage first declined and then remained nearly unchanged, while the inorganic N content of the soil under the N2 fertilizer dosage first increased, then decreased, and then remained nearly unchanged. The trend in inorganic nitrogen content was $A1N1 > A0N1$, $A1N2 > A0N2$, $A0N2 > A0N1$ from 1 to 15 d of incubation, and the difference in inorganic nitrogen content was smaller between the nitrogen fertilization treatments from 25 to 35 d of incubation.

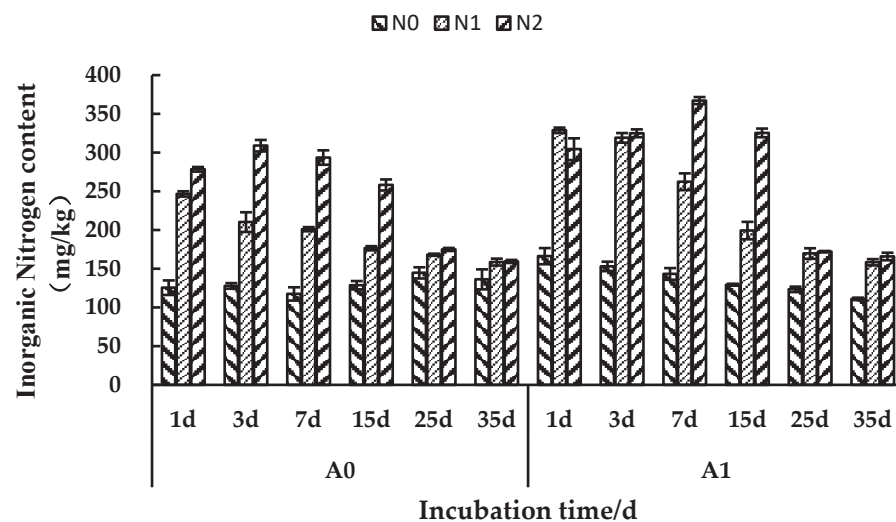
**Figure 3.** Dynamic changes in inorganic nitrogen content in saline soil during cultivation.

Table 6 shows the significance analysis of the effect of microbial fertilizer and nitrogen application on the inorganic nitrogen content of the soil. The results show that there is a significant difference ($p < 0.05$) between nitrogen application and microbial fertilizer on the inorganic nitrogen content of the soil in the 35 d of incubation, and the interaction between microbial fertilizer and nitrogen application has a significant effect on the inorganic nitrogen content of the soil from 1 to 35 d.

Table 6. Variance analysis of the effect of microbial fertilizer and N application on soil inorganic state N content.

Treatment	1 d		3 d		7 d		15 d		25 d		35 d	
	F	p	F	p	F	p	F	p	F	p	F	p
A	101.409	<0.001 *	207.978	<0.001 *	206.777	<0.001 *	101.409	<0.001 *	13.006	0.004 *	8.420	0.013 *
N	1009.699	<0.001 *	913.651	<0.001 *	957.147	<0.001 *	1009.699	<0.001 *	143.508	<0.001 *	127.711	<0.001 *
A × N	42.794	<0.001 *	73.259	<0.001 *	14.696	<0.001 *	42.794	<0.001 *	11.421	0.002 *	19.337	<0.001 *

Note(s): * indicates a significant linear correlation in soil nitrogen content at the $p < 0.05$ level.

4. Discussion

4.1. Effect of Microbial Fertilizers and Different Nitrogen Applications on the Rate of Ammonification of Nitrogen Fertilizers

As nitrogen fertilizer was added as an aqueous solution in this experiment, there was no need for soil wetting to dissolve the nitrogen fertilizer's active ingredients before entering the soil. Hence, each treatment's ammonification rate and net ammonification rate were high and peaked on day 1 of incubation, after which the ammonification rate of each treatment decreased rapidly. Fertilizer application significantly enhances the total soil nitrogen content, organic carbon content, and microbial mass carbon, thereby influencing the intensity and timing of nitrogen transformation processes within the soil [29]. Introduction of exogenous inorganic nitrogen promotes the accumulation of soil ammonium nitrogen, primarily through a reduction in nitrification [30]. The microbial fertilizer utilized in this study exhibits an organic matter content exceeding 60%. Consequently, its application leads to an increase in soil organic matter content and exerts a regulatory effect on soil carbon and nitrogen. Organic materials increase the growth rate of soil microorganisms, contributing to an increase in total microbial biomass and, consequently, an increase in the accumulation of microbial residues. In this study, without microbial fertilizer, the ammonification rate was accelerated by increasing nitrogen application, and the high nitrogen application rate prolonged the nitrogen conversion process, with ammonification as the main effect. The application of microbial fertilizer significantly increased the ammonification rate in N1 application and prolonged the nitrogen conversion process, with the ammonification reaction as the primary role in N2 application. In a comprehensive comparison, the A1N1 treatment had the maximum ammonification rate, and there was no significant difference between A1N2 and A0N2. The ammonification rate of salinized soil with microbial fertilizer was greater than without under the same amount of nitrogen application. The results of Chen et al. [31] and Wang [29] showed that organic fertilizers had a significant slow-release effect on soil nitrogen, and the addition of organic fertilizers significantly enhanced the intensity of soil ammonification, which was similar to the results of this experiment. The study of Wen et al. [32] found that the nitrogen application treatment showed a promoting effect on the soil ammonification rate, and the soil ammonification increased by increasing the amount of nitrogen application, which was consistent with the results of this experiment. We also found that the promoting effect of microbial fertilizer on nitrogen ammonification was related to the amount of nitrogen applied. The promoting effect decreased with increased nitrogen application, which might be because adding microbial fertilizer increased the type and number of microorganisms driving nitrogen transformations and the organic matter content in the soil. However, chemical fertilizer also had an inhibitory effect on microorganisms. Some studies showed [33] that soil salinity and application of nitrogen fertilizer in moderately salinized soil inhibited the reduced promotion effect of microbial fertilizers.

4.2. Effect of Microbial Fertilizers and Different Nitrogen Applications on Nitrification Rates of Nitrogen Fertilizers

Nitrification is an essential part of the nitrogen cycle and is closely related to the ratio of soil ammonium nitrogen to nitrate nitrogen, divided into the ammonia oxidation process—in which ammonium nitrogen is converted to nitrite nitrogen—and the nitrite oxidation process in which nitrite nitrogen is converted to nitrate nitrogen [34]. The net nitrification rates were all negative on the first day of incubation when the soil was probably dominated by denitrification, and the negative values were larger in the treatment with the addition of microbial fertilizer, probably because the microbial fertilizer contained a large amount of organic matter, which temporarily inhibited autotrophic nitrification. The intensity of the reaction increased so that nitrification rates showed a significant decrease and then an increase [35]. This study showed that under the condition of no microbial fertilizer application, N2 application promoted the nitrification reaction process of nitrogen fertilizer compared with N1 application, but the maximum nitrification reaction intensity

decreased, and N2 application prolonged the nitrogen conversion process mainly by nitrification reactions. The application of microbial fertilizer increased the nitrification rate of nitrogen fertilizer, and the nitrification effect of N1 application was stronger than N2 application, which prolonged nitrogen conversion dominated by the nitrification reaction in N2 application. Jia et al. [36] showed that high nitrogen application promoted soil nitrification more significantly, which is consistent with this paper. Yin et al. [37] showed that the nitrification and mineralization of soil nitrogen were significantly enhanced from days 3 to 35 of the culture period. It was found that treatments with microbial fertilizers prolonged the nitrification reaction time and had a greater nitrification reaction intensity, which may be due to the addition of microbial fertilizers, increasing the number of subnitrifying and nitrifying bacteria in the soil and promoting the conversion of ammonium to nitrate nitrogen in the soil.

4.3. Effect of Microbial Fertilizers and Different N Application Rates on Soil N Content

In this experiment, the ammonium nitrogen content of the soil peaked and then decreased rapidly with increasing incubation time, while the nitrate nitrogen then increased rapidly. The ammonium nitrogen in the soil was converted to nitrate nitrogen by the nitrification reaction process because the rapid increase in ammonium nitrogen as a substrate for the nitrification reaction promotes the nitrification reaction and the associated bacterial community. It has been shown that the amount of nitrogen fertilizer determines the amount of mineral nitrogen in the soil [34,38,39]. The high N fertilizer application rate in this study resulted in ammonium N retention in the soil, which was longer with the addition of microbial fertilizer, consistent with the change in ammonification rate above. The reason for the retention may be because high levels of ammonium N in the soil inhibit microbial uptake and utilization of other N sources, which in turn inhibits the conversion of ammonium N to nitrate N, keeping the ammonium N in the soil at a high level [40]. The increase in ammonium N content in soil is the leading cause of ammonia volatilization [18], so high N addition and application with microbial fertilizer may increase the loss of N fertilizer through ammonia volatilization; the effect of N application on the soil nitrate N content was greater for high N fertilizer application treatment than low N fertilizer application treatment, which is consistent with the results of Qin et al. [7]. The nitrate–nitrogen content of low nitrogen application with microbial fertilizer was higher than high nitrogen application with microbial fertilizer and treatments without microbial fertilizer in the early stage of culture, and there was no significant difference in the nitrate–nitrogen content of all nitrogen application treatments in the late stage of culture. In general, the low N fertilizer with microbial fertilizer promoted the conversion of N into more inorganic N for plant uptake and use in the early stage of culture; the content decreased in the middle of the culture but remained high, mainly in the form of nitrate N. The high N fertilizer with microbial fertilizer maintained a high content of inorganic N in the early and middle stages of culture, mainly in the form of ammonium N and nitrate N. All treatments had a higher content of inorganic N in the late stage of culture. The inorganic nitrogen content of all treatments did differ significantly at the later stage of cultivation and was dominated by nitrate nitrogen. In the river loop irrigation area, nitrate–nitrogen is easily soluble in water, so high nitrogen fertilizer addition maintains high nitrate–nitrogen and ammonium–nitrogen contents in the soil for a long time, which will not only easily cause groundwater pollution by leaching but also great fertilizer loss. Meanwhile, the ammonium–nitrogen content in the soil is the highest with a low nitrogen fertilizer dosage, but it is present for a shorter period. Therefore, this study concluded that it is feasible to replace part of the nitrogen fertilizer with microbial fertilizer. The basis of its replacement is to choose a suitable application period and carry out a reasonable reduction in fertilizer chasing during the crop nitrogen demand period, which can provide sufficient nutrients for the crop, improve fertilizer utilization efficiency, and reduce nitrogen loss.

5. Conclusions

Both microbial fertilizer and nitrogen application in moderately saline soils have a significant effect on nitrogen conversion:

- (i) When no microbial fertilizer was applied, an increased nitrogen fertilizer application promoted the ammonification and nitrification of nitrogen fertilizer and reduced the maximum nitrification rate under high nitrogen fertilizer application. A high nitrogen fertilizer application prolonged the process of nitrogen transformation, with ammonification and nitrification reactions as the main effects. From the perspective of fertilizer utilization and the ecological environment, reducing nitrogen application can suppress the intensity and duration of soil nitrification reactions, thereby decreasing the content of nitrate nitrogen in the soil and reducing nitrate leaching losses.
- (ii) The application of microbial fertilizer significantly increased the rate of ammonification and nitrification for the low N fertilizer dosage, the intensity of ammonification and nitrification for the low N fertilizer dosage was greater than the high N fertilizer dosage, and the application of microbial fertilizer prolonged the nitrogen transformation with ammonification and nitrification reactions as the main effects under the high N fertilizer dosage. When microbial bacterial fertilizers are applied together with low-nitrogen fertilizers, there is a higher presence of ammonium nitrogen in the soil. Conversely, when high-nitrogen fertilizers are applied, the soil maintains a consistently high level of nitrate nitrogen, significantly increasing the risk of nitrogen leaching.
- (iii) In terms of nitrogen conversion, the use of microbial fertilizers as a substitute for a portion of nitrogen fertilizers in salinized farmland effectively increases the nitrogen nutrient content required by crops. To capitalize on this benefit, appropriate timing of subsequent fertilization is crucial, allowing the substantial amount of ammonium nitrogen produced by microbial fertilizers to be efficiently utilized. By doing so, the risk of fertilizer loss and environmental pollution can be minimized.

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Article

Temporal and Spatial Characteristics of Soil Salinization and Its Impact on Cultivated Land Productivity in the BOHAI Rim Region

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Abstract: Soil salinization can have an inhibitory effect on crop productivity and pose a serious threat to regional agricultural resource utilization and sustainable development. However, there are scarce studies on the quantitative impact of soil salinization on crop productivity. The purpose of this study is to identify the spatial and temporal characteristics of the cultivated land, the soil salinization degree, and the net primary productivity (NPP) of vegetation in the Shandong region around the Bohai Sea and to couple the quantitative relationship between soil salinization and the productivity of the cultivated land. We found that the amount of cultivated land in the study area gradually decreased from 2001 to 2019. The degree of soil salinization in the cultivated land in the north of the study area increased slightly from 2001 to 2005 and decreased continuously after 2011. The NPP value of the cultivated land increased, fluctuating from 2001 to 2019. The spatial distribution of the NPP value was generally lower in the north than in the south, with Dongying District as the boundary. In addition, in different soil salt content (g/kg) intervals, the change trends in cultivated land NPP varied. When the salt content of cultivated soil was in the range of 0–3 g/kg, 3–7 g/kg, or 7–15 g/kg, for every 1 g/kg increase in salt content, the NPP value decreased by 43.62 gC m⁻²a⁻¹, 30.36 gC m⁻²a⁻¹, and 44.19 gC m⁻²a⁻¹, respectively. These results are expected to provide decision-making support for strengthening the dynamic monitoring and regulation of cultivated land salinization and promoting sustainable utilization of salinized cultivated land in the coastal areas to alleviate the food crisis.

Keywords: cultivated land capacity; soil salinization; net primary productivity; spatio-temporal characteristics; remote sensing; Bohai Rim Region

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1. Introduction

Soil salinization is a form of land degradation caused by natural or human activities [1]. About 8.31×10^8 hm² of soil in the world is threatened by salinization [2]. With the continuous impact of global climate change and human activities, the land area affected by salt is expanding [3]. At the same time, the world has been on the verge of a serious food crisis for the past 50 years [4]. In 2021, the number of hungry people resulting from the worldwide food shortage reached 828 million, 46 million more than that in 2020 [5]. Under the influence of the global COVID-19 pandemic and the locust plague in Africa, the number of hungry people in the world may further increase [6,7]. The total area of salinized soil with utilization potential in China is about 3.6×10^7 hm², accounting for 4.88% of the nationally available land area [8]. This has seriously affected our ability

to realize the goal of increasing grain production, farmers' income, and the sustainable utilization of resources throughout the country. Therefore, the comprehensive utilization of salinized land is of great strategic significance to ensure national food security. The low plain area around the Bohai Sea has been the main battlefield for the development and utilization of salinized land in China in recent years, and it is also the focus of social and academic attention [9,10]. For two consecutive years, from 2015 to 2016, the "No. 1 Central Document" proposed the "implementation of scientific and technological projects for high grain yield and scientific and technological demonstration of saline alkali land transformation" and to "implement the scientific and technological demonstration project of the Bohai granary, increase scientific and technological support, and accelerate the transformation of saline alkali land" [11]. However, due to the shortage of freshwater resources, less precipitation with uneven temporal and spatial distribution, frequent and abnormal droughts and floods caused by climate anomalies, poor saline-alkali land, and urbanization occupation [11], the amount and quality of the cultivated land in the Bohai Rim region have changed greatly in temporal and spatial distribution. In addition, the stability and sustainability of cultivated land productivity have been seriously threatened. It is an urgent task to determine the spatial and temporal change characteristics of cultivated land in salinized areas, the changing trend in the productivity of salinized cultivated land, and the quantitative relationship between the degree of salinization and productivity of cultivated land. This is of great significance for the sustainable development of coastal agriculture, food security, and achieving the goal of zero growth in land degradation [12].

The traditional dynamic monitoring methods for soil salinization mostly use data on soil salt content obtained with field sampling and laboratory testing. Although this method has high accuracy in obtaining data, it is time-consuming, laborious, expensive, and limited in sample size, which is not conducive to large-scale and long-term monitoring [13]. The soil salinometer based on conductivity simplifies the sampling process and helps to quickly obtain soil salt content data at different depths. However, it is still not suitable for long-term monitoring of regional saline soil [14]. Optical remote sensing data have the advantages of wide coverage, low cost, less ground limitation, and rich historical data, and these data have been widely used for the dynamic monitoring and evaluation of soil salinization. This makes it possible to monitor salinized soil on a large scale rapidly and dynamically [15]. Masoud et al. [16] built an inversion model for soil salinization in the central plain of Morocco based on Landsat 8 spectral data, which was used to monitor the degree of salinization in the Dakhla Oasis. Wang et al. [17] constructed inversion models for salinization at different degrees in typical areas of the Yellow River Delta based on UAV and Sentinel-2A images. Tran et al. [18] constructed an enhanced salinity index (ESI) and analyzed the dynamic change characteristics of soil salinization in the Mekong Delta according to a long time series of Landsat images from 1989 to 2018. These are successful cases that used optical remote sensing data to monitor regional soil salinization.

The net primary productivity (NPP) of vegetation refers to the total amount of organic matter accumulated with vegetation photosynthesis minus its own respiration [19]. It reflects the productive capacity of vegetation under the comprehensive influence of climate, terrain, and human factors in the natural environment [20,21]. Research shows that NPP is more sensitive to climate change and human activities than the normalized difference vegetation index (NDVI) [22]. Therefore, it can accurately reflect the status of vegetation productivity and can be also used as an important factor to measure the productivity of cultivated land. Past research confirmed that NPP data in the MOD17A3 dataset could represent the productivity of cultivated land [23]. Soil salinization of cultivated land affects regional NPP values, which harms crop productivity by inhibiting crop growth. Coastal areas have a wide range of salinized farmland, which is a key area for the transformation of low- and medium-yield farmland and improvement in farmland production potential in the future. An in-depth analysis of the impact of soil salinization on cultivated land productivity is essential for achieving efficient utilization of cultivated land resources and ensuring national food security. However, the existing research focused on the correlation

between the quality of non-salinized farmland and NPP [24,25], and research on the relationship between salinization and farmland productivity has not received due attention. Compared with previous studies, this paper attempts to quantitatively elucidate the effects of different degrees of salinized soils on cultivated land productivity by analyzing time series characteristics and their interrelationships between soil salinity and cultivated land productivity. Using these results, this paper then explains the comprehensive management effect of saline cultivated land in a certain period. This approach is more conducive to understanding the characteristics of and trends in the changes to salinized cultivated land, and it is of great significance for the improvement and regulation of local salinized cultivated land. Due to the fact that cultivated land productivity can reflect the degree of soil salinization, we assume that the productivity of cultivated land is highly correlated with soil salt content, and based on the aforementioned analysis, we conduct our research in this paper.

Our main research objectives are as follows: (1) analyze the temporal and spatial characteristics of soil salinization and NPP of cultivated land in the Shandong region around the Bohai Sea from 2001 to 2019 and (2) quantitatively express the influence of soil salinization on cultivated land productivity. Our study aims to elucidate the impact of salinity on cultivated land productivity by analyzing the spatial and temporal dynamic characteristics of salinity and NPP of the cultivated land and to provide support for using quantitative measures to regulate salinity, improve farmland productivity, and alleviate food security problems.

2. Materials and Methods

2.1. Study Area

The study area is located in the Shandong part of the Bohai Sea rim, mainly including the whole areas of Qingyun County, Wudi County, Zhanhua District, Hekou District, Lijin County, Kenli District, Dongying District, Guangrao County, Shouguang City, Hanting District, and Changyi City and partial areas of Pingdu City and Laizhou City. The geographical coordinates are 117°26′–120°19′ E, 36°26′38″19′ N (Figure 1). The area has a high elevation in the south and a low elevation in the north. The geomorphic types include river beach highlands (including riverbed, shoal, natural levee, and crevasse splay in each stage), flood plains, and depressions [26]. The study area is located in the warm temperate zone and is cold in the winter and hot in the summer. The annual average temperature is 9–20 °C, the annual average precipitation is 530–630 mm, and the annual potential evapotranspiration is 1500 mm. The distribution of precipitation is uneven in time and space. In the spring, there is little precipitation and strong evaporation, and salt easily accumulates on the land surface. In summer, there is more rainwater, which easily leads to waterlogging. The soil types are mainly fluvo-aquic soil and saline soil, and silty soil is most widely distributed in the cultivated layer. Groundwater is mainly brackish water, salt water, and brine. The special sedimentary environment, climate conditions, and soil parent materials lead to serious salinization of the cultivated land, and the area of primary salinization in the cultivated land is as high as 70%.

2.2. Data Sources

2.2.1. Remote Sensing Data

The land cover type data were obtained from the results of Landsat remote sensing images produced by Huang Xin's team at Wuhan University [27]. There are five types of land: cultivated land, forest land, water area, construction land (impervious water surface), and tidal flats (unused land). The time series of the images was 2001–2019, and the spatial resolution was 30 m. Landsat remote sensing images from five phases in 2001, 2005, 2011, 2015, and 2019, used for soil salinization inversion, were downloaded from the USGS website (<https://earthexplorer.usgs.gov/> (accessed on 13 November 2022)). ENVI5.3 software was used for preprocessing including radiation calibration, atmospheric correction, and clipping.

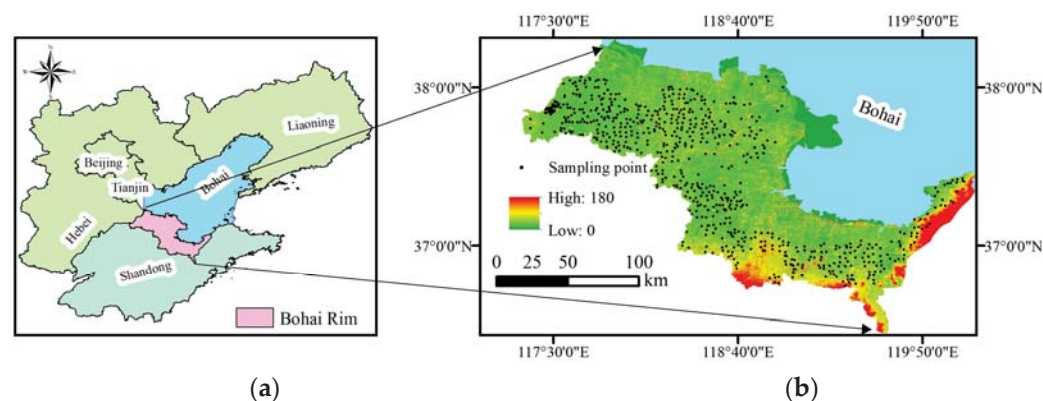


Figure 1. Geographic location (a) and sampling sites (b) in the Shandong area around the Bohai Sea.

The net primary productivity (NPP) data for the vegetation were obtained from the MOD17A3HGF V6 dataset provided by NASA. The annual NPP of the product was synthesized using MOD17A2H [28] to obtain a net photosynthesis product for all 8 days in a given year. The time series was 2001–2019, and the spatial resolution was 500 m. The above data were downloaded using code programming in PIE—Engine cloud platform (<https://engine.piesat.cn/> (accessed on 13 November 2022)). To ensure consistency in the data spatial resolution, Arcgis10.2 software was used to resample NPP on a 30 m grid.

2.2.2. Soil Data

The grid method was used for the layout of the sample sites. Using the remote sensing image map, the study area was covered with $3\text{ km} \times 3\text{ km}$ grids (avoiding aquaculture water surface, salt pans, and current construction land), and one sampling site was designed in the middle of each grid. During the field surveys, the specific sampling locations were determined according to the traffic accessibility and the field cultivated land conditions. A hand-held GPS was used to read the coordinates of the sample sites, and the land use status was also recorded. An EC110 portable conductivity meter was used to measure the soil conductivity at different depths for each layer at a distance of 2.5 cm, 7.5 cm, 15.0 cm, and 22.5 cm from the ground surface. At typical sample points, about 1 kg of soil samples from the plow layer was obtained with soil drills, bagged and sealed, and taken back to the laboratory to test the soil salt content (the soil salt was extracted with water and soil at a ratio of 5:1 and determined using the drying method). The field surveys were carried out from early March to early May 2019. A total of 720 sets of conductivity data were measured, and 537 soil samples were collected.

Using the soil salt content data from the 537 samples obtained from the cultivated layer (measured with the laboratory drying method) and the average soil conductivity data from each depth level in the field, a relationship model between soil salt content and conductivity was established, and the soil salt content of each depth layer at the 720 sample sites in the study area was calculated, respectively. In this way, the tedious laboratory analysis process of obtaining soil salinity data from all sample sites was reduced.

2.3. Methods

A general flowchart for this study is shown in Figure 2. Firstly, the characteristics of soil salinization at different depths in the cultivated land were analyzed using descriptive statistics. Secondly, the transfer matrix method was used to analyze the mutual transformation process between the areas of various land use types from 2001 to 2019, so as to express the spatio-temporal evolution characteristics of the quantity of cultivated land and other land types. Thirdly, the random forest model method was used to inverse the soil salt content for each year, and the spatial interpolation and mapping of inverse distance weights were combined to analyze the temporal and spatial distribution pattern changes in

soil salinization of the cultivated land. Finally, the quantitative impact of cultivated land salinization on NPP was analyzed using the correlation regression method.

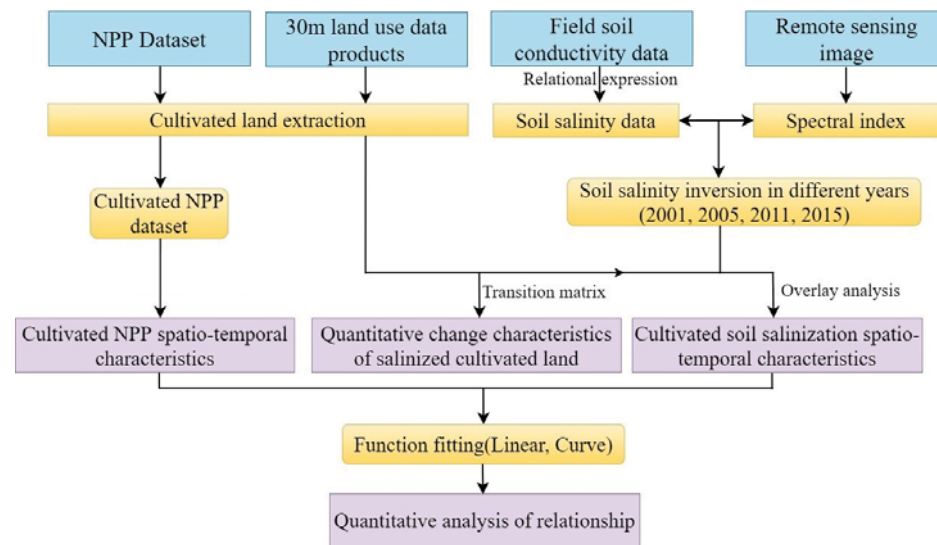


Figure 2. Technology roadmap of this paper.

2.3.1. Descriptive Statistical Analysis Method

Statistical Product Service Solutions (SPSS, version: 23.0) software was used with descriptive statistical methods to analyze the maximum, minimum, variance, mean, median, standard error, kurtosis, skewness, coefficient of variation (CV), and other characteristics of salt content at different depths in the soil layers. The CV reflects the dispersion degree and relative variation in random variables, which can be divided into three levels of variation: weak [0, 0.10), medium [0.10, 1.00), and strong [1.00, ∞) [29].

2.3.2. Analysis of the Land Type Transfer Matrix

The transfer matrix method reflects the following contents: (a) cultivated land area in two periods and (b) the source of increases and the flow direction of decreases in cultivated land. The expression is as follows [30]:

$$S_{ij} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ S_{21} & \cdots & S_{2n} \\ \vdots & \vdots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \quad (1)$$

where S is the total land area; n is the number of land types; and i, j is the land type at the beginning and end of the study period, respectively.

2.3.3. Random Forest Inversion of Soil Salt Content

The random forest machine learning method was proposed by Breiman and Adele Cutler et al. [31] at the beginning of the 21st century. Its basic principle is an integrated learning algorithm based on decision trees as individual learners. It is widely used to solve the problem of overfitting that is present in traditional machine learning models. Its advantage lies in the fact that each decision tree unit is unrelated and randomly arranged. Compared with other machine learning models, it has the advantages of fast training speed, a good prediction effect, and strong robustness [32]. Based on the five Landsat remote sensing images preprocessed in Section 2.2.1 above, the vegetation index [33] and salinity index [34] were calculated using ENVI5.3 software (Table 1). According to the correlation coefficient and variance expansion factor (VIF) for each spectral index and soil salt content, the final spectral indexes for inversion such as RVI, EVI, SI_3 , and SI_5 were determined. An

inversion model was established based on the measured soil salt content data from 2019 and the spectral index from the same period using the random forest method. Regarding the parameter setting for the random forest, the number of decision trees was 200 and the minimum number of leaves was 3. The above process was implemented in Matlab (version: 2021b) software. Equally spaced years were selected to invert the soil salinity in 2001, 2005, 2011, and 2015. (The 2011 dataset was selected to replace the 2010 dataset for inversion due to high cloud cover in the study area during the same period in 2010, resulting in poor inversion results.)

Table 1. Correlation spectral index.

Spectral Index	Expression	Reference
Normalized difference vegetation index	$(\text{NIR} - \text{Red})/(\text{NIR} + \text{Red})$	
Difference vegetation index	$\text{NIR} - \text{Red}$	
Enhanced vegetation index	$2.5 \times (\text{NIR} - \text{Red})/(\text{NIR} + 6 \times \text{Red} - 7.5 \times \text{Blue} + 1)$	[33]
Ratio vegetation index	NIR/Red	
Soil adjusted vegetation index	$(\text{NIR} - \text{Red}) \times 1.5/(\text{NIR} + \text{Red} + 0.5)$	
Salinity index (SI1)	$(\text{Green} \times \text{Red})^{0.5}$	
Salinity index (SI2)	$(\text{Green}^2 + \text{Red}^2 + \text{NIR}^2)^{0.5}$	
Salinity index (SI3)	$(\text{Green}^2 \times \text{Red}^2)^{0.5}$	
Salinity index (SI4)	SWIR_1/NIR	[34]
Salinity index (SI5)	$(\text{Red} - \text{SWIR}_1)/(\text{Red} + \text{SWIR}_1)$	
Salinity index (SI6)	$(\text{Red} \times \text{Blue})/\text{Green}$	
Salinity index (SI7)	$(\text{Red} \times \text{NIR})/\text{Green}$	

2.3.4. Inverse Distance Weight Space Interpolation and Mapping

The principle underlying spatial interpolation analysis with the inverse distance weighting method is based on the basic assumption of “the first law of geography”: “the similarity between two objects decreases with the increase of their distance” [35], and the corresponding weight is calculated according to the distance between sampling sites. The two-dimensional inverse distance weighted interpolation method (IDW) is a multivariate interpolation method used to evaluate the prediction value of S0 at any site based on the assumption of known datasets. It is often used to analyze the spatial distribution of soil salt content, organic matter content, etc. This process was mainly implemented in Arcgis10.7 [36].

2.3.5. Correlation and Regression Analysis

(1) The Spearman correlation coefficient method

The Spearman correlation coefficient is used to determine the correlation between factor variables. The formula is as follows [37]:

$$P = 1 - \frac{6 \sum_{i=1}^n d_i^2}{n(n^2 - 1)} \quad (2)$$

where P represents the Spearman correlation coefficient; n is the total number of samples; and d_i is the rank difference between the soil salt content and NPP of cultivated land.

(2) Regression model construction

The functional relationship between the soil salt content (independent variable) and NPP value (dependent variable) of the cultivated land was established to quantify the impact of salinization on cultivated land crop productivity. It mainly included linear (unitary linear) and curve (unitary quadratic linear, power regression, exponential regression, reciprocal regression) function models to identify the possible relationship (linear or nonlinear)

between the degree of soil salinization and NPP of the cultivated land. These analyses were implemented in Origin 2021. The fitting models are as follows:

$$\text{Univariate linear regression: } Y = \beta_1 X + \beta_0 \quad (3)$$

$$\text{Monadic quadratic linear regression: } Y = \beta_2 X^2 + \beta_1 X + \beta_0 \quad (4)$$

$$\text{Power regression: } Y = \beta_2 X^{\beta_1} + \beta_0 \quad (5)$$

$$\text{Exponential regression: } Y = \beta_2 e^{\beta_1 X} + \beta_0 \quad (6)$$

$$\text{Piecewise linear regression: } Y = \begin{cases} \beta_0 + \beta_1 X, & X \leq \alpha \\ \beta_0 + \beta_1 X + \beta_0(X - \alpha), & X > \alpha \end{cases} \quad (7)$$

where α , β_0 , β_1 , and β_2 are constants.

3. Results

3.1. Descriptive Statistical Characteristics of Cultivated Land Salinization

Based on the conductivity measured using an EC110 conductivity meter, the relationship between soil conductivity EC_0 (us/m) and salt content S_t (g/kg) measured in the laboratory was established as follows:

$$S_t = 0.0021EC_0 + 0.7507, n = 376, R^2 = 0.873 \quad (8)$$

The soil salt contents in the plow layer and each layer at 2.5 cm, 7.5 cm, 15.0 cm, and 22.5 cm at all sample sites were calculated using Equation (8), and then a descriptive statistical analysis of these data was conducted (Table 2). According to the grading standard of “China Salinized Soil”, the degrees of salinization were divided into five grades: non-salinization, mild salinization, moderate salinization, severe salinization, and saline soil. The salt content (g/kg) ranges are (0, 1), [1, 2], [2, 4], [4, 6], [6, ∞] [38].

Table 2. Descriptive statistics for the salt content at different depths in the cultivated land in the Shandong area around the Bohai Sea.

Depth of Soil Layer (cm)	Sample Size	Min (g/kg)	Max (g/kg)	Average (g/kg)	Median (g/kg)	Variance	Standard Deviation	Kurtosis	Skewness	Coefficient of Variation
2.50	720	0.76	55.98	3.56	1.74	44.97	6.71	28.78	5.12	1.88
7.50	720	0.76	40.57	2.95	2.03	13.63	3.69	40.68	5.63	1.25
15.00	720	0.76	33.09	3.00	2.27	8.88	2.98	38.07	5.37	0.99
22.50	720	0.76	29.29	3.13	2.45	6.80	2.61	29.36	4.52	0.83
plow layer	720	0.76	37.53	3.16	2.16	13.59	3.69	30.56	4.94	1.17

It can be seen from Table 1 that the average salt content in the plow layer was 3.16 g/kg, showing moderate salinization. The minimum and maximum values were 0.76 g/kg and 37.53 g/kg, respectively, and the coefficient of variation was 1.17, showing strong variation. The average salt contents in each layer from top to bottom were 3.56 g/kg, 2.95 g/kg, 3.00 g/kg, and 3.13 g/kg, respectively, which were all moderate salinization, showing the characteristic of first decreasing and then increasing in the vertical direction. The kurtosis and skewness of salt content in each soil layer were large, and the data did not show a normal distribution. The medians were in the range of 1.74–2.45 g/kg, which were less than the average values, indicating that the data distributions were right-skewed (positively skewed). The coefficient of variation tended to increase from bottom to top. The coefficients of variation in the 22.50 cm and 15.00 cm layers were 0.83 and 0.99, respectively, showing moderate variation. The coefficients of variation for the salt content in the 2.5 cm and 7.5 cm layers were greater than 1.00, showing strong variation. This was mainly because the upper

soil in the cultivated land was greatly affected by random factors (such as climate, human activities, etc.), which led to strong spatial variability in soil salt content and large difference in salt content in different regions.

3.2. Spectral Index Screening

The correlation analysis results for the soil salt content and spectral index in the study area are shown in Figure 3. There was a highly significant negative correlation between soil salinity and the vegetation index. There was a highly significant correlation between soil salt content and most salt indices (except for SI7). Using the correlation coefficient and variance expansion factor (VIF) for each spectral index and soil salt content, the final spectral indexes for inversion including RVI, EVI, SI3, and SI5 were determined.

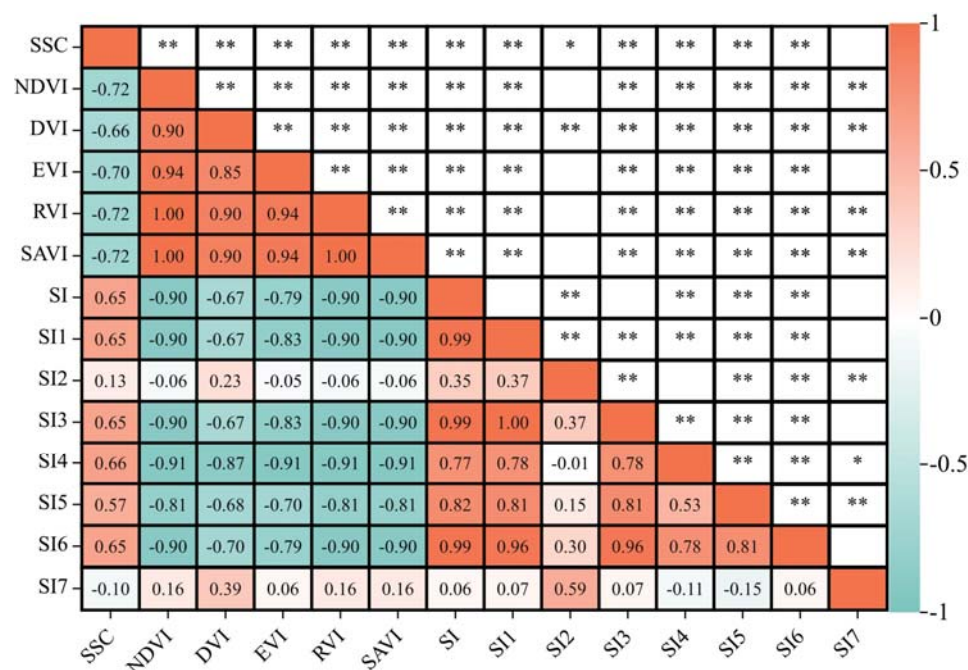


Figure 3. Correlation between soil salt content and the spectral index. “*” indicates that variables are significantly correlated ($p < 0.05$). “***” indicates that variables are significantly correlated ($p < 0.01$).

3.3. Temporal and Spatial Pattern Change Characteristics in Cultivated Land Quantity

The land type area transfer matrix for the study area from 2001 to 2019 is listed in Table 3, and the spatial distribution and proportion for each category are shown in Figure 4. It can be seen that from 2001 to 2019, the land use types were mainly cultivated land and construction land, and the sum of the two areas accounted for more than 80% of the total study area each year. However, the overall area and proportion of cultivated land showed a decreasing trend year by year, and the construction land increased year by year. The total area of cultivated land was 20,724.08 km² in 2001 and 18,719.57 km² in 2019, with a cumulative decrease of 2004.51 km² and a decreased proportion of 9.67%. The average annual decrease was 105.50 km², and the average annual decrease rate was 0.51%. The total area of construction land was 4002.87 km² in 2001 and 5843.58 km² in 2019, with a cumulative increase of 1840.71 km² and an increased proportion of 45.98%. The average annual increase was 96.88 km², and the average annual increase rate was 2.42%. The transfer matrix showed that over the 19 studied years, 1914.59 km² of cultivated land was converted into construction land, while only 323.88 km² of construction land was converted into cultivated land. The net transfer of cultivated land to construction land reached 1590.71 km².

Table 3. Transfer matrix for land use types in the Shandong area around the Bohai Sea from 2001 to 2019.

Year	Type	2019					2001–2019		
		Grassland/km ²	Cultivated Land/km ²	Construction Land/km ²	Woodland/km ²	Water Area/km ²	Mudflats/km ²	Change/km ²	Change (% of Total Area)
2001	Grassland	23.87	85.13	30.87	0.08	26.41	42.59	−87.82	−30.83
	Cultivated land	29.66	18006.31	1914.59	0.97	537.20	252.77	−2004.51	−9.67
	Construction land	0.29	323.88	3370.83	0.04	195.98	123.90	1840.71	+45.98
	Woodland	0.00	2.38	0.26	0.45	0.00	0.00	−0.92	−50.80
	Water area	0.97	147.26	113.18	0.02	941.18	238.67	1197.92	+82.43
	Mudflats	9.67	168.80	432.83	\	929.08	1772.68	−888.42	−26.67

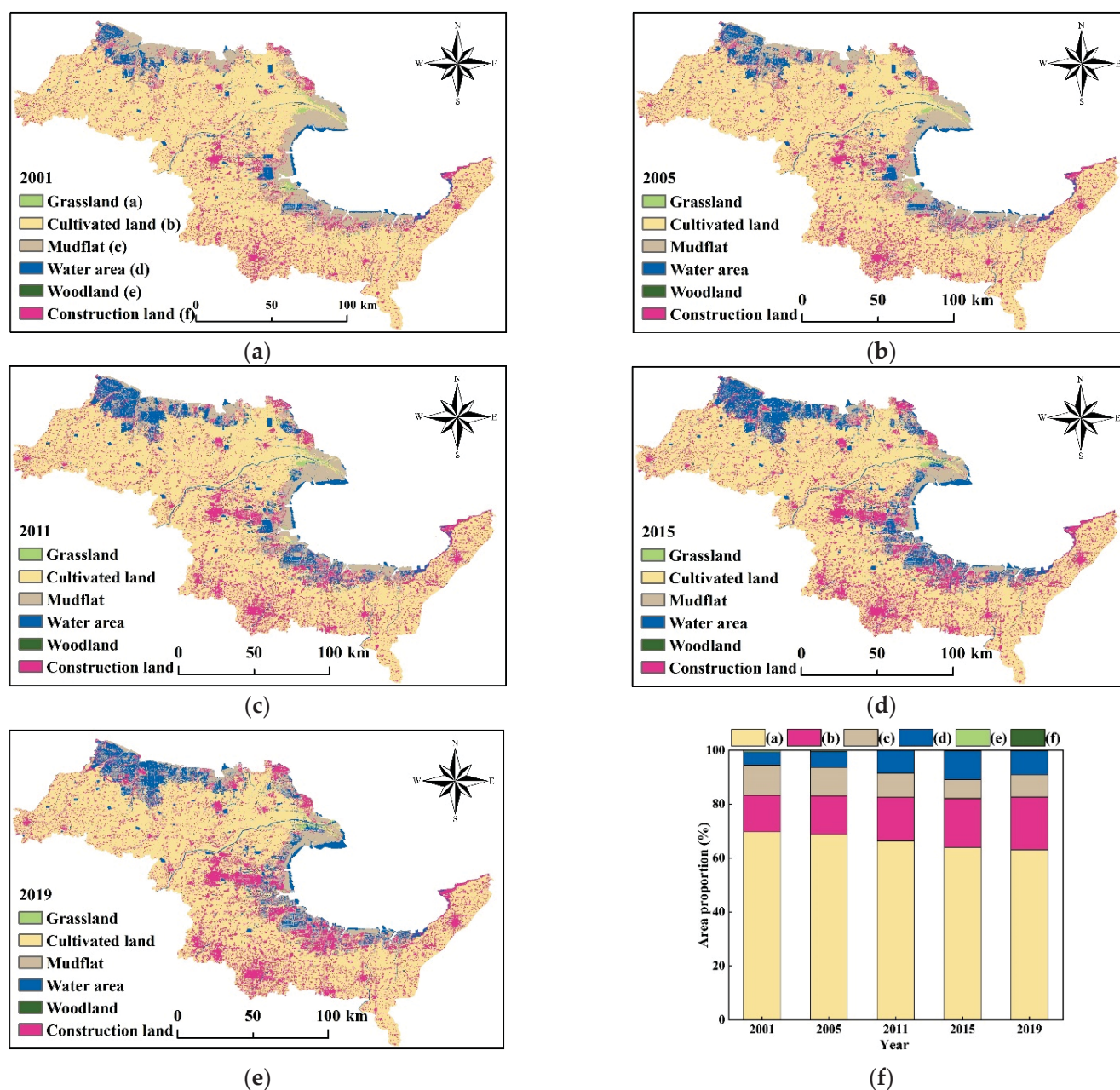


Figure 4. Spatial distribution of land use types in the Shandong area around the Bohai Sea from 2001 to 2019. (a–e) represent the distribution of land use types in the study area in 2001, 2005, 2011, 2015 and 2019 respectively. (f) shows the percentage of area of different land types in different years.

As seen in Figure 4, from 2001 to 2019, the increase in construction land occupied the cultivated land around the original cities and towns and spread around the original cities and towns in 2001. These areas were mainly concentrated in the middle and south of the study area.

The net transfer of cultivated land to water area was 389.94 km², and to mudflats, the net transfer was 83.97 km². In addition, the net transfer of grassland to cultivated land was 55.47 km², and the spatial distribution was very scattered, which benefited from the policy and engineering measures for land consolidation to supplement cultivated land.

3.4. Temporal and Spatial Characteristics of Soil Salinization in Cultivated Land

The 2019 sample data were divided into a training set and a verification set in a ratio of 7:3, and the inversion model was established using the random forest method. The results are shown in Figure 5. The training set's R^2 was 0.833 and RMSE was 1.982 g/kg. The validation set's R^2 was 0.714, and the RMSE was 2.134 g/kg. The training set and validation set had good modeling effects, which were used for the inversion of soil salt content in the study area.

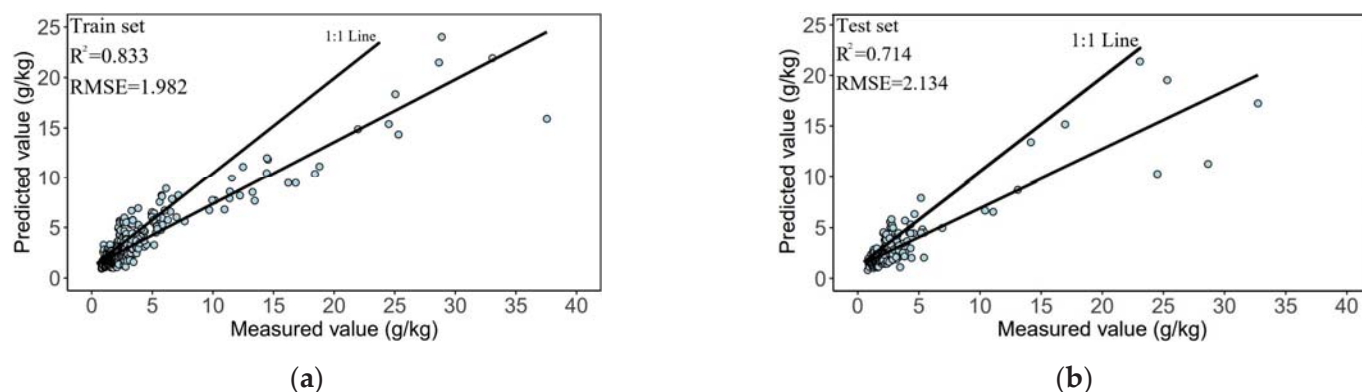


Figure 5. Precision of the random forest prediction model. (a) represents the accuracy of the training set prediction model, (b) represents the accuracy of the validation set model.

Using this model, the soil salt contents of the cultivated land in the Shandong region around the Bohai Sea in 2001, 2005, 2011, and 2015 were inverted, respectively. According to the type of salinization degree, a spatial distribution map was drawn, and then the area and proportions were counted. The results are shown in Table 4 and Figure 6.

Table 4. The areas and proportions of cultivated land with different salinization degrees.

Salinization Degree	Soil Salt Content (g/kg)	Area (km ²)					Proportion (%)				
		2001	2005	2011	2015	2019	2001	2005	2011	2015	2019
Non salinization	<0.1	337.64	169.56	494.48	232.60	27.86	1.63	0.83	2.51	1.23	0.15
Mild salinization	0.1–0.2	4567.23	4215.51	4237.21	5023.18	7149.28	22.04	20.63	21.48	26.47	38.19
Moderate salinization	0.2–0.4	4614.43	3552.67	4469.16	6069.45	7289.96	22.27	17.38	22.65	31.98	38.94
Severe salinization	0.4–0.6	4038.99	4019.65	5352.03	3676.43	1921.91	19.49	19.67	27.13	19.37	10.27
Saline soil	>0.6	7165.80	8480.89	5177.61	3975.10	2330.56	34.58	41.50	26.24	20.95	12.45

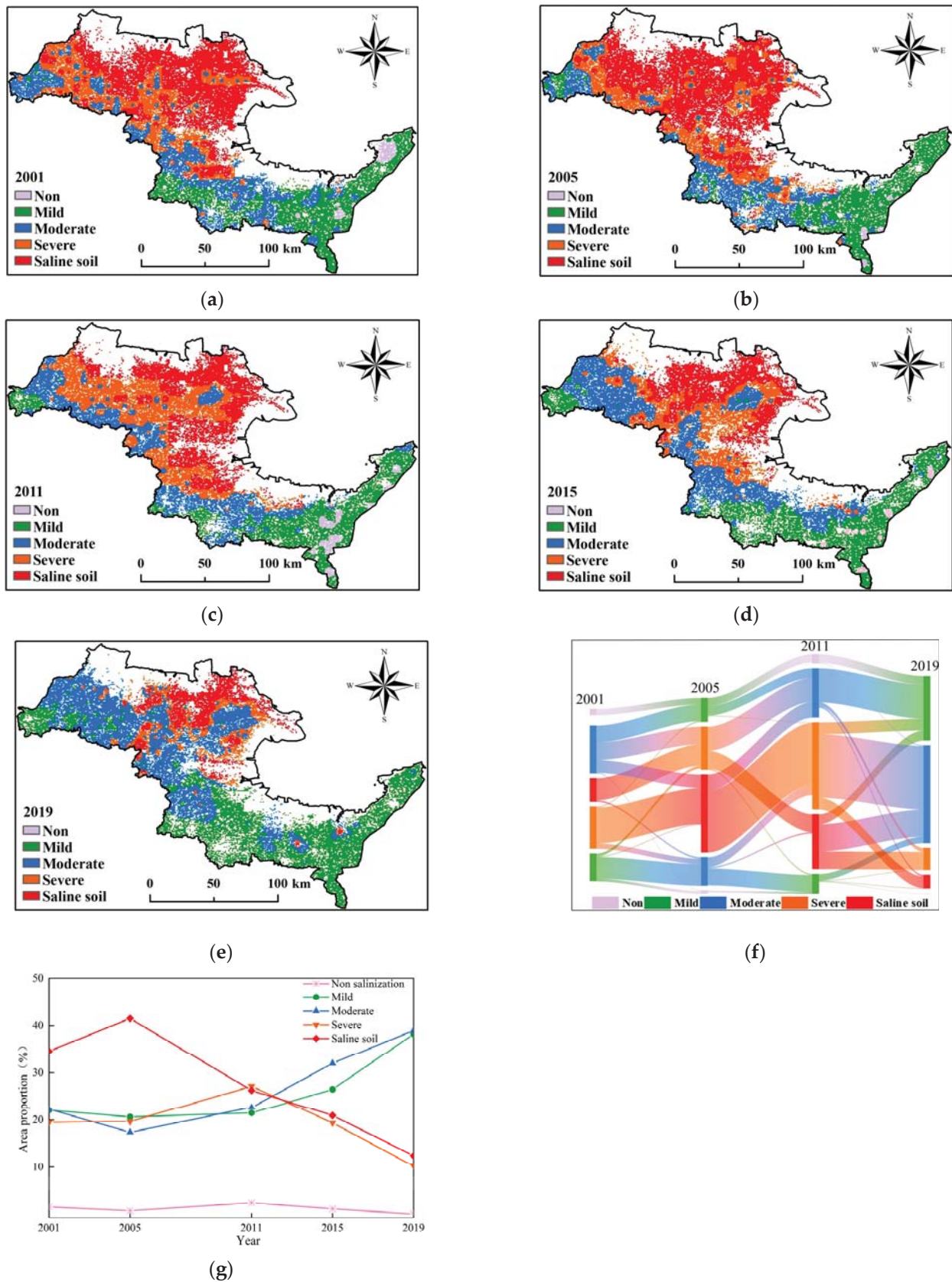


Figure 6. Spatial distribution and area proportion for the cultivated land salinization in the Shandong area around the Bohai Sea from 2001 to 2019. Note: (a–e) show the spatial distribution of soil salinity in different years from 2001–2019, (f) shows the area transfer Sankey diagram for different years, and (g) shows the change in area proportion.

3.4.1. Spatial Distribution of Soil Salinization in Cultivated Land

The area and proportion of cultivated land with different salinization degrees in the study area in 2019 are shown in Table 4, and the spatial distribution is shown in Figure 6e. In terms of the proportion of quantity, the area with moderate salinization accounted for the largest proportion of the total area of cultivated land (38.94%), followed by mild salinization (38.19%), which added up to 77.13%. Severe salinization and saline soil accounted for 12.45% and 10.27%, respectively, while non-salinization only accounted for 0.15%. In summary, the cultivated land in the study area was mainly mild and moderate salinization, which was the main body determining the regional cultivated land productivity. However, the severe salinization and saline soil, accounting for 22.82%, had a significant impact on the quality and productivity of the cultivated land. From the perspective of spatial distribution, the degree of soil salinization in the cultivated land in the study area gradually increased from south to north and from east to west.

3.4.2. Spatial and Temporal Evolutionary Characteristics of Soil Salinization in the Cultivated Land

Figure 6a–e shows the overall characteristics of the spatial distribution of soil salinization in the cultivated land in the study area over time from 2001 to 2019. The overall spatial distribution pattern in soil salinization did not change significantly from 2001 to 2005. Saline soil was mainly distributed in the north and slightly increased, while mild salinization was mainly distributed in the south, and severe salinization and moderate salinization were between the two. From 2005 to 2011, the northern saline soil area decreased significantly, the severe and moderate salinization increased correspondingly, and the southern part was still dominated by mild salinization. From 2011 to 2019, most of the severe salinization and saline soil in the north and middle areas were reduced to moderate salinization.

Figure 6f shows the Sankey diagram for the transfer of cultivated land area, and Figure 6g shows the change in the proportion of cultivated land area with different salinization degrees in the Shandong area around the Bohai Sea from 2001 to 2019. According to the spatial change characteristics shown in Figure 6a–e and the quantitative change characteristics of the cultivated land area with different soil salinization degrees shown in Figure 6f,g, the temporal and spatial evolution characteristics of soil salinization in the cultivated land in the study area can be divided into three stages. (1) From 2001 to 2005, the degree of soil salinization increased slightly. The proportion of saline soil in the cultivated land increased from 34.58% to 41.50%. Most of the areas were transformed from severe salinization, with a transformation area of 1924.46 km². The second was moderate salinization, with a conversion area of 687.45 km². The area with severe salinization soil was roughly kept in balance, with an area of 1147.64 km² transferred into saline soil, and an area of 939.04 km² transferred in from moderate salinization. The moderate and mild salinization soil areas decreased slightly. (2) From 2005 to 2011, the degree of soil salinization decreased slightly. The proportion of saline soil area decreased from 41.50% to 26.24%, and most of the areas were transformed into severe salinization, with a transformation area of 3302.12 km². Severe salinization soil increased from 19.67% to 27.13%, and moderate salinization and mild salinization soils increased slightly from 22.65% to 31.98% and 21.48% to 26.47%, respectively. (3) From 2011 to 2019, the soil salinization degree significantly decreased further. The areas of saline soil and severe salinization decreased on a large scale, and the areas with the two types transformed into moderate salinization soil at 1453.77 km² and 23,365.91 km², respectively. The areas with mild salinization and moderate salinization soils were increasing. This showed that the salinization disaster was greatly improved in the past 10 years with great attention from the country and the joint efforts of the country, academia, and industry.

3.5. Temporal and Spatial Characteristics of the NPP of Cultivated Land

The temporal and spatial characteristics of the NPP of cultivated land in the Shandong area around the Bohai Sea from 2001 to 2019 are shown in Figure 7. It can be seen from Figure 7a that from 2001 to 2019, the NPP values for the cultivated land in the Shandong area around the Bohai Sea in each year were in the range of 296.04–364.54 $\text{gC m}^{-2}\text{a}^{-1}$, and the average value across all years was 330.79 $\text{gC m}^{-2}\text{a}^{-1}$. In the 19 studied years, the NPP value increased by 68.50 $\text{gC m}^{-2}\text{a}^{-1}$, with an average annual growth of 3.61 $\text{gC m}^{-2}\text{a}^{-1}$. The curve showed that the average value for the regional NPP showed an increasing trend with fluctuation, and the linear growth reached a significant level ($p < 0.05$). From 2001 to 2009, the value first increased and then decreased, and from 2009 to 2019, it continued to rise. This period basically coincided with the proposal and implementation of the national and Shandong Province saline-alkali land treatment project, the “Bohai granary” Science and Technology Demonstration Project, and other strategies [10,11]. The increase in the NPP of the cultivated land showed that the improvement in salinized cultivated land produced significant results during this period.

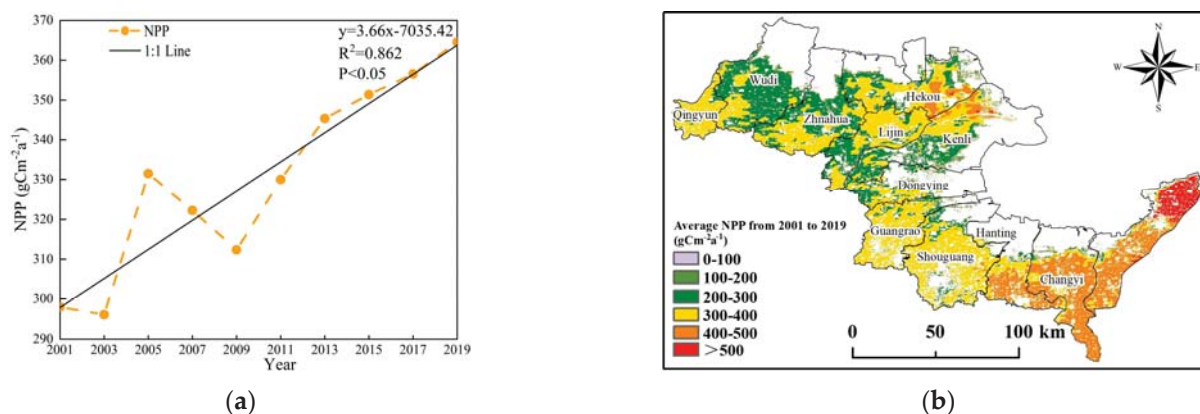


Figure 7. Spatio-temporal characteristics of the NPP of cultivated land in the Shandong area around the Bohai Sea from 2001 to 2019. Note: (a) Interannual change in the average NPP of regional cultivated land and (b) spatial distribution of the average NPP in 2001–2019.

Figure 7b shows that the distribution of the average NPP of the cultivated land in the Shandong area around the Bohai Sea from 2001 to 2019 had obvious spatial heterogeneity. The NPP value in the north was significantly lower than that in the south, roughly bounded by Dongying District in the middle of the study area.

3.6. Analysis of the Influence of the Salinization Degree of Cultivated Land on NPP

3.6.1. Correlation between Soil Salinization and NPP in Cultivated Land

A $3 \text{ km} \times 3 \text{ km}$ grid was established using ArcGIS software, and the NPP value for the cultivated land and soil salt content in different years was extracted for correlation analysis. Figure 8a shows the Spearman correlation coefficient analysis results for both. It can be seen that there was an extremely significant negative correlation between NPP and soil salt content in different years. The correlation coefficients were greater than 0.4, but the correlation coefficients were generally decreasing, with a total decrease of 0.266 from 2001 to 2019. We speculate that the causes of this phenomenon may be the following two points: ① Figure 8b–g shows the results for the correlation between the soil salt content and NPP of cultivated land in different years calculated between partitions. In the range of “salt content $> 6 \text{ g/kg}$ and NPP value between $0\text{--}200 \text{ gC m}^{-2}\text{a}^{-1}$ ”, “salt content between $2\text{--}4 \text{ g/kg}$ and NPP value between $200\text{--}400 \text{ gC m}^{-2}\text{a}^{-1}$ ”, and “salt content between $1\text{--}2 \text{ g/kg}$ and NPP value between $400\text{--}600 \text{ gC m}^{-2}\text{a}^{-1}$ ”, there were high degrees of correlation, which was a “significant” or “extremely significant” negative correlation. ② In addition, the “soil salt content $> 6 \text{ g/kg}$ and NPP value between $400\text{--}600 \text{ gC m}^{-2}\text{a}^{-1}$ ” in 2005 and 2011, the “soil salt content > 6 and NPP value between $600\text{--}800 \text{ gC m}^{-2}\text{a}^{-1}$ ”

in 2019, and the multi-year average “soil salt content between 4–6 g/kg and NPP value between 400–600 gC m⁻²a⁻¹” were positively correlated, which also verified the above speculation about the reasons for the downward trend in their correlation coefficients.

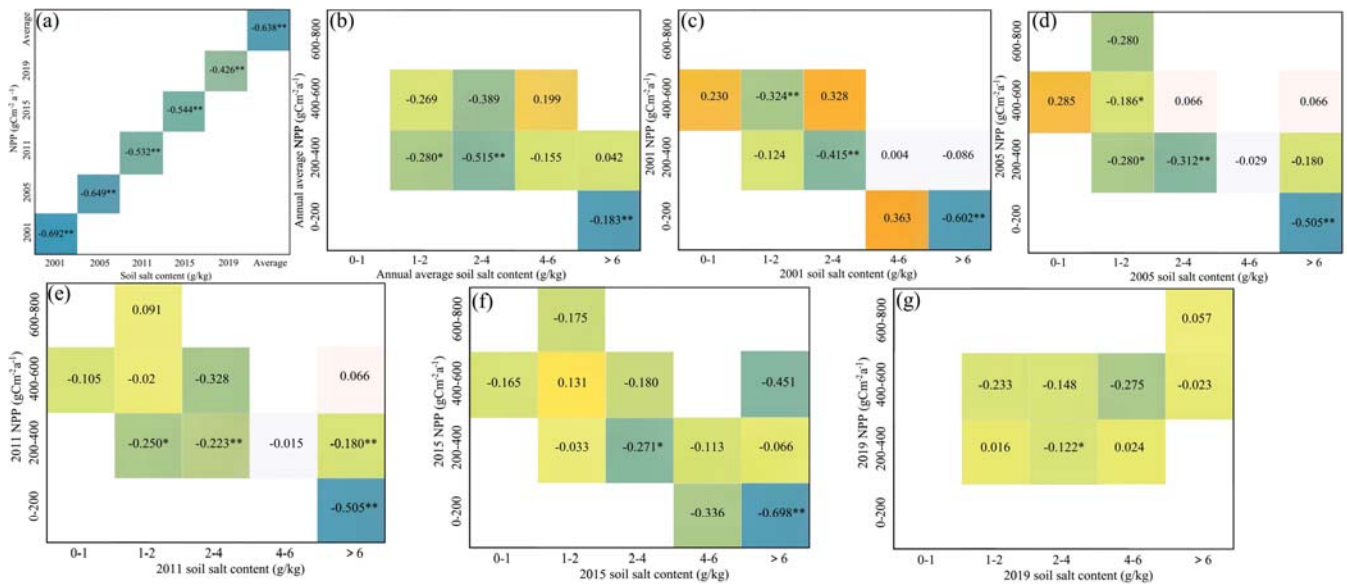


Figure 8. Spearman correlation coefficient between the soil salt content and NPP of cultivated land. (a) shows the correlation between NPP and soil salt content in different years. (b) Denotes the correlation between annual average NPP and soil salt content. (c–g) Correlation between NPP and soil salt content in 2001, 2005, 2011, 2015, and 2019, respectively. Note: “*” indicates that variables are significantly correlated ($p < 0.05$). “**” indicates that variables are significantly correlated ($p < 0.01$).

3.6.2. Fitted Relationship between Soil Salinization and NPP of Cultivated Land

The fitted results for the NPP values and soil salt content of cultivated land in different years are shown in Figure 9. During this study, the R^2 for the fitted nonlinear function results were higher than the fitted linear function results, indicating that the correlation between them was not purely linear. For 2001, 2005, 2011, 2015, 2019, and the multi-year average, the R^2 values of the curve for the fitted models were 0.06–0.12, 0.01–0.02, 0.01–0.07, 0.01–0.04, 0.01–0.05, and 0.03–0.09 higher than that of linear fitted models, respectively. For the curve fitting models, the power function regression model was the best. In summary, the precision of different fitting regression models had advantages and disadvantages, but their overall trends were roughly the same, showing a trend that the NPP value gradually decreased with the increase in the soil salt content of the cultivated land.

In order to perform a quantitative analysis of the soil salt content and NPP, three intervals of 0–3 g/kg, 3–7 g/kg, and 7–15 g/kg were finally selected to achieve piecewise fitting using the power function regression model, considering the difference in slope change and the fitting degree of the piecewise linear regression. The results are shown in Figure 10. In summary, when the salt content of the cultivated soil was in the range of 0–3 g/kg, the fitting accuracy R^2 was 0.54, and the fitting effect was the best. For every 1 g/kg increase in salt content, the NPP value was predicted to decrease by 43.62 gC m⁻²a⁻¹. When the soil salt content of the cultivated land was in the range of 3–7 g/kg, the fitting accuracy R^2 was 0.44. For every 1 g/kg increase in salt content, the NPP value was predicted to decrease by 30.36 gC m⁻²a⁻¹. When the soil salt content of the cultivated land was in the range of 7–15 g/kg, the fitting accuracy R^2 was 0.45. For every 1 g/kg increase in salt content, the NPP value was predicted to decrease by 44.19 gC m⁻²a⁻¹.

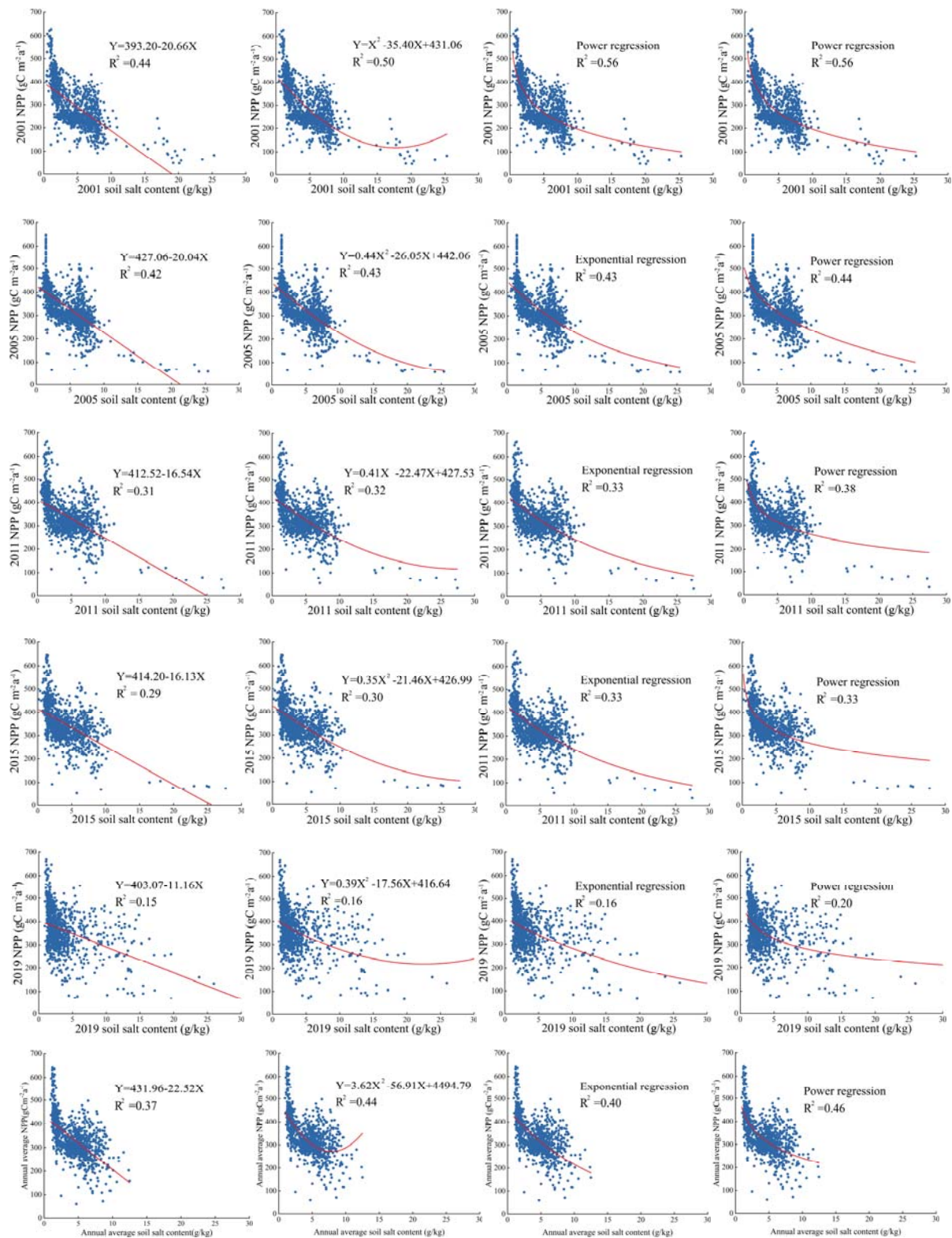


Figure 9. Fitted models for the soil salt content and NPP of cultivated land in different years.

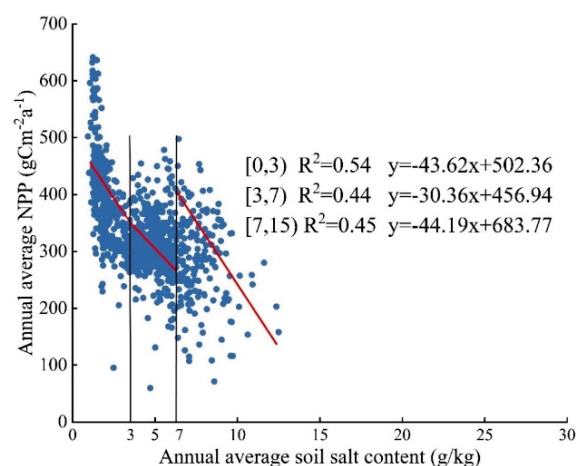


Figure 10. The Spearman correlation coefficient between the soil salt content and NPP of the cultivated land.

4. Discussion

4.1. Quantity Change in Salinized Cultivated Land

From 2001 to 2019, the amount of cultivated land in the Shandong area around the Bohai Sea showed a decreasing trend, and the proportion of cultivated land decreased from 69.71% in 2001 to 62.98% in 2019, with a net area decrease of 2004.51 km². This was mainly related to the rapid development of industrialization and urbanization in the region and the large use of cultivated land, which is consistent with the research results of Zhu et al. [39] on the changes in cultivated land in the Yellow River Delta in the recent 20 years. The development and utilization of unused land have always been one of the main sources of new cultivated land in China [40]. According to statistics, 12.59% of the newly cultivated land in Xinjiang from 2005 to 2008 came from saline–alkali land [41]. The “Bohai Sea Granary Science and Technology Demonstration Project” implemented in the Bohai Rim region from 2013 to 2018 involved 2.6667×10^6 hm² of medium- and low-yield salinized cultivated land treatments. Overall, 3.647×10^5 hm² of the salinized cotton fields was transformed into grain fields, 1.935×10^5 hm² of the saline–alkali land was improved into cultivated land, and the cumulative increase in grain production in five years was 1.41×10^7 t [242]. Only by protecting both the quality and quantity of cultivated land can we truly achieve the goal of steadily improving the quality of arable land and food production in the Bohai Sea Rim region.

4.2. Change in Soil Salinization Degree in Cultivated Land

Due to the special geographical environment in the coastal area, the cultivated land in this area is more seriously affected by salinization than that in the inland area [43]. Fully understanding the temporal and spatial characteristics of soil salinization in coastal areas is essential for mitigating salinization and ensuring regional agricultural development and food security. The salinization degree in the cultivated land in the Shandong area around the Bohai Sea presented a trend with “high salt content near the sea, low salt content far from the sea”, which is similar to the research results of Das et al. (2020) [44] from the coastal areas in central and southern Bangladesh. For areas closer to the sea, there is a higher frequency of seawater immersion of the soil mass, and the salinity of the groundwater is significantly higher than that in other regions. At the same time, due to the low terrain, the soil salt in the high terrain region converges here with the water flow. In this way, under the combined effect of multiple factors, the salt content of cultivated land in the offshore area is high, even several times higher than that in other regions.

The change in the soil salinization degree of cultivated land in the study area over the past 20 years is characterized by several stages. From 2011 to 2019, the improvement in salinized cultivated land achieved remarkable results, and the area of saline soil and

severe salinized soil decreased significantly. This is closely related to the increasing attention paid to the salinization hazards in recent years [45–47], especially the extensive development of saline–alkali land treatment and salinized cultivated land improvement. In future improvement processes, proper consideration should be given to zoning for improvement. For saline soil and severe salinized areas, mechanical deep plowing should be carried out to cut off the soil capillaries, improve the soil water holding capacity, and inhibit salt return, and salt drainage using concealed pipes should be improved to reduce the groundwater level at the same time. For moderately and mildly salinized areas, the drainage and irrigation system should be further optimized, especially using water-saving irrigation technologies such as sprinkler irrigation and drip irrigation, so as to achieve accurate salt regulation.

4.3. Temporal and Spatial Changes in the NPP of Salinized Cultivated Land

At present, there are no research reports on the NPP of salinized cultivated land in the Shandong area around the Bohai Sea. Most of the existing studies focused on all land use types in the Yellow River Delta [48] and the NPP of forest vegetation in a large range in the Yellow River basin [49,50]. The results of this paper showed that, in terms of the time change, the overall NPP of salinized cultivated land in the Shandong area around the Bohai Sea showed a fluctuating upward trend in the past 20 years. With 2009 as the node, the fluctuating trend increased first and then decreased from 2001 to 2009, and then it continued to increase from 2009 to 2019. This may be related to the implementation of projects such as national and Shandong Province's saline–alkali land treatment, saline–alkali medium- and low-yield cultivated land improvement, and other projects. The ecological water supplement measures in the Yellow River Delta may also play a role in diluting the soil salinity and groundwater mineralization in this region [51]. From the perspective of spatial distribution, the average NPP of the cultivated land over the years was high in the southeast and low in the coastal area. The southeast area is relatively high in elevation, with little impact of salinization, and the soil salt content is generally low (mostly mild salinization). As the NPP is affected by the expansion of urban construction land, the values for the cultivated land around some cities and towns were also low ($0\text{--}200\text{ gC m}^{-2}\text{a}^{-1}$). This is also a phenomenon that should be given more attention in the future, and measures should be taken to curb urban expansion, maintain stability, and improve cultivated land productivity.

4.4. Quantitative Relationship between Annual Average NPP of the Cultivated Land and Soil Salt Content

The soil quality of the cultivated land in coastal areas depends to a large extent on its soil salt content (the higher the soil salt content, the lower the quality index) [52]. Some existing research focused on the relationship between cultivated land quality and NPP, and there are a lot of research results [53–55]. Zhuang et al. [12] analyzed the relationship between cultivated land quality (CLQ) and NPP in Sangong River Basin, Xinjiang, and found that the correlation coefficient R^2 was 0.706. For every point of increase in the CLQ value, the annual average NPP increased by $35.318\text{ gC m}^{-2}\text{a}^{-1}$. Wang et al. [56] inversed the temporal and spatial characteristics of cultivated land salinization in the Hetao Plain, Inner Mongolia. Using an overlay analysis of NPP and salt content, it was shown that the NPP in the salinized soil improvement area was in a sustainable growth trend, indicating that the saline–alkali land treatment had achieved certain good results. This is similar to the results of this study. However, the previous studies failed to clarify the quantitative relationship between the salinization degree of cultivated land and its productivity. Different from the above assumptions, this study preliminarily identified the quantitative relationship between the two and divided the influence of the soil salt content on the NPP value into three intervals(g/kg): [0, 3), [3, 7), [7, 15). It was found that the influence degrees of different intervals were different. There was an overall decreasing trend in the correlation coefficient between soil salinity and NPP in cultivated land. We speculate that this may

be due to two factors: (1) the impact of the accuracy error between local NPP and the predicted soil salt content and (2) the impact of the regional improvement in saline soil led to the phenomenon of “high salt content, large NPP value”, which reduced the negative correlation between them. This result made up for the gaps in this field and can help to estimate the productive capacity of cultivated land, delimit key improvement areas, and formulate improvement plans in the future.

4.5. Research Limitations and Future Prospects

We need to acknowledge some small limitations and provide guidance for future research directions. First of all, when inversing the soil salinization of the cultivated land in different years, we only considered one machine learning method and remote sensing image. In the future, we should comprehensively explore multiple methods (linear, nonlinear, and machine learning), use higher resolution satellite images (such as Sentinel series), and fully combine remote sensing and machine learning algorithms to further improve the remote sensing monitoring accuracy of cultivated land salinization. Secondly, a typical coastal region, the Shandong region of the Bohai Rim, was chosen as the case study. We recommend caution in applying the results of this study to inland regions due to the large differences in the soil-forming parent material and the environment from inland arid and semi-arid regions.

5. Conclusions

Soil salinization of cultivated land in coastal area poses a great threat to the sustainable development of agricultural system. The contradiction between the inhibition of soil salinization on productivity and the growing demand for food is becoming increasingly fierce. The research results of this paper confirmed the following. First of all, the temporal change characteristics in the amount of salinized cultivated land in the Shandong area around the Bohai Sea from 2001 to 2019 were explored, showing an overall decreasing trend. We realized the inversion of cultivated land salinization in this region using a long time-series, which indicated that the change processes in cultivated land salinization in this region were mainly divided into three stages: slightly increased in 2001–2005, slightly reduced in 2005–2011, and significantly reduced in 2011–2019. Secondly, the NPP of the cultivated land in this region kept a fluctuating and rising trend. The NPP of the cultivated land in the south of the study area remained stable, and the NPP of the cultivated land in the north had a very significant increasing trend. Finally, the quantitative relationship between soil salt content and NPP in the cultivated land was analyzed. The soil salt content was divided into three intervals, and the change degrees between soil salt content and NPP in different intervals were different. Our research results provide decision-making support for strengthening the dynamic monitoring and regulation of cultivated land salinization and for promoting sustainable utilization of salinized cultivated land in the coastal areas to alleviate the food crisis.

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Article

The Influence of the Osmotic Potential on Evapotranspiration

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Abstract: Climate change is expected to affect the quality of soil and water, resulting in a significant impact on soil water balance in various regions around the world. Soil water potential plays a significant role in influencing evapotranspiration (ET), which is a crucial component of the soil water balance. The matric potential and the osmotic potential are the main components of the soil water potential. The osmotic potential is particularly important in dry soils, salt-affected soils, coastal lands, or when low-quality water is utilized for irrigation. Despite its importance, the impact of osmotic potential on ET has not been well-studied compared to other factors. Therefore, we conducted a study to investigate the impact of osmotic potential on ET from small-scale lab lysimeters planted with grass and equipped with scales and data loggers connected to computers. To create different osmotic potential levels, we irrigated the lysimeters with two different water qualities: distilled water and 4.79 dS.m⁻¹ NaCl solution. The lysimeters were kept in well-watered conditions, and daily ET was monitored. Our results indicate a strong correlation between osmotic potential and ET. After three months of applying the treatments, the lysimeters with lower osmotic potential had a 39% reduction in cumulative ET compared to those irrigated with distilled water. Moreover, the osmotic stress affected plant health, leading to a notable decrease in the leaf area index and exerting a significant influence on evapotranspiration partitioning components, including transpiration and evaporation.

Keywords: osmotic potential; soil salinity; evapotranspiration; water potential; water quality; salt-affected soils; irrigation requirement

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1. Introduction

Climate change is the most severe challenge that faces the whole world in the 21st century. Significant influences on global food security are expected [1], owing to the influences on water resources' quantity and quality, as well as on soil quality. Low precipitation, higher temperatures, and higher potential evapotranspiration, ET_p, resulting in longer, harder, and more frequent droughts, are among the prospective events that result from the changes in weather patterns [2]. In parallel with the increase in temperature, soil and water salinity are likely to increase. Therefore, irrigation demand will significantly grow [3]. Sea-level rise (extremely saline water), along with expected more frequent droughts due to climate change, will affect the soils in coastal lands in addition to the expected influence in the arid and semi-arid regions. Recent studies have clarified that the impacts of climate change on water resources will also affect the wetter areas in central Europe [4]. In Germany, more and longer periods without precipitation are expected in the future [5]. In many studies, an increase in irrigation demand in different parts of the country is identified for the future [6–11]. As a result, improving water use efficiency through irrigation management and adopting advanced irrigation technology has become crucial and is considered one of the key adaption measures [9].

An accurate estimate of actual evapotranspiration (ETa) is crucial for optimizing irrigation scheduling and maximizing water use efficiency [12]. ETa is affected by various plant, meteorological, and soil factors. To determine the ETa rate for a specific crop, the grass reference evapotranspiration (ETo) must first be calculated. ETo is the rate of evapotranspiration from an extensive reference surface of green grass that has a uniform height of 0.12 m height and is actively growing, well-watered, and completely shading the ground [13]. This value can then be adjusted for specific crops using crop-specific factors. This value reduces to the actual ETa dependent on various factors, including soil dryness.

A soil-related key factor that influences ETa is the total soil water potential (Ψ). It consists of two main components: matric (Ψ_m) and osmotic potential (Ψ_o). The Ψ_o is a function of soluble salt content and it is influenced by the solute transport within the soil profile [14]. Unlike the other factors, the impact of Ψ_o on ET has not been sufficiently investigated in experimental studies. The rate of water flow from the soil to the plant root is controlled by the difference in the total water potential between the two ends of the pathway [15]. The same dynamic controls the water flow from the plant root to the plant leaf. Any change in Ψ_o affects the value of Ψ in the root zone and influences the transpiration rate of the plant. The effect might be amplified when soil becomes dry due to the concentration of soil solution. In dry or semi-arid conditions, salts accumulate in the root zone and at the soil surface, which produces very low values of the Ψ near the plant roots [16]. Electrical conductivity has been shown to have a significant impact on ETa [17–19], as well as on evaporation from bare soil surfaces [20–22].

In previous studies, researchers tried to model the response of water uptake by plants as a function of the electrical conductivity of soil saturated-paste extract (ECe), e.g., [17,23–25]. More recently, [26] modeled the ETa of tomato plants in response to ECe. However, the responses of ET to the in situ Ψ_o and specific ionic stresses are not clearly understood [26]. Therefore, the field irrigation scheduling is still based on retention curves which express water content just as function of the matric potential and disregard Ψ_o . Moreover, the influences of Ψ_o on ET are also neglected in most of the indirect methods for ET estimation, specifically micrometeorological methods, which are widely used. This oversight can lead to inaccurate irrigation scheduling and reduced irrigation efficiency. To address this issue, researchers utilizing the FAO56 crop water requirements method [13] have recommended adjusting the crop coefficient factor (K_c) to account for the stress coefficient (K_s) when salinity affects the plants [27,28]. However, the FAO56 approach for computing K_s for saline stress needs to be validated with a soil water balance [29].

The influence of osmotic potential on the soil water balance, including evapotranspiration, is qualitatively widely recognized, especially in areas affected by salt. However, the actual extent of its impact on evapotranspiration and its two constituents, namely, evaporation and transpiration, remains poorly understood, partly because experimental data on this are scarce. To address this knowledge gap, we conducted a laboratory study using small-scale lysimeters planted with grass and exposed to various osmotic conditions resulting from irrigation with varying water qualities. Our hypothesis was that osmotic potential in the bulk soil significantly affects the soil water balance, and our goal was to elucidate and quantify this influence, including its effects on evapotranspiration and its two constituents.

2. Materials and Methods

2.1. Experimental Setup

To accomplish our objective, we conducted a laboratory experiment using four small lysimeters that were equipped with scales and data loggers and planted with grass. The experiment involved two different irrigation water quality treatments, each replicated twice. The lysimeters, which were constructed from PVC cylinders with an inner diameter of 230 mm, were packed to a height of 200 mm and had a soil volume of 8.3 L. We filled each with 11.8 kg of air-dry sandy loam soil material. Table 1 shows some of the soil properties. The lysimeters were positioned on a workbench behind windows located on the west side

of a laboratory at TU Braunschweig, Germany, where they were exposed to natural sunlight (refer to Figure 1). The experiments took place for about five months including about three months for data collection, from September until end of November, 2020.

Table 1. Basic soil properties.

Sand	Silt	Clay	EC (1:1)	Bulk Density
0.65 kg kg ⁻¹	0.29 kg kg ⁻¹	0.06 kg kg ⁻¹	0.59 dS m ⁻¹	1.43 g cm ⁻³



Figure 1. Experimental setup. (Left): Moist soil with the grass seeds. (Right): Four mini-lysimeters with DL6 data loggers mounted on scales after 18 days of initial growth.

The lysimeters were placed on weighing balances (DS 36K0.2, Kern and Sohn GmbH, Balingen, Germany) and connected to DL6 data loggers (METER Group Inc., Pullman, WA, USA). The hydraulic properties of the material have been determined at soil samples of 250 cm³ that were packed to the same bulk density. We used the simplified evaporation method with the HYPROP (Hydraulic Property Analyzer, METER Group GmbH, Munich, Germany) system to obtain the retention and conductivity data and to fit parametric models to the data (Figure 2). The electrical conductivity of 1:1 (weighing ratio) dry-soil:water extracts was measured using an electrical conductivity meter with measurement correction to 20 °C.

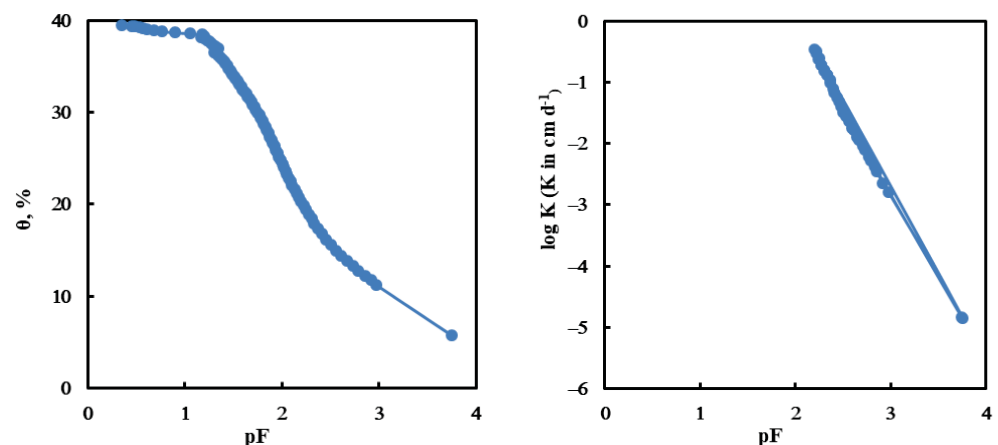


Figure 2. Retention curve and hydraulic conductivity curve of the material used in the small lysimeters. pF is defined by $pF = \log_{10}(-h)$, where h is the matric potential expressed as pressure head in cm.

2.2. Initial Conditions

The lysimeters were packed in air-dry conditions, and the surface of the lysimeters was irrigated with distilled water until the moisture content reached the proper level ($\theta = 20\%$) for seed germination. Then, the lysimeters were planted with grass seeds (*Lolium perenne*). Each lysimeter received 1.3 g of seeds, which was evenly distributed on the soil surface (Figure 1, left). After seed germination, the lysimeters were manually irrigated

with distilled water in all treatments. Irrigation occurred when the mean volumetric water content decreased by 5%. When the plants reached a height of 12 cm, all lysimeters were harvested and the plant leaves were weighed to verify that all lysimeters had the same plant density. Thereafter, the grass continued to grow and when the plant height reached 12 cm, the irrigation treatments were applied.

2.3. Irrigation Treatments

The experiment consisted of two irrigation water quality treatments, each in two replicates. Two lysimeters were irrigated with distilled water ($EC = 0 \text{ dS m}^{-1}$), whereas the other two were irrigated with a 2560 mg L^{-1} NaCl solution ($EC = 4.79 \text{ dS m}^{-1}$ at 20°C). The osmotic potential of the pure saline solution was -1747 hPa . The use of distilled water is, of course, unusual in normal irrigation practice, but in this experiment our goal was not changing the total electrolyte content in the control treatments.

The plants were grown in well-watered conditions during the experiment, i.e., the volumetric water content of all treatments was kept between 15 and 20%. When the mean moisture content approached the lower threshold, irrigation was applied to increase the volumetric water content again to 20%, controlled by the lysimeter's weight. Table 2 shows the irrigation scheduling for the experiment. Plant height was also maintained at 12 cm during the experiment by cutting the grass three times a month.

Table 2. Irrigation scheduling.

Date	Distilled Water Irrigation, mm	Saline Water Irrigation, mm
7 September 2020	5.4	4.3
10 September 2020	11.3	8.1
16 September 2020	9.8	8.6
20 September 2020	10.9	8.7
23 September 2020	9.2	7.2
28 September 2020	11.2	7.4
2 October 2020	8.0	0.0
5 October 2020	0.0	9.3
9 October 2020	13.9	0.0
12 October 2020	0.0	8.4
14 October 2020	11.2	0.0
19 October 2020	9.7	8.2
23 October 2020	7.55	0.0
29 October 2020	9.6	8.8
5 November 2020	10.8	0.0
9 November 2020	8.9	9.6
16 November 2020	13.6	0.0
20 November 2020	0.0	9.2
23 November 2020	13.7	0.0
27 November 2020	9.7	0.0
Total irrigation, mm	174.5	97.9
Number of irrigation events	17	12

The changes in moisture, bulk electrical conductivity, and matric potential for each lysimeter were monitored. The evolution in osmotic potential in each lysimeter was calculated using Equations (2) and (3) considering the changes in soil moisture and bulk electrical conductivity. Daily and accumulated evapotranspiration were calculated based on the weighing balances data. The relationship between the evolution of osmotic potential and the daily evapotranspiration rate has been obtained. At the end of the experiment, when the soil became air-dry, samples were collected from three different depths (0–7, 7–14, and 14–20 cm) in each lysimeter to estimate the electrical conductivity and the spatial salt distribution.

2.4. Calculation of Osmotic Potential

Ψ_o can be estimated in soil solution using the Van't Hoff equation if both the concentration of solute and the ionic composition are known:

$$\Psi_o = -CiRT \quad (1)$$

where C (Mol L^{-1}) is the molar concentration of the solutes, i (-) is the osmotic coefficient, R ($8.31 \text{ J K}^{-1} \text{ mol}^{-1}$) is the gas constant, and T (K) is the absolute temperature. However, the soil solution contains different salts; therefore, the use of the Van't Hoff equation requires knowledge of the chemical composition of the soil solution.

Alternatively, Ψ_o (atm) can be estimated from EC_e (dS m^{-1}), using the U.S. Salinity Laboratory Staff model [30]:

$$\Psi_o = -0.36 EC_e \quad (2)$$

In this work, we apply this empirical Equation (2), and express Ψ_o in units of hPa. The removal of water from the system will increase the salinity in the soil. We calculate the temporal evolution of the Ψ_o in the lysimeter in response to different volumetric water contents (θ) by the simple relationship given by Campbell [31]:

$$\Psi_o(\theta) = \Psi_o(\theta_s) \frac{\theta_s}{\theta} \quad (3)$$

where θ_s is the volumetric water content at saturation and θ is the reduced water content due to evapotranspiration. To ensure the representativeness of our osmotic potential estimations, we calculated the average value of Ψ_o for the entire volume of the lysimeter, under the assumption that the lysimeter's dimensions provided an adequate representation of the grass root-zone. Hereby, we assume that absorbed ions by the plant root are neglected, and, furthermore, we neglect the local spatial variability of θ and C due to root water uptake and evaporation.

2.5. ET Partitioning

For partitioning the two components of evapotranspiration, we applied the following procedure: We estimated the ground coverage (GC) fraction from pictures collected on the first day after applying the treatments, on day 20 when the influence of saline solution on plant health was firstly observed, and on day 86, which was the last day of the experiment. The images were processed in MATLAB using the CANOPEO tool. This tool was developed at Oklahoma State University and can be freely downloaded (<https://canoqueoapp.com> (accessed on 3 February 2023)) to be integrated with MATLAB; it is capable of accurately estimating the GC by processing images or videos [32,33]. Figure 3 shows the original and processed images for GC estimation.

Leaf area index, LAI ($\text{m}^2 \text{ m}^{-2}$) is calculated from the GC (%) values using the linear model suggested by [34] for grass as follows:

$$LAI = 0.0299 \times GC \quad (4)$$

The evaporation (E) part (mm d^{-1}) is calculated using a model related the ET (mm d^{-1}) and LAI values [35], and the transpiration (T) part is calculated as complementary term by subtracting E from ET:

$$E = \exp(-0.6 LAI) ET \quad (5)$$

$$T = ET - E \quad (6)$$

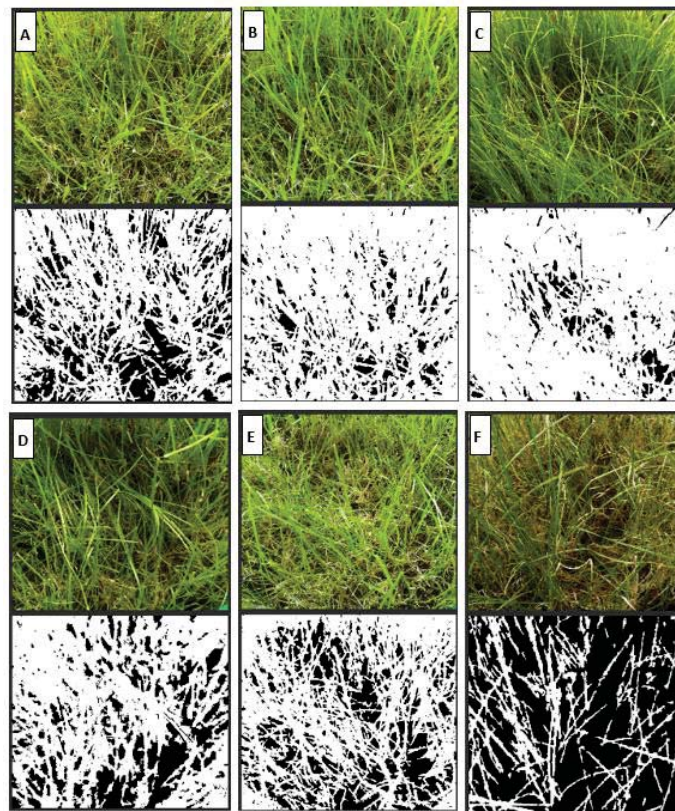


Figure 3. Original and processed images used in GC estimation. The images are labeled as (A–C) for the distilled water treatment at days 1, 20, and 86 after treatment application, and (D–F) for the saline water treatment at days 1, 20, and 86 after treatment application.

3. Results and Discussion

Figure 4 shows the temporal evolution in the Ψ_o values calculated by Equation (3) for both treatments during the experiment. The small variability between the two replicates indicates that the measured values are representative for the system. The trend of the Ψ_o values for the lysimeters that were irrigated with distilled water (blue curves) appears to be stable throughout the study period due to the stability of the total amount of soluble salts in the soil. However, a very slight change has been observed due to the drying–wetting cycles, which lead to a change in the concentration of the soil solution.

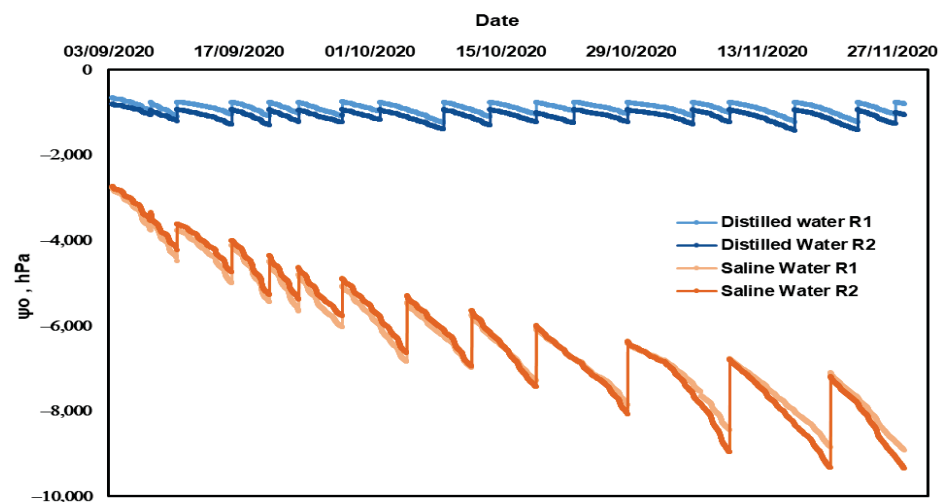


Figure 4. Evolution in Ψ_o values for the lysimeters during the experiment.

The evolution of Ψ_o for the saline water treatments is depicted by the orange data. The trend shows an almost linear decrease in the calculated mean osmotic potential due to the irrigation with saline water during the study period, caused by the added salt by each irrigation event. An instant increase in the Ψ_o value is observed directly after each irrigation event in response to the dilution process for the soil solution. After that, the Ψ_o values start to decrease following the drought process that concentrates the soil solution. Due to the higher salinity level in the saline treatment, the influence of drying–wetting cycles on the Ψ_o are far more pronounced compared to the distilled water treatment, and the impact increases after each irrigation event due to the ongoing salt accumulation.

Figure 5 shows the average daily evapotranspiration for the treatments studied. Evapotranspiration rates varied from day to day due to meteorological conditions and decreased in both treatments. This general trend followed the change in environmental conditions with shorter daylight hours as the experiments began in early September and continued through late November. The reduction in daily ET in the saltwater treatments was prevalent already from the beginning, but became more pronounced over time. The reduction started at about 10% and reached 55% after three months of applying the treatments.

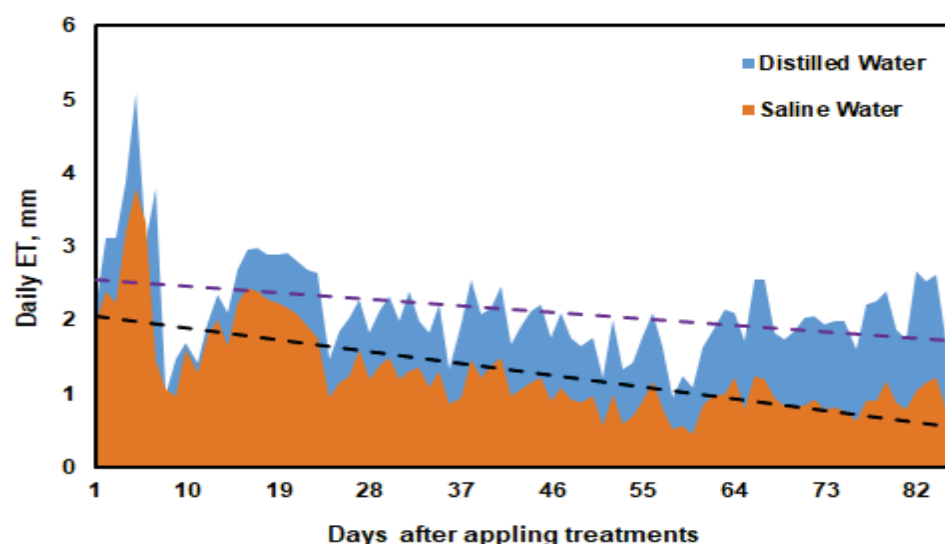


Figure 5. Average daily evapotranspiration values for the treatments during the experiment.

Since soil moisture was kept high enough to meet the ETo requirement, the relative reduction in the salt treatment is entirely due to the effect of salt on both evaporation and transpiration. The change in soluble salt content leads to a decrease in evaporation rate due to the reduction in water vapor pressure [36]. On the other hand, the transpiration rate decreased due to the effects on the gradient of soil water potential between soil and plant root, which controls the flow of water through the soil–plant system [15,16]. With ongoing time, this was superimposed by a deterioration in plant health, which was observed in the salt treatment from about 20 days after treatment, as shown in Figure 6.

Figure 7 shows the effect of the experimental treatments on cumulative evapotranspiration. At the end of the experiment, accumulated evapotranspiration reached 112 mm in the saline treatment, while it was 184 mm in the treatments irrigated with distilled water. The reduction in cumulative evapotranspiration was 39% during the experimental period. It is noteworthy that irrigation with saline water resulted in a reduction in the number of irrigation events required, with a recorded frequency of 12 events, compared to the 17 events observed in the distilled water treatment (Table 2).

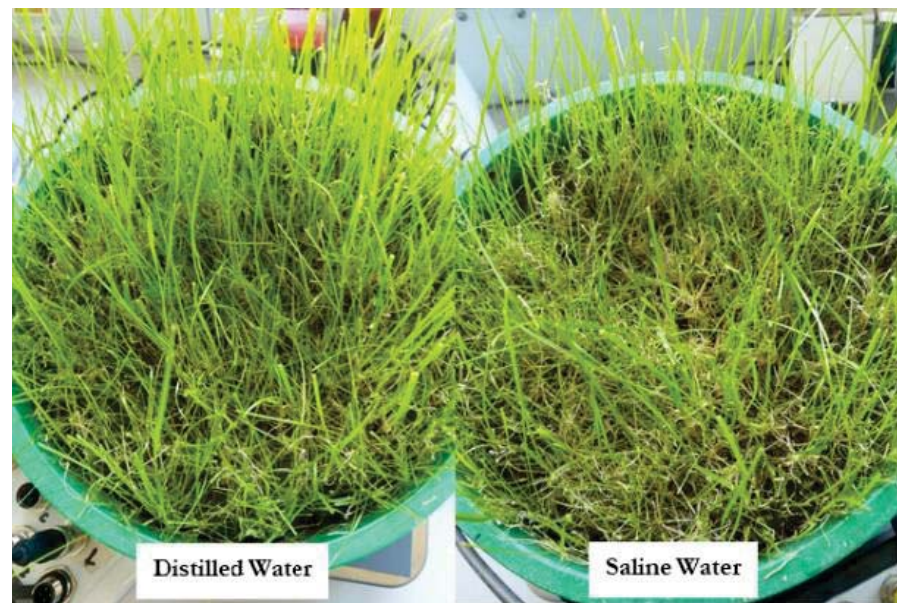


Figure 6. Reduced plant health of the saline irrigated variant, 20 days after applying the treatments.

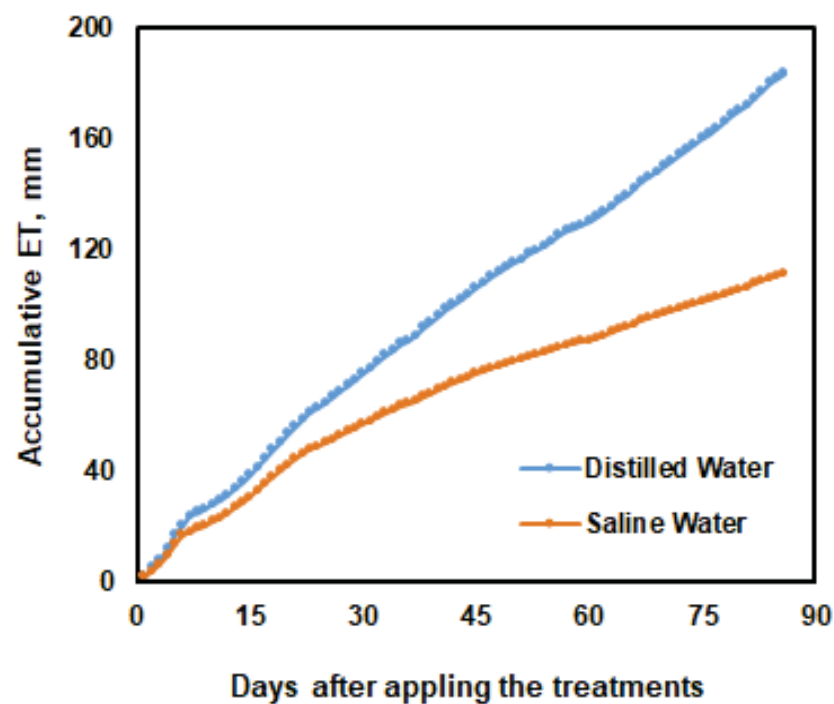


Figure 7. Cumulative evapotranspiration in response to the experimental treatments.

The underlying cause can be attributed to the influence of osmotic stress, which affects plant water uptake by influencing the hydraulic gradient in the root zone. As a consequence, this influence leads to a reduction in water loss through transpiration from plant leaves [15,16]. Additionally, the accumulation of soluble salts affects water vapor pressure, resulting in a reduction in evaporation from the soil surface [20]. These combined effects caused a reduced amount of cumulative evapotranspiration for osmotic stress-treated plants, and, accordingly, a reduced amount and frequency of required irrigation events.

The partitioning of ET into its components, E and T, is illustrated in Figure 8. The figure displays the response of E and T to Ψ_o on the first day after treatment application, on day 20, when the impact on plant health was first observed, and on day 86, which was the final day of the experiment. The data show a roughly comparable immediate response from

both ET components on the first day after treatments. The values for E and T for the saline water treatment on day 1 were 0.54 mm d^{-1} and 1.44 mm d^{-1} , respectively, while they were 0.60 mm d^{-1} and 1.58 mm d^{-1} for distilled water treatment. Thus, both components were reduced by roughly 10%.

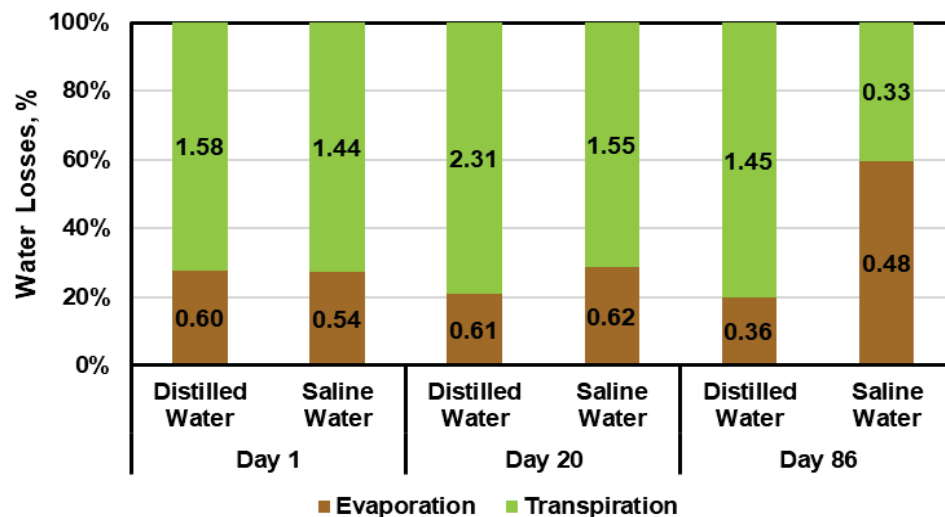


Figure 8. Partitioning of ET.

In the further course of the experiment, the increasing impact of saline solution on plant health is reflected in the reduction in GC and LAI, as presented in Table 3 for three key dates. The relative decrease in the transpiration component for the saline water treatment became stronger with time. On day 20, the values for E and T for the saline water treatment were 0.62 mm d^{-1} and 1.55 mm d^{-1} , while they were 0.61 mm d^{-1} and 2.31 mm d^{-1} for the distilled water treatment. In the further course of the experiment, the evaporation rate for the saline water treatment was, interestingly, slightly higher than that of the distilled water treatment, which can be attributed to the decrease in GC, which, in turn, increased the available surface area of the soil for evaporation. On day 86, this effect was most pronounced due to the substantial reduction in GC and LAI (Table 3) for the saline solution treatment, which showed an evaporation value of 0.48 mm d^{-1} compared to the distilled water treatment with 0.36 mm d^{-1} . In contrast, transpiration was lowered in the saline variant down to 0.33 mm d^{-1} compared to the distilled water treatment with 1.45 mm d^{-1} .

Table 3. GC, LAI, and partitioning of ET components.

Treatment	Day	GC (%)	LAI ($\text{m}^2 \text{ m}^{-2}$)	ET (mm d^{-1})	E (mm d^{-1})	T (mm d^{-1})
Distilled water	1	71.8	2.15	2.19	0.60	1.58
	20	87.5	2.62	2.91	0.61	2.31
	86	90.6	2.71	1.81	0.36	1.45
Saline water	1	72.5	2.17	1.98	0.54	1.44
	20	69.6	2.08	2.18	0.62	1.55
	86	29.0	0.87	0.81	0.48	0.33

The reduction in ET and its components in the saline solution treatment is due to the two-phase growth response to salt stress [37], which includes an osmotic process caused by salt accumulation in the root zone, reducing osmotic potential and plant growth, and an ion-specific process leading to further reduction in plant growth due to soil nutrient balance and plant cellular processes.

The relationship between Ψ_o and E_{Ta} is presented in Figure 9. E_{Ta} in this figure refers to the daily evapotranspiration from the lysimeters that were irrigated with saline solution, while the E_{To} refers to the evapotranspiration from the lysimeters that were irrigated

with distilled water. We assume that the evapotranspiration values for the distilled water treatment can serve as a reference for comparison. The data in Figure 9 show a strong and roughly linear relationship between ET_a/ET_o and Ψ_o . The decreasing Ψ_o in the root zone causes a significant reduction in the daily evapotranspiration. At the lowest values of Ψ_o , when it reached about -9000 hPa, the ET_a/ET_o ratio was about 0.4, i.e., the reduction in the daily evapotranspiration reached 60%.

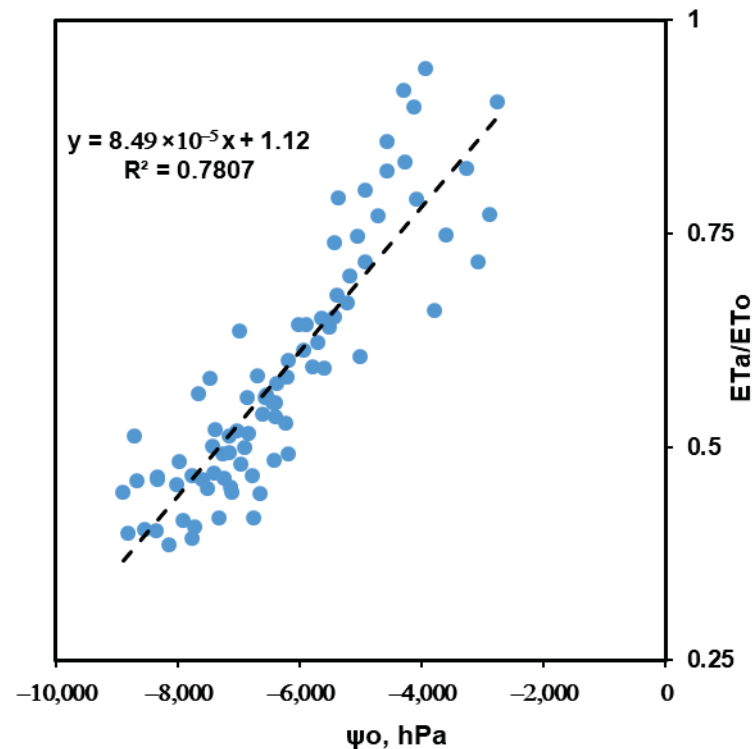


Figure 9. The influence of Ψ_o on the ET_a/ET_o ratio.

We attribute this reduction to two factors. The first factor is the water potential gradient, which controls the water flow through the soil–root–leaf–atmosphere system, as well as the water flow directly from the soil to the atmosphere. Water potential directly controls the function of leaves, roots, and microbes, and gradients in water potential drive water flows throughout the soil–plant–atmosphere continuum [38]. The transpiration rate from plant leaves is determined by the water potential gradient between the root surfaces and the leaves, divided by the plant resistance factor. When the water potential decreases, the hydraulic gradient is reduced and the plant resistance factor increases, leading to a reduction in the transpiration rate [15].

The second factor is the plant-health factor, which refers to the effect on plant biological activities and the nutrient balance. The impact of the second factor leads to a reduction in LAI and thus affects transpiration and, complementarily, increases relative evaporation. The influence on plant health is strongly correlated to the type of the prevalent ions in the soil solution and their concentration, as well as to the plant-specific parameters such as plant type, growth stage, species and variety [37].

The simple linear relation in Figure 9 allows the calculation of the reduction in ET in response to the decrease in the osmotic potential in the root zone. Mathematically, and based on the collected data, the evapotranspiration under osmotic influence (ET_{Ψ_o}) can be expressed as:

$$ET_{\Psi_o} = f \times ET_o \quad (7)$$

where

$$f = \begin{cases} 5.8 \times 10^{-5} \times \Psi_o & \text{for } \Psi_o < \Psi_o^* \\ 1 & \text{for } \Psi_o \geq \Psi_o^* \end{cases} \quad (8)$$

In Equation (8), Ψ_o^* is the threshold point at about -1400 hPa, up to which there is no significant impact from the Ψ_o with respect to the reference. Equation (8) shows that beyond this threshold, a 1000 hPa decrease in Ψ_o causes an 8.5% decrease in ET_{Ψ_o}/ET_0 . A 100% decrease in ET would be reached if the osmotic potential drops to $-13,200$ hPa, which is about $11,800$ hPa from the threshold. This value is close to that of [39], who found that Perenne grass can turn yellow within two weeks when the electrical conductivity of the growing medium (Hoagland solution) reaches 24 dS m^{-1} , corresponding to an osmotic potential of about -8800 hPa. Equation (8) is based on empirical data of our experiment and we expect that it may depend on the plant species and the dominating ion type in the soil solution. The model should be tested in real-field conditions under wide range of soil salinity cases.

Figure 10 finally shows the electrical conductivity of the 1:1 soil:water extracts for the studied treatments, obtained in three depth layers after the end of the experiment. The results indicate a strong salt accumulation due to the irrigation with saline solution, but also a relative accumulation of native salt in the soil in the control. The electrical conductivity of the top layer reached 8.2 dS m^{-1} for the saline water treatment, while it was 0.76 dS m^{-1} for the distilled water treatment. These results indicate that primarily due to evaporation, most of the soluble salts moved to the upper layer. For the distilled water treatment, the electrical conductivity for the top layer was 0.76 dS m^{-1} , while it was 0.12 and 0.09 dS m^{-1} for the middle and lower layers, respectively. In the case of the saline solution treatment, the electrical conductivity for the upper, middle, and lower layers was 8.20 , 0.95 , and 0.46 dS m^{-1} in succession. The illustration of the salinity distribution shows the importance of the soil water flow, whether the flow is within the soil profile or through the soil–atmosphere or soil–plant systems. This is particularly important in arid and semi-arid regions, salt-affected soils, coastal lands, and when low-quality water is used for irrigation. When the salts accumulate near the soil surface, they apply a driving force to the soil surface and affect the water flow. The accumulation of soluble salts on the soil surface results in an increase in hydraulic gradient by reducing the osmotic potential, thereby stimulating the movement of water from the soil body towards the surface. On the other hand, precipitation of salts on the soil surface reduces the flow of water from the soil to the atmosphere, due to the mulching effect of the precipitated salts on the soil surface.

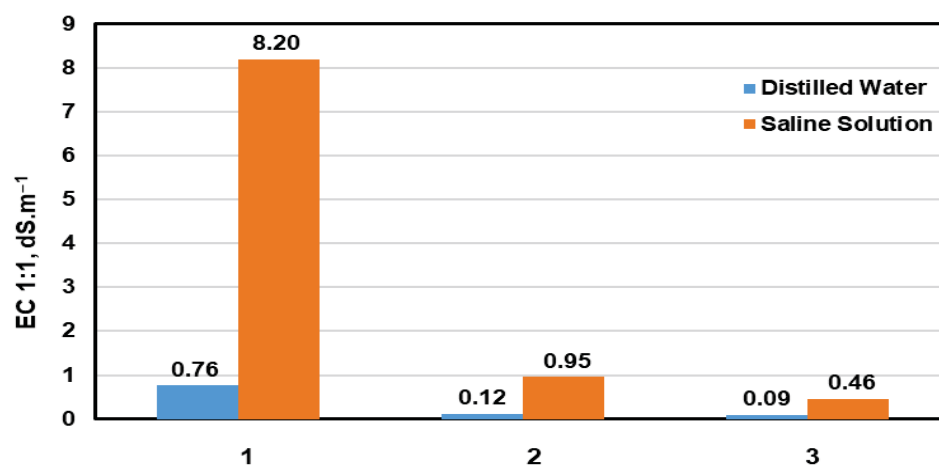


Figure 10. Electrical conductivity at the soil surface (1), mid layer (2), and lower layer (3).

4. Conclusions

In an experimental study, we investigated the impact of osmotic potential on evapotranspiration from small-scale laboratory lysimeters planted with grass. To achieve this, we used two different water quality levels for irrigation. The first level involved the use of distilled water for irrigation, which ensured a constant total salt content in the lysimeters during the experiment and maintained the mean osmotic potential at a stable level. In

contrast, the second treatment involved the use of a 4.79 dS m^{-1} NaCl solution for irrigation, which continuously decreased the osmotic potential throughout the study. We used average values in the lysimeters in this study to find a relationship between ET reduction and osmotic potential, because a detailed characterization of the spatiotemporal local distribution and evolution of osmotic potential in the root zone, including salt accumulation in the near rhizosphere, would be beyond the goal of this study, both in terms of measurement and practicality of the model.

Our results indicated a strong relationship between the mean osmotic potential in the system and the evapotranspiration. We observed a 10% reduction in daily evapotranspiration immediately after applying the treatments, with the reduction reaching approximately 55% at the end of the study. The cumulative evapotranspiration reduced by 39% over the three-month data collection period. These findings highlight the importance of considering osmotic potential in water balance studies, irrigation scheduling, and watershed management, particularly in regions with arid and semi-arid climates, salt-affected soils, coastal areas, and when using low-quality water, such as wastewater, for irrigation. However, large-scale field studies are needed to investigate the role of osmotic potential in evapotranspiration under more complex natural conditions and to consider different water and soil qualities and salinity compositions.

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Article

Remote Sensing Monitoring of Soil Salinity in Weigan River–Kuqa River Delta Oasis Based on Two-Dimensional Feature Space

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Abstract: Soil salinization is a serious resource and ecological problem globally. The Weigan River–Kuqa River Delta Oasis is a key region in the arid and semi-arid regions of China with prominent soil salinization. The saline soils in the oasis are widely distributed over a large area, causing great harm to agricultural development and the environment. Remote sensing monitoring can provide a reference method for the management of regional salinization. We extracted the spectral indices and performed a correlation analysis using soil measurement data and Sentinel-2 remote sensing data. Then, two-dimensional feature space inversion models for soil salinity were constructed based on the preferred spectral indices, namely, the canopy response salinity index (CRSI), composite spectral response index (COSRI), normalized difference water index (NDWI), and green atmospherically resistant vegetation index (GARI). The soil salinity in a typical saline zone in the Weigan River–Kuqa River Delta Oasis was monitored and analyzed. We found that the inversion of the CRSI-COSRI model was optimal (R^2 of 0.669), followed by the CRSI-NDWI (0.656) and CRSI-GARI (0.604) models. Therefore, a model based on the CRSI-COSRI feature space can effectively extract the soil salinization information for the study area. This is of great significance to understanding the salinization situation in the Weigan River–Kuqa River Delta Oasis, enriching salinization remote sensing monitoring methods, and solving the soil salinization problem in China.

Keywords: soil salinization; two-dimensional feature space; remote sensing monitoring; Weigan River–Kuqa River Delta Oasis

1. Introduction

Today, soil salinization is a widespread soil degradation and land desertification phenomenon [1]. It is a negative result of the movement of soil salts caused by a combination of natural conditions such as different surface morphologies, climatic conditions, and hydrological factors [2,3]. It is also a global resource problem caused by a combination of irrational human activities that do not take into account the laws of nature and the increasingly fragile ecological environment [4,5]. Saline soils are widely distributed in China, especially in the arid and semi-arid provinces in northwestern China such as Gansu, Ningxia, and Xinjiang [6], where salinization is serious due to the influences of human and natural factors. This substantially restricts the development of the agricultural industry, the sustainable use of land resources, and the security and stability of the environment [7,8]. Therefore, the monitoring inversion of accurate salinization information and mastering the salinity of regional arable farmland are important goals that scholars have tried to support through research.

Accurate and rapid information on the soil salt distribution is an important prerequisite for achieving the goal of managing and utilizing saline soils on a large scale [9,10]. With the continuous innovation in remote sensing techniques and the improvement in the spectral and spatial resolution of remote sensing images, efficient, convenient, and multi-dimensional methods for monitoring salinity information have been developed [11]. Researchers have gradually found that the data carried by different remote sensing images can be used to identify, classify, and extract the salinization information for a more accurate quantitative inversion monitoring of parameters related to soil salinity in different regions [12]. As the research means of the inversion analysis of soil salinization based on remote sensing image data is gradually becoming common, it has become an important method for research on qualitative and quantitative soil salinization, dynamic analysis, information extraction, monitoring, and forecasting [13,14]. A remote sensing monitoring model was constructed with the aim of determining the correlations between the measured soil salt content and multiple remote sensing modeling factors [15]. Based on the research and analysis of many scholars in China and abroad, it has been found that the spectral feature space modeling method can be applied to construct a remote sensing soil salinity monitoring model [16–18]. Frontier research results have confirmed that the characteristic spatial models constructed based on remotely sensed parameters have a significant correlation with the soil salinity data. The construction of different combinations of eigenspace inversion models with different dimensions using quantitative indicators from different data sources is gradually becoming a mainstream tool for soil salinity monitoring [19]. For example, Jianli Ding et al. [20] extracted the modified soil adjusted vegetation index and moisture index from remote sensing images and constructed a two-dimensional feature space based on them. Their results showed that this two-dimensional feature space was well-correlated to the surface soil salinity in an oasis in an arid zone. Bing Guo et al. used the synergistic relationship between soil and vegetation to construct a two-dimensional feature space model and found that the model has the potential to monitor soil salinization in the Yellow River Delta region [21]. Juan Feng et al. [22] used the relationships between various factors such as the surface albedo to construct a feature space. Their results showed that this monitoring model based on surface albedo and the soil adjusted vegetation index could analyze the degree of soil salinization in their study area accurately and efficiently. Lingling Bian et al. [23] quantitatively explored the relationships between the soil salinity and several surface parameters in the Yellow River Delta region. Their results showed that this feature space model, constructed based on the salinity index and surface albedo, had a strong predictive ability and provided a favorable reference for the inversion of soil salinization in China's seaside areas. It can be seen that the inversion results obtained by constructing monitoring models with different uses for study areas with different geographical features were significantly different [1,2]. It has become a hot topic in the field to calculate and select the spectral parameters of remote sensing images with high correlations to the soil salinity in a study area and to construct a specific feature space model based on them [24–26], in order to further improve the accuracy and efficiency of the inversion of the saline soils.

Therefore, with the objective of the monitoring and inversion of regional soil salinization, in this study, a typical saline zone in the Weigan River–Kuqa River Delta Oasis in Xinjiang was taken as the study area. Based on field soil data and Sentinel-2 remote sensing image data, we calculated and selected the optimal spectral index and then constructed a variety of different combinations of soil salinity two-dimensional feature spaces, quantified and analyzed the feature space scatter plot, constructed a soil salinity inversion model, and analyzed the spatial distribution of the soil salinity in the study area. We then conducted remote sensing monitoring of the soil salinity in a typical saline zone in the Weigan River–Kuqa River Delta Oasis. This is of great practical importance to further master advanced remote sensing technology monitoring methods, effectively manage and utilize land resources, and optimally promote the sustainable development of the oasis region.

2. Materials and Methods

2.1. Study Area

The Weigan River–Kuqa River Delta Oasis is located in the Xinjiang Uygur Autonomous Region, China, covering the Xinhe, Kuche, and Shaya Counties. It is located in the southern part of the middle Tianshan Mountains and on the northern edge of the Tarim Basin in southern Xinjiang (Figure 1) and is a representative of typical oases in arid regions [20]. The study area in this typical saline zone is mainly located in Kuche County, where the climate is dry, precipitation is scarce and unevenly distributed, and the evaporation is much greater than the precipitation [27]. The salts in the groundwater and deep soil rise to the surface along soil capillaries under strong evaporation and accumulate, causing regional salinization of the soils. In addition, the lack of effective engineered drainage facilities inside the oasis has made it difficult to reasonably circulate the soil salinity inside the oasis, thus causing increased salinization and seriously affecting the development of oasis agriculture in the region.

2.2. Soil Data Collection and Processing

In this study, we conducted surface soil sampling and an environmental investigation in the typical saline area in the Weigan River–Kuqa River Delta Oasis in July 2022. During the sampling process, the soil sampling points were evenly distributed throughout the study area and were distributed in the periphery of the oasis, the oasis–desert interlacing zone, and the inner area of the oasis, covering different vegetation cover types, land use types, and soil types, with a total of 78 soil sampling points. During the expedition, based on the team's previous experience and results on the soil salinity content in the study area, several representative areas were visited. The salinized soils of the study area with different degrees of salinity were photographed and recorded (Figure 2). After the sample collection, the samples were placed in aluminum boxes and sampling bags were marked with corresponding numbers. The specific coordinates of the sampling points, land use patterns, soil salinity, vegetation types, and cover were recorded in detail to facilitate subsequent analysis. Finally, the collected soil samples were transported to the laboratory for air-drying, grinding, removing impurities, and sieving to determine the soil salinity data required for the study.

2.3. Remote Sensing Image Acquisition and Pre-Processing

Sentinel-2 optical images with a spatial resolution of 10 m were selected as the remote sensing data source for this study. The Sentinel-2 image data for the Weigan River–Kuqa River Delta Oasis were obtained from the official website. The images were chosen to completely cover all of the sampling points, and 5 July 2022 was chosen as the imaging time for correspondence with the acquisition of the field data. The weather in the study area during this period was clear, with few clouds and rain, dry ground, and sparse vegetation growth, which made the remote sensing images more effective and facilitated the inversion of the ground soil salinity. The acquired images were pre-processed using remote sensing information processing software such as SNAP, ENVI, and ArcGIS to lay the foundation for the subsequent inversion and application.

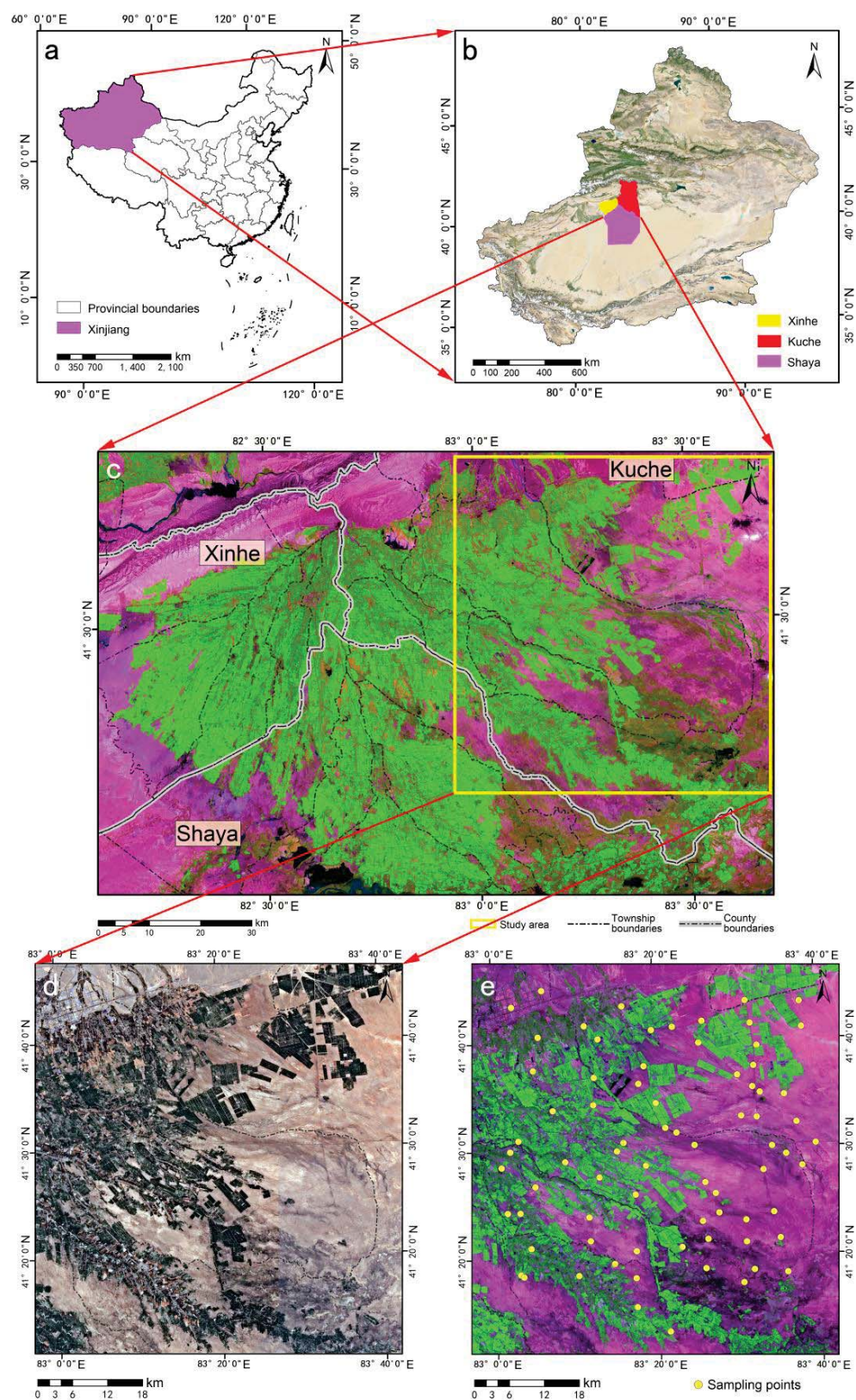


Figure 1. (a) Location of the study area in China. (b) Location of the study area in Xinjiang. (c) Sentinel-2 image of the Weigan–Kuqa River Delta Oasis. (d) Topographic map of the study area. (e) Distribution of the sampling sites in the study area.

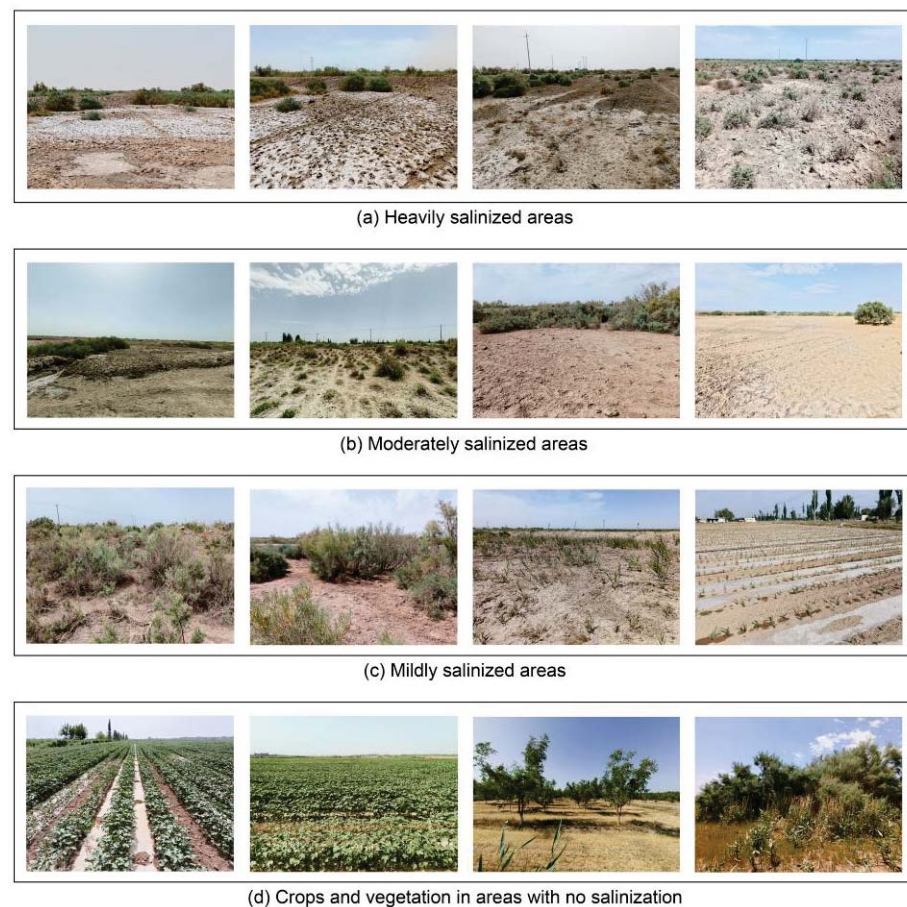


Figure 2. Soil types with different degrees of salinization in the study area.

2.4. Spectral Index Calculation and Normalization

The pre-processed remote sensing image data were rich in spectral information about the various features, which was contained in the reflectance of the different wavelength bands in the remote sensing data [28,29]. Since the spectral information contained in a single band is very limited, after extracting the spectral reflectance data from each band of a remote sensing image, a combination operation can be performed between the different bands to obtain more and richer information [30–33]. Since salinized soils have stronger spectral reflectance in the near-infrared band and visible band than other types of soils, multiple salinity indices composed of reflectance information in different wavelength bands based on remote sensing data can directly monitor different levels of soil salinity [34]. In addition, some researchers have found that vegetation indices can also be used as indirect parameters to discriminate saline soils by expressing different vegetation species and their coverage [35]. At the same time, soil salinity changes have a great relationship with the water circulation process as salt moves with water, and soil salinity is prone to shift with water changes. Therefore, water indices can also be one of the most indirect parameters to participate in the monitoring of soil salinity [9]. The canopy response salinity index (CRSI), normalized difference water index (NDWI), and soil adjusted vegetation index (SAVI) were selected from the 22 commonly used soil salinity-related spectral indices (Table 1). The reflectance of the different wavelength ranges in the multispectral data from the Sentinel-2 remote sensing images corresponding to each sampling point was extracted using ArcGIS, and the spectral indices in the study area were calculated and analyzed using the formulas in the ENVI software. Finally, a series of spectral indices were calculated and correlated with the measured soil salt content to obtain the optimal spectral indices with a high correlation to the measured soil salt content for use in the subsequent modeling.

Table 1. Spectral indices and calculation formulas.

Spectral Index	Calculation Formula	Reference
Composite Spectral Response Index (COSRI)	$\frac{B+G}{R+NIR} \times \frac{NIR-R}{NIR+R}$	[36]
Canopy Response Salinity Index (CRSI)	$\sqrt{\frac{(NIR \times R) - (G \times B)}{(NIR \times R) + (G \times B)}}$	[37]
Difference Vegetation Index (DVI)	$NIR - R$	[38]
Green Atmospherically Resistant Vegetation Index (GARI)	$\frac{NIR - [G + 0.9(B - R)]}{NIR + [G + 0.9(B - R)]}$	[39]
Intensity Index 1 (Int1)	$\frac{G+R}{2}$	[40]
Intensity Index 2 (Int2)	$\frac{G+R+NIR}{2}$	[40]
Normalized Difference Salinity Index (NDSI)	$\frac{R-NIR}{R+NIR}$	[41]
Normalized Difference Vegetation Index (NDVI)	$\frac{NIR-R}{NIR+R}$	[42]
Normalized Difference Water Index (NDWI)	$\frac{G-NIR}{G+NIR}$	[43]
Ratio Vegetation Index (RVI)	$\frac{NIR}{R}$	[44]
Salinity Index (S1)	$\frac{B}{R}$	[45]
Salinity Index (S2)	$\frac{B-R}{B+R}$	[45]
Salinity Index (S3)	$\frac{G \times R}{B}$	[45]
Salinity Index (S5)	$\frac{B \times R}{G}$	[45]
Salinity Index (S6)	$\frac{R \times NIR}{G}$	[45]
Soil Adjusted Vegetation Index (SAVI)	$\frac{(1+L)(NIR-R)}{NIR+R+L}$	[46]
Salinity Index (SI)	$\sqrt{B \times R}$	[41]
Salinity Index 1 (SI1)	$\sqrt{G \times R}$	[47]
Salinity Index 2 (SI2)	$\sqrt{G^2 + R^2 + NIR^2}$	[48]
Salinity Index 3 (SI3)	$\sqrt{G^2 + R^2}$	[48]
Salinity Index 7 (SI7)	$\frac{R \times NIR}{G}$	[49]
Salinity Ratio Index (SRI)	$(R - NIR) \times (G + NIR)$	[50]

Note: *B* is the blue band, *G* is the green band, *R* is the red band, *NIR* is the near infrared band, and *L* is the soil adjustment coefficient, which is generally close to 0.5.

In order to eliminate the effect of the differences in the magnitude and units of the data for the different variables, the maximum and minimum values of the spectral indices for the study area were obtained, the data were standardized [51,52], and the original values were mapped to the interval (0, 1) via standardization. The formula is as follows:

$$\text{Result} = \frac{DN - DN_{min}}{DN_{max} - DN_{min}} \times 100\% \quad (1)$$

where Result is the normalized value; *DN* is the original image element value; *DN_{min}* and *DN_{max}* are the minimum and maximum values of the band, respectively.

2.5. Two-Dimensional Feature Space Inversion Models

Based on the results of many researchers in China and abroad in recent years, it was found that a two-dimensional feature space method that uses different soil parameters to form various combinations can be effectively applied to construct a remote sensing soil monitoring model [53–55] that provides a good reference for the monitoring of soil salinization. In this study, we analyzed the shape, distribution characteristics, and correlation of the feature space scatter plot based on practical experience to determine the mutual variation trends between the different covariates. The distance from any point

in the two-dimensional feature space of the soil salinity covariates to a certain feature reference point was used to reflect the different levels of soil salinity.

The distribution pattern of the soil salinity was obtained through a statistical combination of the faceted information so that the corresponding two-dimensional feature space inversion model could be established using the spatial feature covariates of the scatter plot [56,57]. Based on this, the degree and distribution of the salinization of the soils in the study area were characterized. The above eigenspace inversion model was combined with the measured soil salinity for accuracy verification and comparison, and the determination coefficient R^2 was used to reflect the model accuracy. The closer R^2 is to 1, the higher and more stable the fitting effect of the model. R^2 is mathematically defined as follows [58]:

$$R^2 = 1 - \frac{\sum(\hat{y}_i - y_i)^2}{\sum(y_i - \bar{y}_i)^2} \quad (2)$$

where y_i is the measured value; $\bar{y}_i$ is the mean sample value; $\hat{y}_i$ is the predicted value; $i = 1, 2, \dots, n$. Finally, the optimal feature space model was selected according to the accuracy verification results for the inverse analysis of the spatial distribution of the soil salinity in the study area.

3. Results

3.1. Spectral Index Analysis and Data Normalization

Correlation analysis between the above 22 spectral indices and the measured soil salinity was performed to obtain a table of the correlation coefficients between the spectral indices and soil salinity (Table 2). The analysis revealed that among the spectral indices, the CRSI, composite spectral response index (COSRI), NDWI, and green atmospherically resistant vegetation index (GARI) had the highest correlations with the soil salinity in the study area, with R^2 values of -0.622 , -0.612 , 0.609 , and -0.605 , respectively. Among them, the CRSI had the highest correlation and was the salt index directly related to the study target, so it was combined with the other three indices separately as the modeling factors in the construction of the inversion model when constructing the two-dimensional feature space, and the four preferred spectral indices were normalized (Figure 3).

Table 2. Correlations between the spectral indices and soil salinity.

Spectral Index	Correlation Coefficient	Spectral Index	Correlation Coefficient
COSRI	-0.612	S2	0.229
CRSI	-0.622	S3	0.444
DVI	-0.576	S5	0.557
GARI	-0.605	S6	-0.420
Int1	0.538	SAVI	-0.576
Int2	0.341	SI	0.554
NDSI	0.576	SI1	0.539
NDVI	-0.576	SI2	0.195
NDWI	0.609	SI3	0.538
RVI	-0.516	SI7	-0.420
S1	0.224	SRI	0.558

3.2. Two-Dimensional Feature Space Model Construction and Analysis

The normalized CRSI values were used as the horizontal axis, and the normalized COSRI, NDWI, and GARI values were used as the vertical axis to build two-dimensional feature space scatter plots (Figure 4). Based on the distribution characteristics of the soil salinity in the study area shown by the scatter plots, it can be seen that there were significant differences in the spatial distributions of the soils with different degrees of salinization. As shown in Figures 5–7, the green area in the feature space scatter plot represents the vegetation, which is mainly located in the upper right in the CRSI-COSRI and CRSI-GARI

scatter plots and in the lower left in the CRSI-NDWI scatter plot. The yellow area and the orange area represent slightly saline soils and moderately saline soils, respectively. The red area represents heavily saline soils and is mainly located in the lower left in the CRSI-COSRI and CRSI-GARI scatter plots and in the upper right in the CRSI-NDWI scatter plot.

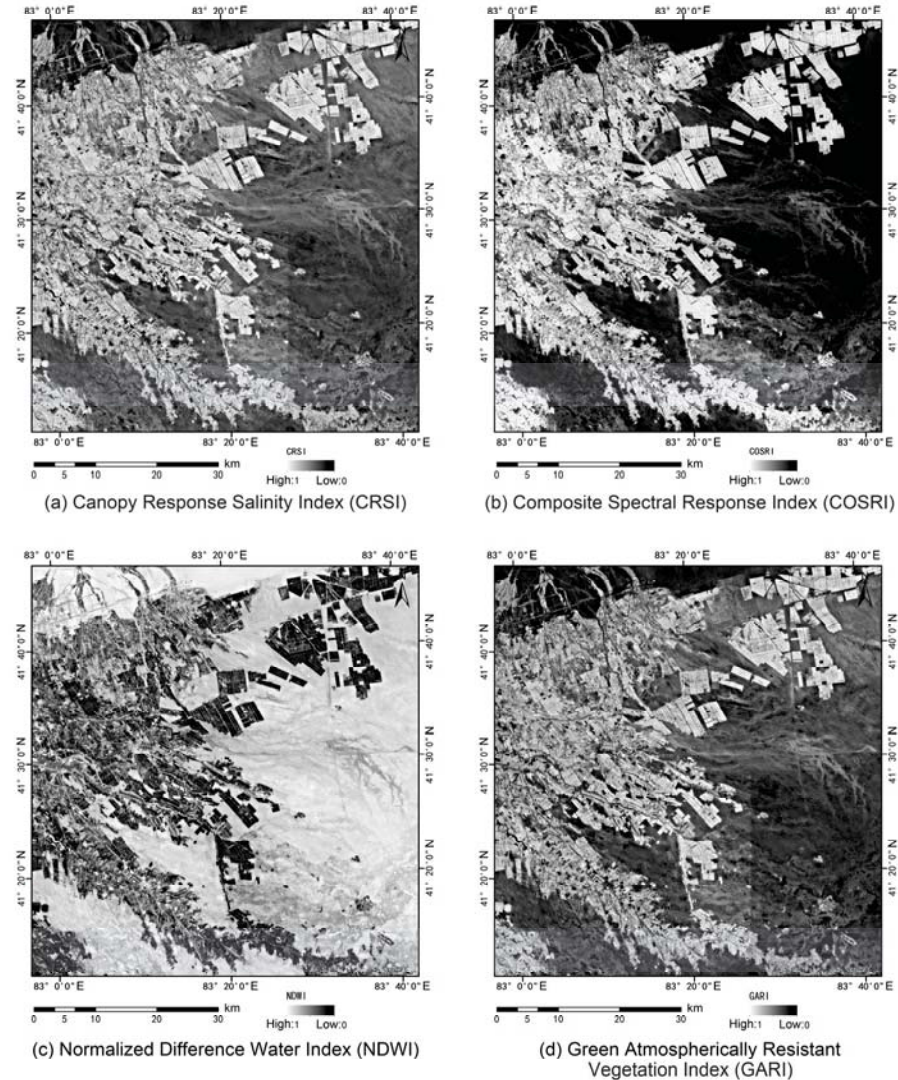


Figure 3. Preferred spectral index normalization results.

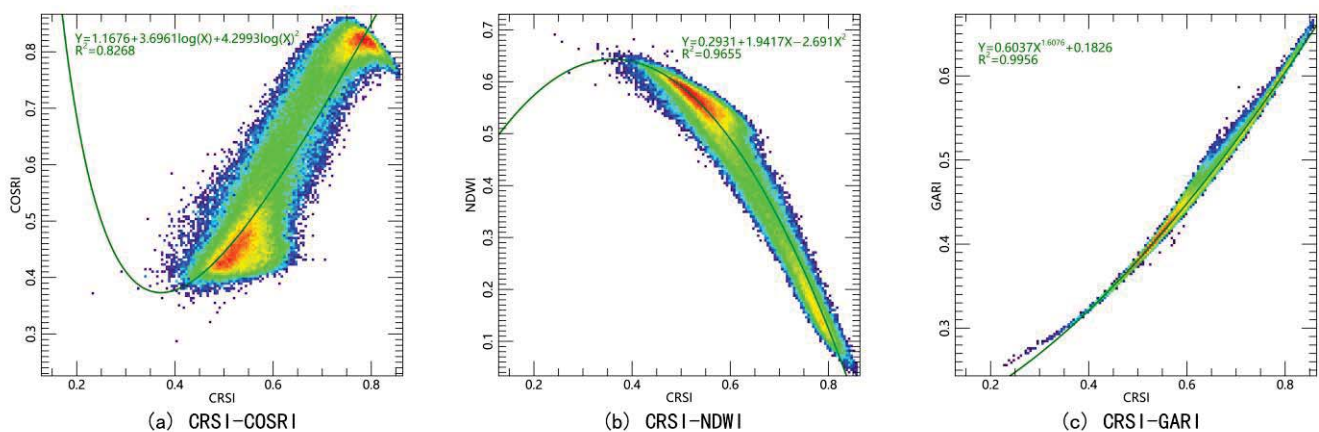


Figure 4. Two-dimensional feature space scatter plots.

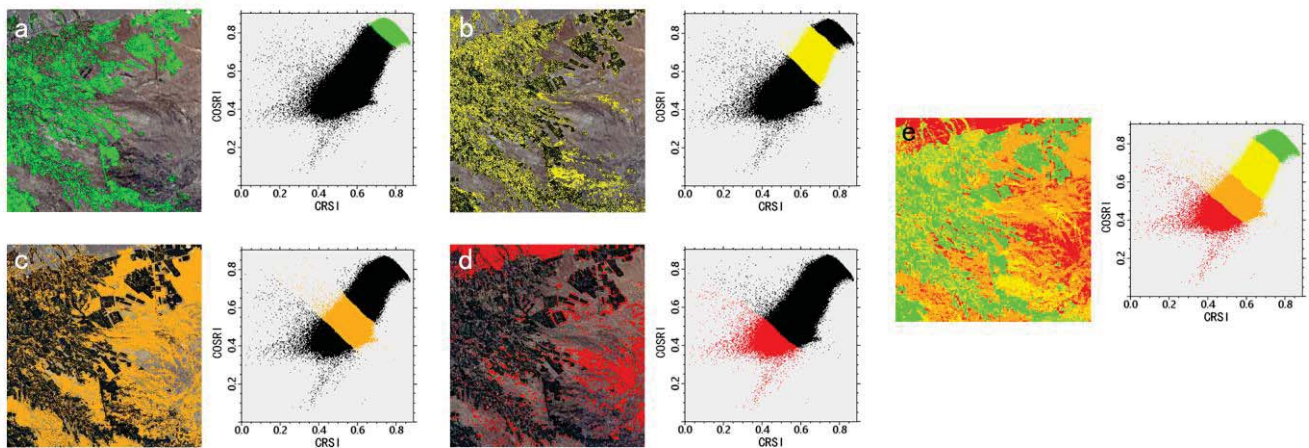


Figure 5. Distribution of salinization degree in the CRSI-COSRI two-dimensional feature space: (a) vegetation; (b) slightly saline soils; (c) moderately saline soils; (d) heavily saline soils; (e) spatial distribution of different degrees of soil salinization.

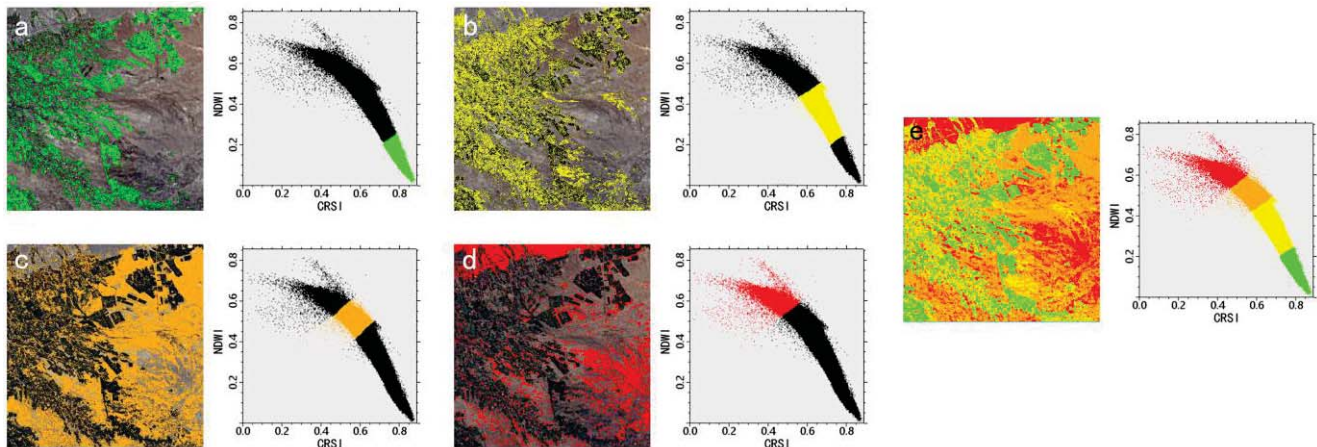


Figure 6. Distribution of salinization degree in the CRSI-NDWI two-dimensional feature space: (a) vegetation; (b) slightly saline soils; (c) moderately saline soils; (d) heavily saline soils; (e) spatial distribution of different degrees of soil salinization.

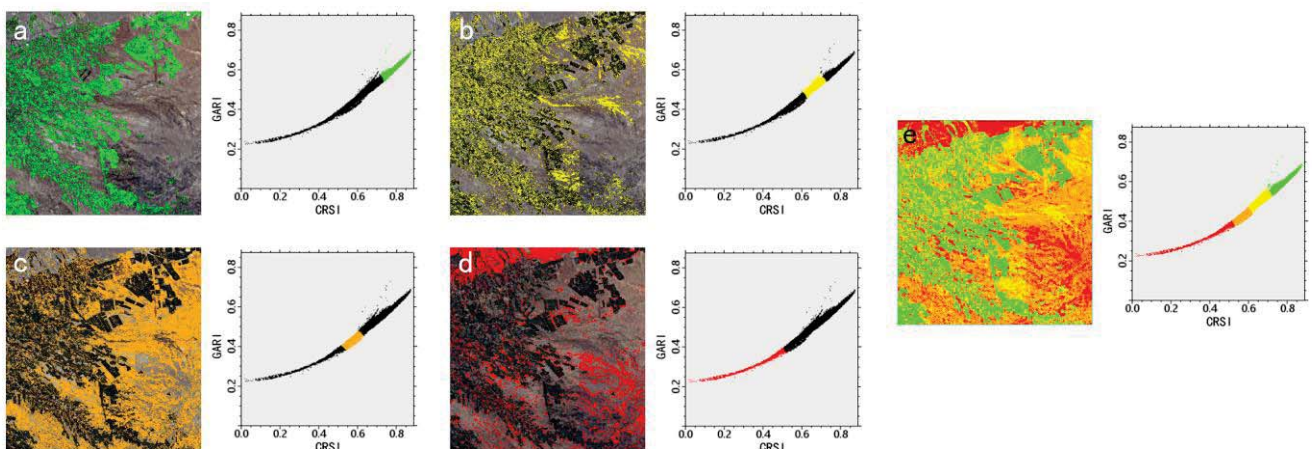


Figure 7. Distribution of salinization degree in the CRSI-GARI two-dimensional feature space: (a) vegetation; (b) slightly saline soils; (c) moderately saline soils; (d) heavily saline soils; (e) spatial distribution of different degrees of soil salinization.

Figure 8 shows the simplified schematic diagrams of the three two-dimensional feature spaces, and it can be seen that there were clear linear relationships between the combinations of spectral indices. In the CRSI-COSRI and CRSI-GARI two-dimensional feature space schematic diagrams, the point at coordinates (1, 1) was used as the feature reference point. This is the point in the study area with the best crop vegetation growth, the highest plant cover, and the lowest surface soil salinity. The distance from any point in the scatter plot to the reference point of the feature reflects the different degrees of soil salinization in the study area. The greater the distance from the reference point, the more severe the soil salinization, and the shorter the distance from the reference point, the less severe the soil salinization. In the CRSI-NDWI two-dimensional feature space schematic diagram, the point with coordinates (1, 0) was used as the feature reference point. The greater the distance from any point in the scatter plot to this feature reference point, the more severe the soil salinization, and the shorter the distance, the less severe the soil salinization.

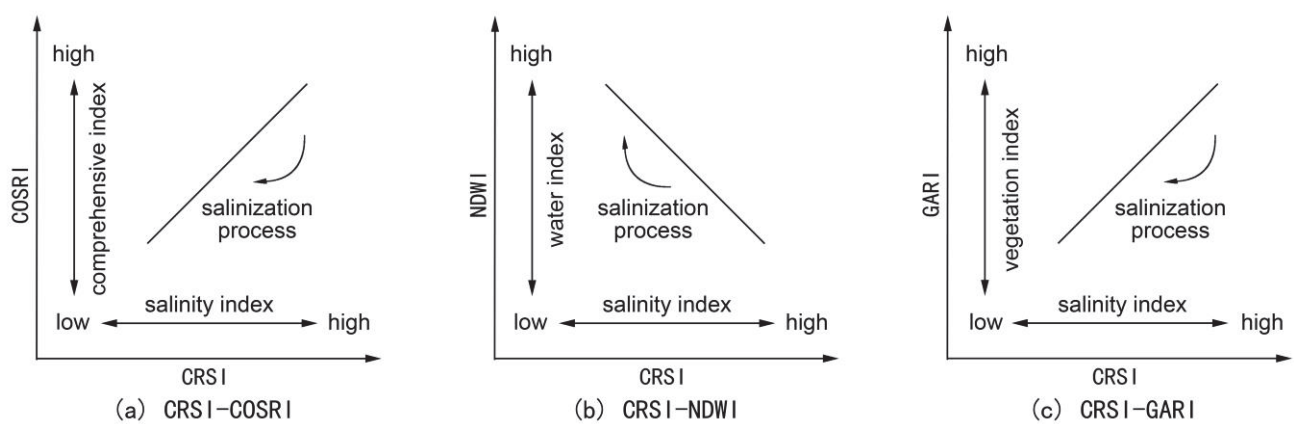


Figure 8. Simplified schematic diagrams of the two-dimensional feature spaces.

Based on the point-to-point distance equation in the two-dimensional coordinate system that expresses the above feature space principles, two-dimensional feature space remote sensing monitoring models for soil salinity were constructed as follows:

$$\text{CRSI} - \text{COSRI} = \sqrt{(\text{CRSI} - 1)^2 + (\text{COSRI} - 1)^2} \quad (3)$$

$$\text{CRSI} - \text{NDWI} = \sqrt{(\text{CRSI} - 1)^2 + (\text{NDWI})^2} \quad (4)$$

$$\text{CRSI} - \text{GARI} = \sqrt{(\text{CRSI} - 1)^2 + (\text{GARI} - 1)^2} \quad (5)$$

Using Equations (3)–(5), soil salinization inversions were performed for the entire study area, and the accuracy of the inversion results was verified based on the actual field measurements (Figure 9). Among them, the logarithmic function models of the CRSI-COSRI and CRSI-NDWI two-dimensional feature spaces had the best fits, with R^2 values of 0.669 and 0.656, respectively. The power function model of the CRSI-GARI two-dimensional feature space had the best fit, with an R^2 value of 0.604. According to the criteria for evaluating the validation capability of the model, which were empirically concluded by the researchers [59], if $R^2 > 0.4$, the characteristic covariates in the prediction model can be considered to have some correlation to the soil salinity information in the study area. If $R^2 > 0.5$, the model can be considered as more sensitive to the soil salinity content and can predict the soil salinization information to some extent. It can be seen that the R^2 of all three models in the feature space model based on Sentinel-2 image spectral index proposed in this study was greater than 0.6. The feature covariates in the models had a high sensitivity to the soil salinity information. The three soil salinity inversion models could predict the degree of surface soil salinity more accurately and had a good soil salinity

inversion ability. Among them, the best soil salinity monitoring model for the study area was the CRSI-COSRI two-dimensional feature space model with an R^2 of 0.669.

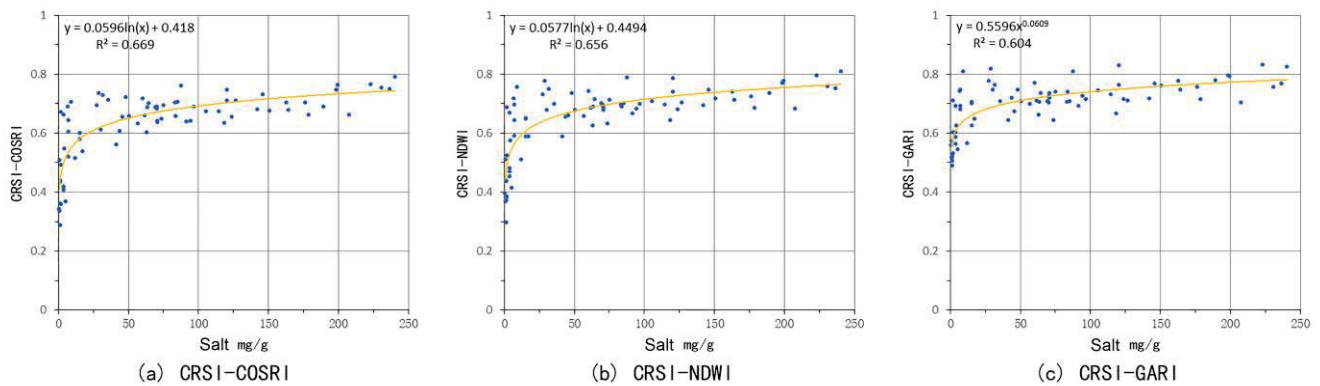


Figure 9. Accuracy verification of the two-dimensional feature space modeling results.

3.3. Spatial Distribution of Soil Salinization

The Jenks natural interruption point grading method is a grading method based on statistical theory and the principle of clustering. The principle of this method is to construct a cluster, which ends when the variance between groups reaches the maximum and the variance within groups reaches the minimum. Thus, the advantage of this grading method is the ability to minimize the sum of the variances within each class [60,61]. In order to more clearly and unambiguously distinguish the different levels of soil salinization, the grading method was used to classify the soil salinity inversion results of the CRSI-COSRI, CRSI-NDWI, and CRSI-GARI two-dimensional feature space inversion models for the study area. Four salinity intervals (i.e., non-saline, mild salinization, moderate salinization, and severe salinization) were established, and the regional salinity level breakpoint monitoring indicators (Table 3) and salinity distribution maps (Figure 10) were obtained for the three two-dimensional feature space soil salinity monitoring models.

Table 3. Soil salinization level breakpoint monitoring indicators.

Salinization Degrees	Non-Saline	Mild Salinization	Moderate Salinization	Severe Salinization
CRSI-COSRI	$>0.24, \leq 0.39$	$>0.39, \leq 0.56$	$>0.56, \leq 0.69$	$>0.69, \leq 1.27$
CRSI-NDWI	$>0.10, \leq 0.38$	$>0.38, \leq 0.56$	$>0.56, \leq 0.70$	$>0.70, \leq 1.27$
CRSI-GARI	$>0.13, \leq 0.54$	$>0.54, \leq 0.66$	$>0.66, \leq 0.76$	$>0.76, \leq 1.26$

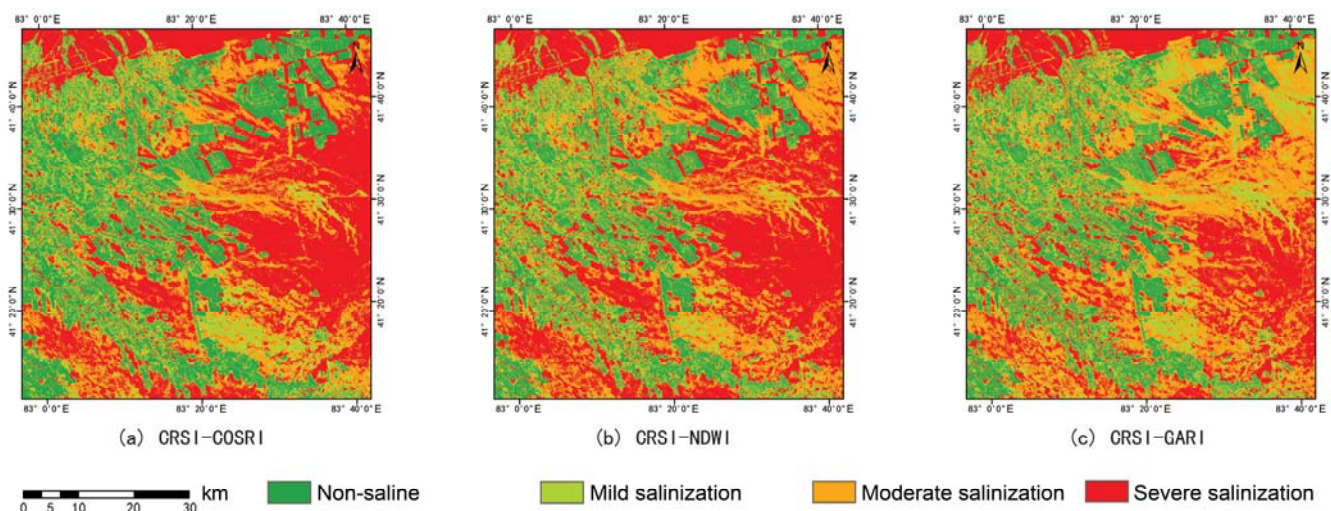


Figure 10. Soil salinity inversion grade distribution.

As shown in Figure 10, the areas of moderate and severe salinization in the study area were large, and the overall soil salinization in the study area was high. The heavily saline areas with the highest salinity were mainly located in the northeastern part of the study area in the oasis-desert staggered zone, in the eastern part of the oasis-peripheral desert area, and in the southern part of the oasis-desert staggered zone. Some of these areas such as the central part of the oasis-desert staggered zone in the study area showed more severe salinization. The interior of the oasis was dominated by mostly non-salinized soils, with lightly salinized areas scattered among them, and the overall soil salt content was low. With the outward extension toward the edge of the oasis, areas of light and moderate salinization began to appear. Overall, the salinization was higher in the eastern region than in the western region, and there was a transition from mild salinization to moderate salinization to heavy salinization from east to west. Taking the edge of the oasis as the starting point, the further away from the oasis, the more salinization of the soil. Up to the desert area in the eastern part of the study area, due to the sparse natural vegetation, low rainfall, and excessive evaporation ratio, the salinity gradually rose to the surface under the effect of strong evaporation, and the water desalinization remaining led to the accumulation of soil salinity day by day, finally forming the current situation of a more serious salinization degree. In summary, the inversion results and spatial distribution prediction of soil salinization in the study area showed a better result. This is consistent with the actual salinization situation in the study area observed during the fieldwork undertaken for this study.

4. Discussion

At present, with the development of remote sensing image modeling and monitoring technology, the construction of feature space models has been increasingly used to monitor soil salinity in salinized areas. The two-dimensional feature space can clearly express the distribution pattern of the factors affecting the soil salinization process. In this study, the typical saline zone in the Weigan River–Kuqa River Delta Oasis in Xinjiang was taken as the study area. Based on Sentinel-2 remote sensing images and the field soil survey data, after selecting the optimal spectral index, remote sensing inversion models were constructed using the CRSI-COSRI, CRSI-NDWI, and CRSI-GARI two-dimensional feature spaces, and the spatial distribution pattern of the soil salinization in the study area was analyzed and studied. The following conclusions were obtained.

1. The validation results of the two-dimensional feature space modeling showed that the three soil salinity inversion models could accurately reproduce the degree of the surface soil salinization. Among the models for the inversion of the surface soil salinity in the study area, the CRSI-COSRI two-dimensional feature space monitoring model constructed using the salinity index and composite index was the most accurate, followed by the CRSI-NDWI two-dimensional feature space monitoring model constructed using the salinity index and the water body index, and the CRSI-GARI two-dimensional feature space monitoring model constructed using the salinity index and the vegetation index was the least accurate.
2. The common characteristics of the spatial distribution of the salinization in the inversion of the two-dimensional feature space model constructed in this study were that the overall proportion of the soil salinization in the study area was large, and the degree of salinization gradually increased from the inner oasis to the oasis–desert inter-lacing zone to the outer oasis area. This was generally consistent with the monitoring results of previous researchers and the results of our field sampling campaign.

Analyzing and discussing the above research results, and combining the results of many researchers in recent years, it can be seen that the feature spatial modeling method using various combinations of different feature parameters can be effectively applied to the modeling of the remote sensing monitoring of soil salinity. The spatial inversion model of the soil salinity characteristics can be established by using the principle of the spatial characteristics of a scatter diagram by obtaining the distribution pattern of soil salinity

through the statistical combination of the faceted information of the selected parameters. This can effectively distinguish saline soils from non-saline soils, characterize the degree of salinization and the distribution of soils in the study area, and provide a good reference for monitoring the soil salinity information. The CRSI-COSRI two-dimensional feature space constructed in this study was more accurate than the CRSI-NDWI and CRSI-GARI two-dimensional feature spaces. The reason for this is that for the CRSI and COSRI, as a salinity parameter and composite parameter that directly reflect the degree of salinization, respectively, their two-dimensional feature space inversion models can better fit the typical saline area in the Weigan River–Kuqa River Delta Oasis where the salinization is more severe. The two-dimensional feature space model is more suitable for this study area than the other two models composed of indirect features. The CRSI-NDWI two-dimensional feature space can also be monitored with a high accuracy in the study area because of the strong relationship between the soil salinity changes and the water circulation processes, and the ease of soil salinity transfer through water changes.

Analysis of the inversion results of the model constructed in the paper shows that the moderate and heavy salinization areas were mainly located in the desert areas on the periphery of the oasis in the eastern part of the study area and in the oasis–desert interlacing zone in the southwestern part of the study area. This may be due to the fact that the desert areas on the periphery of the oasis are not heavily used for large land development, and that the topography of the oasis in the Weigan River–Kuqa River Delta Oasis is high in the north and low in the south. The spatial distribution of the soil salinity is directly affected by the flow of the surface water and groundwater, and the salts gradually rise to the surface and accumulate under the effect of strong evaporation. In contrast, due to the limited precipitation and high evaporation in the oasis–desert interlaced zone region, which hinders the leaching of salts to greater soil depths, soil salts from higher areas tend to accumulate in lower areas, which also leads to waterlogging in the downstream watershed area in the southern part of the region. In addition, the intense evaporation movement causes the soil salts to accumulate in the surface water. Some of the more saline areas within the oasis are due to a lack of effective engineered drainage facilities, which makes it difficult to circulate the soil salts within the oasis, thus causing increased salinity.

5. Conclusions

The use of remote sensing monitoring technology to extract soil salinity information has become a hot topic in the field of remote sensing research. Many scholars in China and abroad have gradually developed new technical means and research methods to achieve more abundant research results through the high-precision monitoring of regional soil salinity [62–64]. In this study, three two-dimensional characteristic spatial monitoring models of soil salinity were constructed based on the soil salinity-related spectral indices. Based on the inversion results, the spatial distribution status of soil salinity and its distribution characteristics in the typical saline zone of the Weigan River–Kuqa River Delta Oasis were analyzed. This provides a favorable basis for the spatial distribution and prediction of regional salinization.

At the same time, the two-dimensional feature space model can clearly express the distribution pattern of factors affecting the soil salinization process in the study area, and the two-dimensional feature space scatter diagram between various soil salinization parameters has been investigated by many scientists. Although the results of the CRSI-COSRI two-dimensional feature space soil salinity inversion model were better for the specific arid semi-arid oasis environment in our study area, the generalizability of the model to other regions requires further study and evaluation. The two-dimensional feature space model can be constructed by selecting suitable spectral feature parameters according to the different surface morphology, climatic conditions, hydrological factors, and human intervention measures, which can extract the soil salinization information more scientifically, accurately and efficiently. In light of the future development path of soil salinity quantification, the two-dimensional feature space model may no longer be able to satisfy the simultaneous

participation of multiple factors related to soil salinity in the analysis and display. With the gradual development of remote sensing monitoring methods, the emergence of advanced technologies can help promote the development of soil salinity characteristic space research to the three-dimensional or even multi-dimensional characteristic space. Efficient use and timely innovation of remote sensing monitoring models for soil salinization are of great practical significance to comprehensively grasp the degree of salinization in the region, maintain the soil fertility quality and productivity level, promote sustainable agricultural development, and enhance the comprehensive management and utilization of regional soil salinization.

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Article

Membrane Processes Treatment and Possibility of Agriculture Reuse of Textile Effluents: Study Case in Tunisia

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Abstract: Several processes have been developed to treat the textile effluents. Membrane technologies are among the most reliable processes for purifying these effluents. However, due to high costs, only reduced quantities are being treated. The recycling practices of treated textile effluents (TTE) in agriculture have not been appropriately explored. This work evaluates the quality of waters treated by membrane processes and puts forward a scenario for optimizing TTEs in agriculture. Four types of TTE have been tested to irrigate *Sesbania bispinosa* plants: water from biological treatment (BT) and water from three membrane processes after BT (Ultrafiltration (UF), Nanofiltration (NF), and Reverse Osmosis (RO)). The results indicate that the NF and RO membranes have a high affinity to remove monovalent and multivalent ions. Indeed, the removal of SO_4^{2-} , Na^+ , and Cl^- by NF was 83, 61, and 55%, respectively. Thus, the RO reduces approximately 96% of these elements. Irrigation with NF and RO waters has no negative effect on the soil and *Sesbania* plants, contrary to BT and UF waters. It appears that the reuse of TTE resulting from BT is not a good alternative; however, by carrying out additional treatments by NF and RO, their reuses have been made possible. The achieved results are a proposal to simultaneously solve three major problems affecting most of the world's population: (1) environmental pollution by reducing the discharge of untreated textile effluents and improving the quality of this discharged water; (2) the pressure on water resources in the agricultural sector by replacing a conventional resource with a non-conventional resource (TTE); and (3) the lack of fodder, especially in the summer, by opting for crops that adapt to the quality of these TTE.

Keywords: treated textile effluents; membrane treatments; water reuse in irrigation; non-conventional waters; water characterization; soil; *Sesbania bispinosa*

1. Introduction

The textile industry generates large volumes of contaminated wastewater [1,2] that constitute a source of pollution of surface water and groundwater [3,4]. Consequently, environmental legislation requires that textile factories should treat these effluents before their discharge. Generally, industrial on-site water treatment plans carry out a primary or physico-chemical pre-treatment [5] followed by biological treatments that reduce dissolved pollutants (mainly organic matter). However, these traditional decontamination systems do not seem sufficient, especially for agricultural reuse.

Several enhanced purification processes have been developed in the industrial sector to further eliminate pollutants such as chemical oxidation, electrolysis, biodegradation, adsorption, chemical coagulation, and membrane processes [6–10]. Among them, membrane

processes have shown interesting results [11–13]. In terms of pore sizes, there are four types of membranes; microfiltration (MF) (0.05–1.0 μm), ultrafiltration (UF) (0.005–0.5 μm), nanofiltration (NF) (0.0005–0.01 μm), and reverse osmosis (RO) (0.0001–0.001 μm) [14].

MF membranes can be used for versatile fields needing separation of bacteria, aerosols, viruses, and innumerable macromolecules from fluids [15]. They are used in wastewater treatment; as a pretreatment filter before UF, NF, and RO membrane-based processes; for separation of macromolecules in pharmaceutical industry; and also in textile effluents treatment [15,16]. Indeed, literature indicates that ceramic MF membranes showed a considerable removal efficiency to BOD (39%), sulfates (34%), chlorides (33%), TDS (31%), color (26%), COD (25%), and turbidity (21%) from textile effluents treatment study [16]. The disadvantage of this process is that the expected degree of purification in MF is lower than in other membrane processes [15].

UF process is typically used to remove viruses, emulsified oils, metal hydroxides, colloids, proteins, and other high molecular weight materials from water and other solutions [17]. It operates at low transmembrane pressure to remove dissolved substances, and its membranes are capable of handling high flux [18]. Furthermore, Barredo-Damas et al. [19] deduced that ceramic UF membranes can be used as an alternative pretreatment to adapt textile effluent for a later stage of NF and RO.

The combination of UF and RO is known as NF, which combines a high removal rate with low energy consumption [20]. It is a very selective process for separating salts, sugars, or dye molecules [21]. Thus, Aouni et al. [22] deduced that the NF process is effective in reducing conductivity, COD, and color in industrial effluents. Indeed, a study that deals with the performance of a certain NF membrane (NF-270-2540 FILMTEC NF) showed that this process effectively reduces dyes, COD, and organic carbon [23].

RO is a method that removes various species and is widely used in the desalination process [20]. Due to the fact that RO membranes are prone to scaling and fouling, RO is rarely a stand-alone treatment process [24]. RO processes can simultaneously remove hardness, color, many types of bacteria and viruses, and organic contaminants such as agricultural chemicals [25].

In addition to the harmful effects of untreated textile effluents on the environment, there is also the problem of water scarcity [26], the high demand for water in the agricultural sector [27], and the lack of fodder in some countries. This implies that the reuse of these treated waters in agriculture, by adopting plants to the quality of these waters, can be a form of recycling water and nutrients. Their environmental impacts can be reduced [28]. Another problem that arises in the agricultural sector is the use of chemical fertilizers, especially nitrogenous fertilizers that lead to the eutrophication of surface and groundwaters and the degradation of the quality of the environment [29–31]. This has drawn attention towards the use of nitrogen-fixing plants in order to increase soil fertility. This is the case of *Sesbania bispinosa* (Fabaceae family).

Many studies have focused on wastewater depollution processes and their characterization for reuse in agriculture [32]. In a circular economy approach, some authors have assessed the possibility of reusing treated textile effluents as an influent in textile dyeing processes. Some researchers have studied the problems of soil salinization, whereas others have been interested in the behavior of metallic trace elements (MTEs) present in these waters with respect to irrigated soils as well as organic matter [33,34] and enzymatic activity as a bioindicator of the quality of irrigated soils [35]. However, few studies have been carried out on the agricultural valorization of textile effluents subjected to different membrane treatments. It is within this context that our work exists, which aimed to propose effective systems for depolluting textile effluents and to evaluate the possibility of reusing them in agriculture. This was carried out through (i) the characterization of wastewater from a textile dyeing plant subjected to biological treatment (BT) and complementary treatments by UF, NF, and RO; (ii) the determination of the physico-chemical modifications of the soil induced by these treated effluents and; (iii) the evaluation of their effects on the “*Sesbania bispinosa*” plant.

2. Materials and Methods

2.1. Soil Sampling Site

The soil for the microcosm study was taken from the layer 0–30 cm of agricultural land of Ksar Hellal region (Monastir Governorate, Tunisia). This region is under semi-arid climate with an average annual rainfall of 300 mm. The samples were taken at random from three points. The soil distribution size according to the Robinson method shows a sandy loamy texture with 63.2% of sand, 17.3% of clay, and 16.1% of silt.

2.2. Textile Effluent Treatment

The textile effluents were available from the sewage treatment plant of the Sitex Textile Company, located close to the soil-sampling site in Ksar Hellal. This company specialized in the production of Denim fabrics and uses the indigo blue dye ($C_{16}H_{10}N_2O_2$) in the production processes. It is a dye insoluble in water and poorly soluble in solvents [8]. The sewage treatment plant performs only the biological treatment (BT) of textile effluents by activated sludge. Membrane treatment units have been set up on a pilot in the industry's wastewater treatment plant to ensure the additional treatment of BT water by Ultrafiltration (UF), Nanofiltration (NF), and Reverse Osmosis (RO). The membrane characteristics are shown in Table 1 below:

Table 1. Membrane characteristics.

Parameters	UF Membrane [8]	NF Membrane NF 270 [36,37]	RO Membrane BW30 [36,37]
Material	TiO ₂	Polyamide	Polyamide
Membrane area (m ²)	0.155	2.5	2.5
Molecular weight cut-off (MWCO)	150 kDa	200–400 Da	>100 Da
Manufacturer	Dow Filmtec, Santa Ana, CA, USA	Dow Filmtec, Santa Ana, CA, USA	Dow Filmtec, Santa Ana, CA, USA
Salt rejection (%)	-	50	99.4
NaCl rejection (%)	-	50	-
MgSO ₄ rejection (%)	-	98	-
Pure water permeability (L/m ² h. bar)	220 ± 15	7.6 ± 0.2	3.2 ± 0.2

2.3. Water Irrigation

Four qualities of TTE were used for irrigation: (i) biological treatment water (BT), (ii) Ultrafiltration (UF), (iii) Nanofiltration (NF), and (iv) Reverse Osmosis (RO). In addition, well water (W) pumped from a 45-m-deep aquifer was used as a control.

2.4. Experimental Setup

The experiment was carried out in 2019 at the National Institute for Research in Rural Engineering, Water, and Forests (INRGREF). The chosen device was in total randomization. The plant material used was *Sesbania bispinosa*. *Sesbania* seeds were planted in pots filled with peat and watered with drinking water. Seed emergence took place on 27 March 2019. At the five to six leaves stage, the seedlings were transferred to plastic pots (30 cm: diameter × 32 cm: height) loaded with 15 kg of soil at the rate of two seedlings per pot. The pots were aligned in five rows with five repetitions per water quality for a total of 25 pots. A cycle of 25 irrigations, for each quality of water, was carried out with a dose set at 28.6 mm for each pot. Since the plants' transfer to the pots (13 May 2019), the diameter and length of the stems were regularly monitored. At the flowering stage (2 September 2019), the plants were collected. The harvest consisted of manually extracting each plant from the soil, with the entire root system. The roots were washed with distilled water. Biomasses were determined by weighing fresh and dry matter from leaves, stems, and roots. The dry matter was determined after placing the fresh matter in the oven at 60 °C until the stabilization of the dry weight.

After grinding the dry matter of the plants, the different organs were analyzed for their contents in potassium (K⁺), sodium (Na⁺), and metallic trace elements (Cr, Co, Cu, and Ni). K⁺ and Na⁺ were determined by flame spectrophotometry (Jenway, PFP7, France) and MTEs by atomic absorption spectrophotometry (Perkin Elmer, AAnalyst 400 AA Spectrometer; WinLab32 Software).

2.5. Soil Sampling and Analysis

The soil characteristics were determined before and at the end of the irrigation cycle. At the end of the experiment, soil samples were taken at several heights from each pot. The samples were taken manually using plastic gloves, air-dried, and passed through a 2 mm sieve. Soil samples were homogenized before.

pH was determined using a digital pH meter (XS instruments, pH 70+ DHS, Italy) from a soil-water mixture 1/2.5. Electrical conductivity and mineral elements were determined from the soil solution extracted from the saturated soil paste (EC_e) according to the US Salinity Laboratory Staff [38] by conductimetry (AZ instruments-8361-Cond. & TDS Pen, Taiwan). K^+ and Na^+ soil contents were determined by flame spectrophotometry (Jenway, PFP7). The Ca^{2+} , Mg^{2+} , Cl^- , and HCO_3^- ions were assayed by titrimetry; SO_4^{2-} ions were assayed by nephelometry using a UV-Visible spectrophotometer (Jenway 6305, France). MTE contents were determined by atomic absorption spectrophotometry [39]. The choice of analyzed MTEs was based on the Tunisian standard NT 106.02 for textile industry's treated wastewater discharges.

2.6. Water Analysis

Treated textile effluents and well water were sampled in polyethylene bottles at three different dates and analyzed for the pH, electrical conductivity (EC_w), mineral composition (K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} and HCO_3^-), and MTEs contents.

2.7. Statistical Analysis

At least three replicates were performed for each data, and the means were compared by Tukey's test at the confidence level of 0.05 using SPSS software (IBM SPSS statistics, v20). The different letters presented in the figures and tables indicate significant differences at $p < 0.05$. The bars indicate the standard deviation (SD).

3. Results and Discussion

3.1. Physico-Chemical Quality of Treated Textile Effluent (TTE)

3.1.1. Biological Treatment

The effluents leaving the textile dyeing plant after BT do not comply with Tunisian Standards NT 106.02 for discharge water and NT 106.03 for reuse in agriculture. This is due to exceeding values of pH (8.6), EC (8.1 dS/m), and Cl^- (28.5 me/L) and SO_4^{2-} (27.1 me/L) ions contents (Table 2) related to the use of sodium dithionite ($Na_2S_2O_4$). This reducing agent is used to make indigo blue soluble in water, whose pH becomes alkaline, with pHs varying between 8.0 and 9.5. Similarly, Chockalingam et al. [40] report that an effluent sample collected from the city of Salem in Tamilnadu, India, contains a blue dye with a pH of 8.6. Vigneshpriya and Shanthi [41] also mentioned a pH of 9.5 for the effluent collected from Karur, a textile town in Tamilnadu.

3.1.2. Membrane Treatments

By carrying out additional treatments to BT effluents, we observed an improvement in their qualities. In fact, the pH remained basic after UF and NF (7.9–8.4), and became neutral with RO (7.1) (Table 2). These pH values are consistent with the two Tunisian standards NT 106.02 (6.5–9.0) and NT 106.03 (6.5–8.5).

Textile wastewater has high conductivity due to the use of various salts during the dyeing process [42–45]. This is the case in our study, where we found that the BT effluents exhibit a high electrical conductivity (8.1 dS/m) that exceeds the Tunisian Standards NT 106.03 and NT 106.02. Additional treatments with UF, NF, and RO have contributed to a significant reduction ($p < 0.05$) in the salinity of water to 7.01, 2.62, and 0.20 dS/m, respectively. A slight reduction was observed following UF treatment. Özgün et al. [46] have shown that this type of treatment can be considered as a pre-treatment method before proceeding to NF. The NF treatment made it possible to reduce the amount of salts contained in the BT water to three times less, whereas with the RO we managed to

desalinate the textile effluents. Therefore, it can be inferred that nanofiltration (NF) plays an important role in reducing the salinity levels of textile effluents, as demonstrated by Aouni et al. [22]. It is important to note that the NF treatment process is used in pre-treatment unit operations in seawater desalination processes [47,48]. Regarding RO, this treatment process effectively eliminates salinity in biologically treated textile effluents. Thus, the higher salinity reduction efficiency for the RO membrane is due to its relatively denser selective surface layer compared to the NF membrane [49]. The mineral ion contents strongly increase after BT compared to the well water (Table 2), but significantly decrease after adding NF and RO, with values complying with the Tunisian Standards. The lowest eliminations of chemical elements were observed with UF treatment. The removal of SO_4^{2-} , Na^+ , and Cl^- were, respectively, 13, 10, and 12%. The NF shows an efficiency to reduce these elements; indeed, SO_4^{2-} was reduced by 83% and Na^+ and Cl^- were reduced, respectively, by 61% and 55%. Several researchers note that NF is characterized by a high rejection coefficient of multivalent ions (up to 90% for sulfate ions) compared to monovalent ions such as Na^+ and Cl^- (less than 60%) [50,51].

Table 2. Characterization of the well water (W) and the TTE. The average values are compared to the Tunisian standards. W: Well water; BT: Biological treatment; UF: Ultrafiltration; NF: Nanofiltration; RO: Reverse Osmosis; and ECw: electrical conductivity of irrigation water. ND: Not determined.

	Complementary Treatments					Tunisian Standards	
	W	BT	UF	NF	RO	NT 106.02	106.03
Cations							
pH	7.2 ± 0.14 a *	8.6 ± 0.17 a	7.9 ± 1.80 a	8.4 ± 0.46 a	7.1 ± 1.04 a	6.5–9	6.5–8.5
Ecw (dS/m)	2.20 ± 0.12 b	8.13 ± 0.63 d	7.01 ± 0.37 c	2.62 ± 0.20 b	0.20 ± 0.03 a	5	7
Ca^{2+} (me/L)	8.90 ± 1.29 b	11.80 ± 1.82 b	8.60 ± 4.26 b	2.10 ± 0.22 a	ND		
Mg^{2+} (me/L)	6.20 ± 0.27 b	15.30 ± 0.97 d	12.00 ± 1.70 c	4.40 ± 1.11 b	ND		
K^+ (me/L)	0.13 ± 0.76 a	3.33 ± 0.53 b	3.07 ± 0.13 b	0.30 ± 0.34 a	0.12 ± 0.06 a		
Na^+ (me/L)	10.48 ± 2.25 b	51.78 ± 4.88 d	46.50 ± 3.68 d	20.31 ± 0.41 c	2.00 ± 0.44 a		
Anions							
Cl^- (me/L)	11.56 ± 0.63 b	28.53 ± 4.88 c	25.22 ± 4.74 c	12.74 ± 1.70 b	0.81 ± 0.10 a	19.75 (700 mg)	56.41 (2000 mg)
HCO_3^- (me/L)	4.50 ± 2.20 b	24.90 ± 1.60 e	21.10 ± 1.52 d	8.80 ± 1.64 c	0.50 ± 0.50 a		
SO_4^{2-} (me/L)	8.41 ± 1.99 b	27.14 ± 3.37 c	23.57 ± 2.85 c	4.72 ± 1.31 ab	1.12 ± 0.59 a	10.41 (500 mg)	
SAR	2.82 ± 0.75 a	7.68 ± 0.58 b	9.56 ± 2.68 bc	12.82 ± 2.56 c	ND		
Cd (mg/L)	ND	0.08 ± 0.01 b	0.08 ± 0.01 b	0.01 ± 0.01 a	ND		0.01
Co (mg/L)	ND	0.62 ± 0.12 b	0.50 ± 0.12 b	0.06 ± 0.07 a	0.01 ± 0.01 a		0.1
Cr (mg/L)	0.01 ± 0.00 a	0.21 ± 0.04 b	0.24 ± 0.05 b	0.04 ± 0.01 a	0.02 ± 0.01 a	0.5	0.1
Ni (mg/L)	ND	0.74 ± 0.02 c	0.63 ± 0.04 b	0.06 ± 0.05 a	0.02 ± 0.01 a	1	0.2

* The means of five observations (±SD) followed by the different letters in each line are significantly different according to Tukey's test at the level of $p < 0.05$.

Knowing that RO is a water desalination technique, we assumed that the BT water subjected to RO complies with the standards regarding major ions. Indeed, Na^+ and Cl^- were eliminated by 96% and 97%. Thus, 96% of the sulfates in the biological treatment waters were rejected.

These results indicate that the NF and RO membrane methods can be considered as promising technologies that can be used for the treatment of textile effluents. The reason for the greater use of membrane filtration systems in the textile sector is mainly due to, for example, the membrane's ability to remove pathogenic microorganisms and salts as well as to control the disinfection by-products (DBP) precursor [6,22]. Other treatment processes have proven to be more efficient for the removal of dyes such as ozonation [52] and adsorption [53,54]. According to Mohammad Ali et al. [53], the use of $\text{Fe}_3\text{O}_4\text{-SiO}_2$

nanoparticles as an adsorbent material leads to the elimination of 99% of the methyl blue dye from aqueous solutions. Although both processes have their own advantages, there are also disadvantages associated with their uses. Membrane fouling is the main limitation of wastewater filtration which limits the performance of membranes [24,55], whereas the application of adsorption methods can be limited by the inconvenience of regeneration and the high price when using activated carbon [56]. Consequently, several studies have proposed to obtain a hybrid treatment process combining membrane techniques and adsorption with cost/performance advantages [57,58].

The sodium risk of irrigation water is generally expressed by the sodium adsorption ratio (SAR). This index quantifies the proportion of Na^+ ions in relation to Ca^{2+} and Mg^{2+} ions in the water. SAR values for irrigation water ranged from 2.8 for well water to 12.8 for nanofiltered water. The SAR for RO water was not determined because Ca^{2+} and Mg^{2+} ions were not detected. Several researchers mention that high SAR values indicate a substitution of Ca^{2+} or Mg^{2+} for Na^+ in the soil through the cation exchange process, which causes a reduction in soil permeability and restricts the circulation of air and water through the soil system, thus leading to the development of alkaline soil [59–61]. This is not the case in our study, where we deduce according to the classification of Richards (1954) based on the values of SAR [59] that all water qualities belong to the category “excellent”, except for NF water, which belongs to the “good” category. Accordingly, this explains how TTE can be used in irrigation without risk to the soil.

MTEs' contents exceed those set by the Tunisian Standards except for NF and RO.

Therefore, we deduce that the biological pre-treatment as carried out in our case study partially improves the water quality, and the water resulting from this treatment remains highly polluting. A complementary approach is essential for healthy use. Membrane treatments of textile effluents by NF and RO allow, to different degrees, improvements in quality, suggesting either the recycling of water in the factory's production line, or agricultural recovery. Nevertheless, these techniques are energy-intensive, resulting in high costs, and produce highly concentrated water discharges. Therefore, other options are to be considered in synergy with these techniques or separately. Agricultural recovery seems to be the unavoidable option but comes up against the high salinity of water from biological treatment, which exceeds the salinity tolerance of most plants and affects the properties of soils irrigated by these waters. Softening by coupling with well water is a simple and inexpensive solution.

3.2. Impact of Irrigation by TTE on Soil Quality

The soil before irrigation (IS) exhibits a fairly neutral pH (7.3). After irrigation by BT, UF, and NF waters, soil pH significantly increases ($p < 0.05$), however, it remains near neutral with RO waters (Table 3). Such alkaline waters may reinforce the soil sodicity condition and have adverse effects on microflora and crop growth [62,63].

Soils irrigated by BT waters showed a dominance in Na^+ and Cl^- ions compared to control soil where Ca^{2+} and Cl^- slightly dominate, whereas no significant differences were noticed with UF and NF waters; Cl^- concentration significantly decreased ($p < 0.05$) after RO water. However, Na^+ is one of the most undesirable elements in soil. This element decreases the permeability of the soil, which reduces the water available for the plants and can affect their germination [64]. Awasthi et al. [65] showed that calcium and magnesium are low in sodium soil. It is the opposite in our soils except when using RO water that is demineralized.

The highest ECe in soil irrigated by BT are in correlation with the high concentrations of Na^+ and Cl^- ions in these soils (ECe = 11.5 dS/m). Lower ECe values were recorded for the less salinized soils irrigated by UF, NF, and RO (8.3, 6.6, and 1.5, respectively).

The results of MTEs analyses (Cd, Co, Cr, and Ni) in the soil treated by the different qualities of water are presented in Table 3. The concentrations do not vary very significantly depending on the irrigation water. Indeed, despite the concentrations that exceed the Tunisian standard NT 106.3 in BT and UF waters, the MTEs contents in the soil are well

below the range of values set by Kabata-Pendias and Pendias [64] and the maximum tolerable fixed by the WHO [66].

Compared to the soil in its initial state (IS: before irrigation), irrigation with RO water causes a reduction in MTE levels. This suggests that these elements are leached by drainage water or absorbed by plants. This leaching depends on several factors such as soil pH and texture [67]. Thus, Kabata-Pendias and Pendias [64] mentioned that the pH and the total concentrations of some MTEs such as Cd and Ni are very close. Indeed, the solubility of metals is high in acid soils [64,68]. Under more alkaline conditions, as is the case in our study ($7.3 < \text{pH} < 8.6$), the solubility of some MTEs is not correctly predicted by pH [69] because under these conditions, pH is most often coupled with other physico-chemical characteristics such as organic carbon content and soil texture [69,70].

On the other hand, an increase in MTE contents in the soil was observed in the case of irrigation by BT waters with a lesser extent in the case of UF and NF waters. This reflects a phenomenon of accumulation of MTEs in the soil while remaining within the standards. The accumulation effect of MTEs should be studied in the long term to assess the impact of these waters on the quality of the soil since several studies have deduced that the long-term use of wastewater could affect the quality of the soil through MTEs pollution and increased salinity [71,72].

Thus, it has been shown that the content of MTEs, essentially Cr, in the surface layer of the soil is known to increase due to contamination from various sources, the main ones being industrial wastes such as Cr pigments and tannery waste and leather manufacturing waste [64].

Table 3. Effects of irrigation by TTE on the soil. IS: Initial status; W: Well water; BT: Biological treatment; UF: Ultrafiltration; NF: Nanofiltration; and RO: Reverse Osmosis.

	Complementary Treatments						Ranges and Maximum Tolerable of ETM in the Soil (mg/kg)	
	IS	W	BT	UF	NF	RO	[64]	[66]
pH	7.4 ± 0.13 a *	7.5 ± 0.29 a	8.7 ± 0.19 c	8.2 ± 0.11 b	8.3 ± 0.08 bc	7.3 ± 0.07 a		
E _C e (dS/m)	1.21 ± 0.07 a	5.24 ± 0.03 b	10.90 ± 0.71 e	8.31 ± 0.30 d	6.66 ± 0.26 c	1.53 ± 0.20 a		
Cations								
Ca ²⁺ (me/L)	5.60 ± 0.65 a	13.00 ± 2.12 a	39.63 ± 4.42 b	30.10 ± 9.38 b	15.50 ± 6.01 a	5.50 ± 1.00 a		
Mg ²⁺ (me/L)	3.7 ± 0.27 a	9.50 ± 1.68 b	14.88 ± 2.87 b	12.00 ± 4.47 b	9.50 ± 2.52 b	2.00 ± 0.50 a		
K ⁺ (me/L)	0.34 ± 0.01 ab	0.49 ± 0.11 bc	0.59 ± 0.08 c	0.50 ± 0.11 bc	0.50 ± 0.13 bc	0.20 ± 0.02 a		
Na ⁺ (me/L)	4.44 ± 0.27 a	30.24 ± 1.97 b	52.02 ± 0.95 d	39.78 ± 6.67 bc	41.71 ± 9.21 cd	7.95 ± 0.53 a		
Anions								
Cl [−] (me/L)	6.77 ± 1.18 a	33.13 ± 1.43 b	54.68 ± 15.43 c	40.63 ± 3.62 b	33.54 ± 7.21 b	6.77 ± 1.20 a		
HCO ₃ [−] (me/L)	2.50 ± 0.00 a	4.37 ± 0.48 ab	11.50 ± 1.78 c	7.60 ± 2.86 b	3.80 ± 0.27 a	3.83 ± 1.26 a		
SO ₄ ^{2−} (me/L)	2.25 ± 0.67 a	15.66 ± 1.36 a	43.37 ± 13.47 b	35.25 ± 5.28 b	30.65 ± 6.30 b	4.36 ± 1.31 a		
MTE								
Cd (mg/kg)	0.66 ± 0.38 abc	0.76 ± 0.09 bc	0.96 ± 0.02 c	0.86 ± 0.04 bc	0.55 ± 0.09 ab	0.37 ± 0.04 a	0.08–1.61	4
Co (mg/kg)	0.89 ± 0.50 a	1.64 ± 0.42 b	1.77 ± 0.31 b	1.71 ± 0.15 b	1.36 ± 0.17 ab	1.02 ± 0.15 a	3–58	-
Cr (mg/kg)	4.12 ± 0.61 bc	3.47 ± 0.28 ab	5.21 ± 0.26 d	4.26 ± 0.31 c	4.21 ± 0.26 c	3.16 ± 0.28 a	4–1100	-
Ni (mg/kg)	2.83 ± 0.83 ab	2.40 ± 0.76 ab	3.50 ± 0.22 c	2.79 ± 0.26 ab	2.56 ± 0.19 ab	1.96 ± 0.97 a	3–110	107

* The means of five observations ($\pm$ standard deviation) followed by the different letters in each line are significantly different according to Tukey's test at the level of $p < 0.05$.

3.3. Impact of TTE on *Sesbania* Plants

3.3.1. Effects on Biomass

One of the effects of irrigation on the plant is a significant decrease ($p < 0.05$) in the yield of dry and fresh matter of *Sesbania* plants after irrigation with BT water (Figure 1), but an improvement with NF and RO waters. This is related to the difference in concentration of salts in the soil [73]. Indeed, up to 6.66 dS/m (4.3 g/L) of salt in the

soil solution (NF), the growth of the aerial parts of *Sesbania* is not affected, which is also observed in wheat varieties [74].

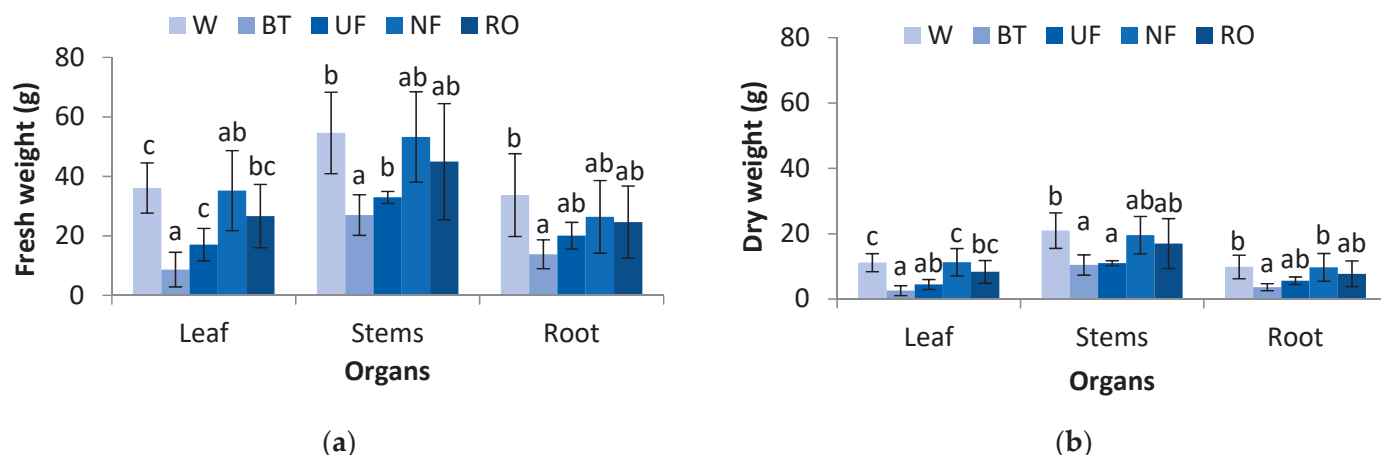


Figure 1. Variation of fresh and dry weight of *Sesbania bispinosa* plants irrigated by TTE. (a) Variation of fresh weight of *Sesbania bispinosa* plants; and (b) variation of dry weight of *Sesbania bispinosa* plants. W: well water; BT: Biological Treatment; UF: Ultrafiltration; NF: Nanofiltration; and RO: Reverse Osmosis. The means of three observations followed by the different letters in each organ are significantly different according to Tukey's test at the level of $p < 0.05$.

3.3.2. Effect on the Aerial Parts

The growth in length and diameter of the plants' aerial parts is not influenced when irrigating with NF and RO waters (Figure 2). The variation of the stems' length and diameter appears to be gradual with time with an average length of the aerial part until the flowering stage of 106 cm, corresponding to normal growth. On the other hand, irrigation with BT and UF waters reduced plant growth.

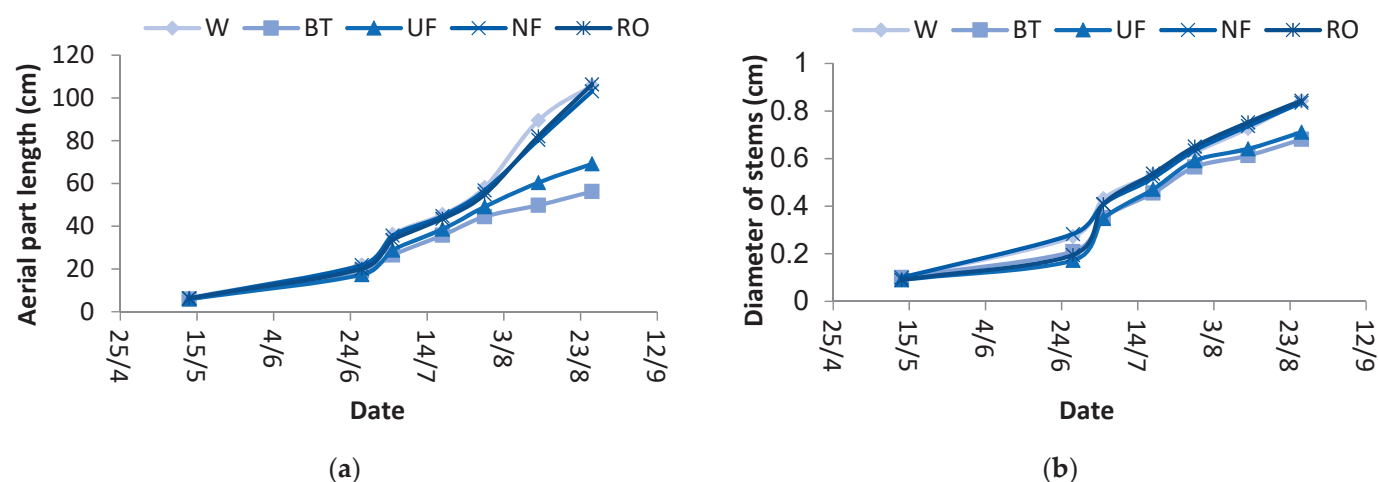


Figure 2. Growth evolution of the aerial parts of *Sesbania bispinosa*. (a) Aerial part length; and (b) diameter of stems. W: Well water; BT: Biological treatment; UF: Ultrafiltration; NF: Nanofiltration; and RO: Reverse Osmosis.

The impact of BT and RO water irrigation can be clearly distinguished by observing the plants at the end of the irrigation cycle (Figure 3). This impact is possibly due to soil salinity. Indeed, beyond 6.66 dS/m, which corresponds to the EC of the soil irrigated by NF waters, the growth of *Sesbania* plants decreased significantly. This effect was also found by Cherifi et al. [74].

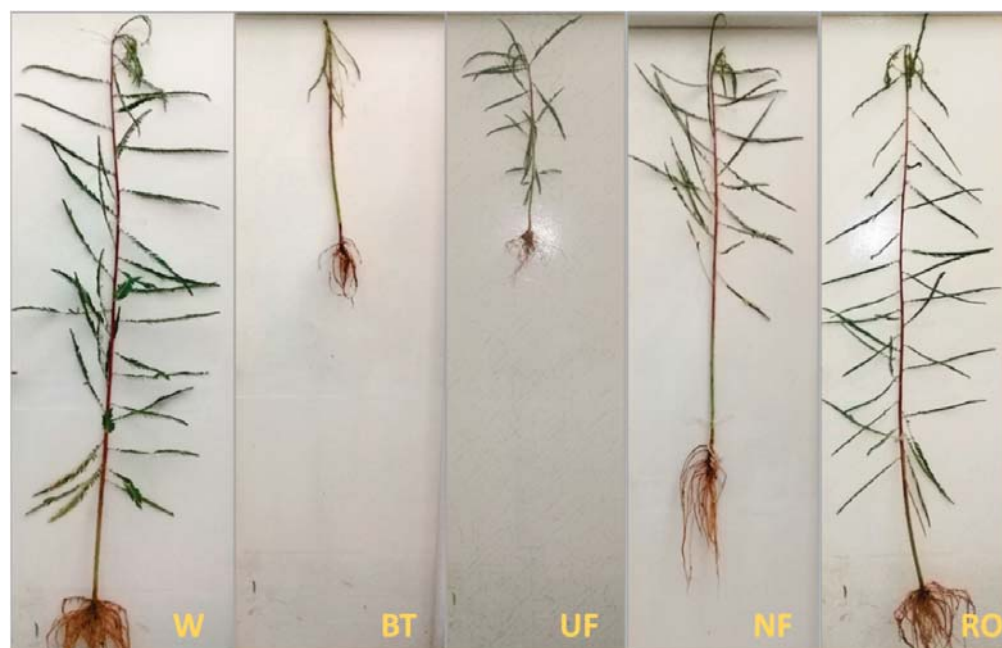


Figure 3. Effect of TTE irrigation on the growth of aerial parts of *Sesbania bispinosa*. W: Well water; BT: Biological treatment; UF: Ultrafiltration; NF: Nanofiltration; and RO: Reverse Osmosis.

3.3.3. Effect on the Root

The high frequency of nodule formation in the roots of *Sesbania* plants irrigated with well water (Figure 4a) is reduced with UF and NF waters (Figure 4c,d). Nodulation frequency was very low when BT water was used (Figure 4b). Thus, nodulation is sensitive to the different qualities of TTE, especially the high salinity of waters and soil. This effect on *S. bispinosa* is like that on alfalfa [75], *Sesbania sesban* [76], and durum wheat (*Triticum durum* Desf. “Massa”) [77].

For plants irrigated with RO waters (Figure 4e), the granular sensation in the roots decreased slightly compared to control plants. In this case, the salinity problem no longer arises, and another factor is involved. This decrease can be attributed to the low concentration of sulfates in the soil and therefore low assimilation of this element by *sesbania* plants. Indeed, the assimilation of sulfates in plants is an essential pathway since they constitute a source of reduced sulfur for various cellular processes [78]. They play a key role in symbiotic nitrogen fixation (SNF) [79,80]. Sulfate deficiency has been shown to limit the development of root nodules due to low synthesis of nitrogenase, a bacterial nitrogen-reducing enzyme produced by nitrogen-fixing bacteroids [81–83]. This effect was observed by Varin et al. [79], who deduced that S deficiency in *Trifolium repens* reduced nodule development due to low nitrogenase production. Furthermore, Schneider et al. [80] suggest that sulfate deficiency has a direct impact on SNF and limits protein biosynthesis without adverse effects on the plant.

Thus, Allen and Allen [84] showed that the absence of nodules does not necessarily indicate the inability of the plant to enter an effective symbiosis. Several factors can negatively affect rhizobium populations and nodule formation, such as unfavorable soil type and soil pH, insufficient solar radiation, and extreme temperature conditions [84]. In the case of soybeans, Tu [85] showed that their inability to nodulate at high salt concentrations is due to a decrease in rhizobial colonization. Overall, root branching (root hairs) of *Sesbania* decreased with increased salinity in the soil solution compared to plants irrigated by well water.



Figure 4. Effect of TTE on the roots of *Sesbania bispinosa*. (a) Well water (W); (b) Biological Treatment (BT); (c) Ultrafiltration (UF); (d) Nanofiltration (NF); and (e): Reverse Osmosis (RO).

3.3.4. Effect on the Mineral Composition of *Sesbania*

The accumulation of salts in the soil is followed by the accumulation of Na^+ and Cl^- ions in *Sesbania* plants. Indeed, up to 6.66 dS/m (4.3 g/L), which corresponds to the ECe of soils irrigated by NF waters, *S. bispinosa* accumulated Na^+ in the aerial parts with low

concentrations in the roots (Figure 5a). Beyond 8 dS/m of salt in the soil solution (BT and UF), *Sesbania* is under saline stress conditions and Na^+ concentrations increase significantly in roots and stems. The aerial parts exhibited the greatest quantity of Na^+ , which may be a strategy of *Sesbania* to cope with salt stress [77]. A similar behavior was observed by Hajlaoui et al. [86] in two forage maize (*Zea mays* L.). The sequestration of Na^+ in the vacuole is an important and cost-effective strategy for an osmotic adjustment that reduces cytosolic Na^+ concentration [87,88]. It protects the cytoplasm, allows the plant to reduce its cellular water potential and, as such, prevents the loss of water [89]. 22

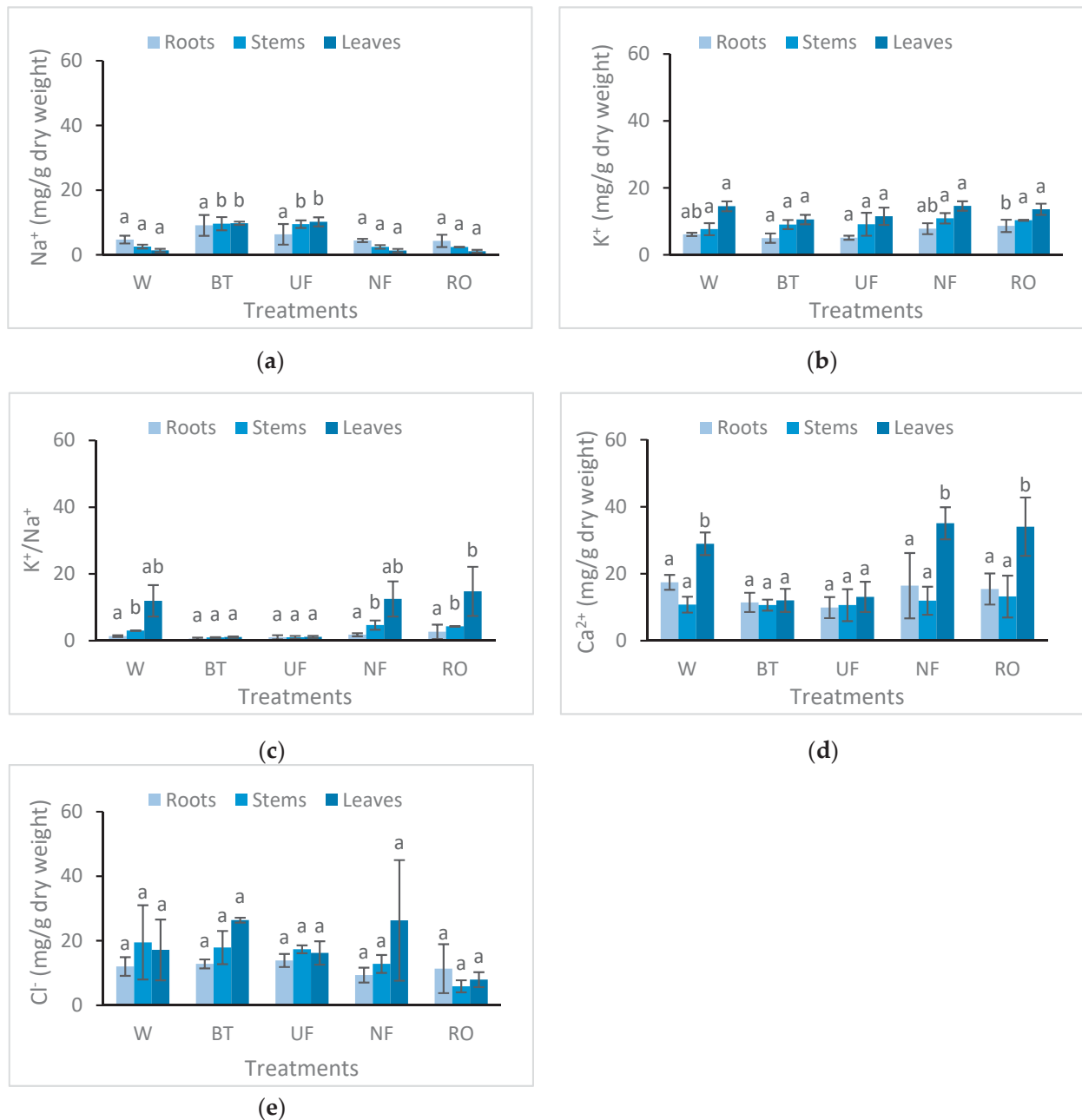


Figure 5. Effects of TTE on the mineral nutrition of *Sesbania* plants. (a) Na^+ concentration; (b) K^+ concentration; (c); K^+/Na^+ ratio; (d) Ca^{2+} concentration; and (e) Cl^- concentration. W: Well water; BT: Biological treatment; UF: Ultrafiltration; NF: Nanofiltration; and RO: Reverse Osmosis. The means of three observations ($\pm$ standard deviation) followed by the different letters in each organ are significantly different according to Tukey's test at the level of $p < 0.05$.

In this present study, K^+ was mainly in the aerial part of *Sesbania* (Figure 5b) with unchanged concentrations compared to the reference plants but regardless of the concentrations in Na^+ . The same effect was reported in the literature, where the absorption of K^+ decreases and can even stop with high doses of Na^+ [86,90,91]. Indeed, K^+ and Na^+ ions are always in competition to penetrate plant cells due to their physico-chemical similarity [92,93]. Thus, the K^+/Na^+ selectivity ratio is an index that describes the threshold of toxicity by Na^+ , a high K^+/Na^+ ratio indicating less Na^+ toxicity [94,95].

Therefore, we established the K^+/Na^+ selectivity ratio. Our results show that the K^+/Na^+ ratio (Figure 5c) decreases with the increase in the salinity of the treated effluents and that of the soil. This ratio is lower in the roots than in the leaves. This is consistent with a previous study on tomatoes [96]. Cramer et al. [97] demonstrated that at high salt concentrations, Na^+ displaces Ca^{2+} from the plasmalemma of root cells, leading to an increase in membrane permeability, causing an efflux of K^+ and modifying the K^+/Na^+ selectivity ratio.

The highest levels of Ca^{2+} ions were recorded in the leaves of the plants, regardless of the irrigation water used (Figure 5d). A significant decrease in Ca^{2+} ($p < 0.05$) was observed in plants irrigated with BT and UF waters, whereas no negative effect was observed with NF and RO waters.

Cl^- ions content (Figure 5e) remained like those of the control plant, whereas it was reduced in the case of irrigation with RO waters and slightly increased in the leaves in the case of BT irrigation waters.

MTEs contents were under the detection limit and thus were not recorded neither in the aerial parts of *Sesbania*, nor in the roots, indicating that there was no translocation from soil to plant regardless of the irrigation water. This could be due to the sandy-loamy soil texture that reduces the available fraction of MTEs [98]. In relation to the MTE contents recorded in the soil, these results indicate that the MTEs are not assimilated by the plant, but rather leached by the drainage water.

4. Conclusions

Our work has made it possible to define the risks of textile effluents, the limit of the biological pre-treatment in progress in the factory, the constraints of the advanced treatment of membrane techniques, and to study the possibility of agricultural valorization of textile effluents treated through the choice of a fodder plant that can adapt to the quality of these waters. The results of this work studying membrane treatment processes for the decontamination of textile effluents and safe reuse in agricultural sector suggest that biological treatment alone cannot be considered neither to decontaminate textile effluents nor for reuse in irrigation, which requires additional treatments to improve their qualities. Our results find that additional treatments of these waters by Nanofiltration and Reverse Osmosis improve the physico-chemical quality of textile effluents and make them suitable for reuse in agriculture. Indeed, these two qualities of treated waters are coherent with the Tunisian standard NT 106.03 and can be reused in agriculture. Thus, according to the WHO guidelines on MTE levels in soil, no degree of restriction is required when irrigating with these waters. However, given the dominance of sodium and chloride ions in the soil, control measures must be taken to avoid the risk of soil salinization. We also deduce that the presence of MTEs in the waters of nanofiltration and reverse osmosis and in the soil did not affect the growth and mineral composition of *Sesbania*. As an alternative, given that the major problem of BT textile effluents is salinity and due to the high cost of RO treatment, softening by coupling with other water qualities such as well water is a simple and inexpensive solution to consider for sustainable unconventional water recovery. Couplings of membrane treatment processes can be envisaged. Thus, internal recycling is also a method to be developed by industries. Finally, the choice of treatment of textile effluents and their reuse in agriculture, the sector that consumes the most water, appears beneficial for water-scarce countries because it reduces pressure on conventional water resources and limits discharges into

the environment. On the other hand, the production of fodder irrigated by treated textile effluents by membrane processes can be envisaged in order to reduce the fodder deficit of livestock.

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Article

Rare-Metal Mineralization in Salt Lakes and the Linkage with Composition of Granites: Evidence from Burabay Rock Mass (Eastern Kazakhstan)

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Abstract: This paper represents the results of a study of the chemical composition of salt lakes within the Burabay rock mass in eastern Kazakhstan. We sampled water and bottom deposits, geochemically analyzed the composition of the salt lakes, and performed aerial photography of the lakes to geometrize them. We studied the linkage between the rare-metal mineralization of granites of the Burabay rock mass and the salt lakes within the territory. Based on the obtained data, we identified the prospects of the survey area for rare metals. The surveys included 15 water samples and 15 bottom-deposit samples. To identify the source of salt in the lake water and deposits, the chemical composition of Burabay rocks was analyzed and seven samples of coarse-grained and porphyritic granites were selected. It was established that the water and bottom deposits accumulated elevated concentrations of valuable components (i.e., Sr, Rb, and U); this fact may be considered as an argument for conducting special surveys of small lakes in the region. The results obtained can be used for conducting further explorations and mining operations in the survey area in order to revive the rare-metal industry in the region, which will allow the development of new high-tech production and the creation of new jobs in this sphere.

Keywords: mineral deposit; rare metals; water; salt lakes; rock mass; the Great Altai; Kazakhstan

1. Introduction

Currently, the behavior of such rare-earth elements (REEs) as Li, Sr, Rb, Th, W, and U in natural water is the subject of detailed studies [1,2]. The interest in REEs' abundance in natural water is associated with their potential use as indicators of geochemical processes; this requires an understanding of the migration features and fractionation rules of certain rare-earth elements [3–5]. The unambiguous interpretation of REEs' behavior in natural water is complicated by various processes involving the formation of water complexes, colloid transport, ion exchange, and adsorption, leading to the fractionation of the elements in aqueous solutions in comparison with the source rock [6–10].

Over the last years, the mineral stocks of large salt lakes have become objects of increased interest and intense study as sources of the commercial extraction of potassium salt, magnesium salt, soda, and sodium sulfate [11–14], as well as lithium compounds, bromine, potassium, boron, and rare elements. Salars in South America and salt lakes in China and Mongolia are the classic examples, since their reserves of valuable components (i.e., lithium, boron, bromine, etc.) amount to hundreds or thousands of tons [15,16].

The attractiveness of lake water's use as a mineral stock depends upon the following factors: the availability of large renewable field reserves within large hydrogeological

systems; environmental cleanliness in the context of extraction and production; the possibility of applying evaporative water concentration with the sequenced separation of valuable components; and the low cost of the products owing to the integrated use of hydro-mineral stocks [17].

Recently, the hydro-mineral resources of both large and smaller salt lakes, which occur widely in Central Asia, have attracted increasing attention [18,19]. This interest results from the gradual depletion of large lake basins on one hand and, on the other, the large number of small salt lakes with an extended spectrum of elements for potential raw-material recovery (i.e., uranium, lithium, and rare elements) [20,21]. Zadereev et al. [22] presented research reviewing the status, trends, and drivers of inland saline lakes in Europe and Central Asia, assessing the effects of direct drivers on ecosystem health and biodiversity and highlighting the need for improved water-management and conservation measures. In [23], the authors present a study on the extraction of lithium from salt-lake brines in China using a membrane process. Li et al. [24] investigated the origin and enrichment mechanisms of lithium in a lithium-rich salt lake in West Kunlun, Xinjiang, China, using hydrochemical and lithium-isotope analyses to uncover the genesis of brine-type lithium deposits and to contribute to a deeper understanding of lithium sources and their enrichment processes. Xu et al. [25] investigated the effects of salinity on the composition of dissolved organic matter in salt lakes at the molecular level. Specifically, their study focused on two salt lakes, Qinghai Lake and Daihai Lake, which have similar geographical and climatic conditions but differ in their salinity levels. The results showed that at higher salinity levels, the dissolved organic matter had a larger average molecular weight, a higher oxidation degree, and lower aromaticity. Additionally, the proportion of vulnerable dissolved organic-matter compounds reduced, while the proportion of refractory compounds increased.

The purpose of [26] was to comprehensively utilize magnesium and lithium resources in salt-lake brine for resource sustainability. The study reviewed the latest advances in magnesium/lithium separation and lithium recovery from salt-lake brines, including extraction, adsorption, membrane, and electrochemical methods, as well as reaction-coupled separation technology. The review also discusses the roles of various electrode materials in lithium recovery using electrochemical methods and the potential of reaction-coupled separation technology for highly efficient magnesium/lithium separation and the simultaneous preparation of high-value magnesium-based functional materials. Borzenko et al. [27] developed a new concept to explain the diverse geochemical types of salt lakes, with a particular focus on those in the Transbaikalian region. The study uses hydrogeochemical-field data and thermodynamic calculations to demonstrate that in addition to evaporation, interactions with rocks play a significant role in the formation of salt-lake composition. The study provides evidence that such processes are most common in soda lakes, which have high pH values, carbonate-ion concentrations, and high precipitation of Ca, Mg, and Fe carbonates. Additionally, the study highlights the role of sulphate reduction in the formation of sulphate-type lakes and how the presence of an oxidizing environment and sulphides in rocks can provide additional sources for sulphates. Overall, the study presents a new understanding of how landscape-climatic and geological-geochemical conditions shape the chemical compositions of salt lakes.

The studies described above provide further insights into the potential uses of mineralized waters, the factors that contribute to their mineral content, and their environmental impact. This is why small salt lakes in Kazakhstan are of considerable interest. A significant part of the state's territory has a dry and almost arid climate [28]. Brackish and salt lakes located in arid basins are widespread within the land. The salt-clay rocks and brine from the Aral Sea, the brine from the solonchak and drying lakes of the Caspian Depression, and the territory of the Chu River basin and other regions of the Republic of Kazakhstan arouse considerable interest. The Zaisan depression in eastern Kazakhstan is one of these regions. The hydromineral resources of the objects are almost unexplored. Therefore, the purpose of this paper is to study the macro- and microcomponent composition of small salt lakes in eastern Kazakhstan [29–32].

The territory of Eastern Kazakhstan is part of the Late Paleozoic Altai collision system formed upon the collision of the Siberian and Kazakhstan continents [33]. The geological structure was shaped in the Late Carboniferous–Early Permian; it contains sedimentary formations and intrusions of granitoid composition. The largest intrusion is the Kalba–Narym batholiths, stretching from North-West to South-East for more than 300 km (Figure 1).

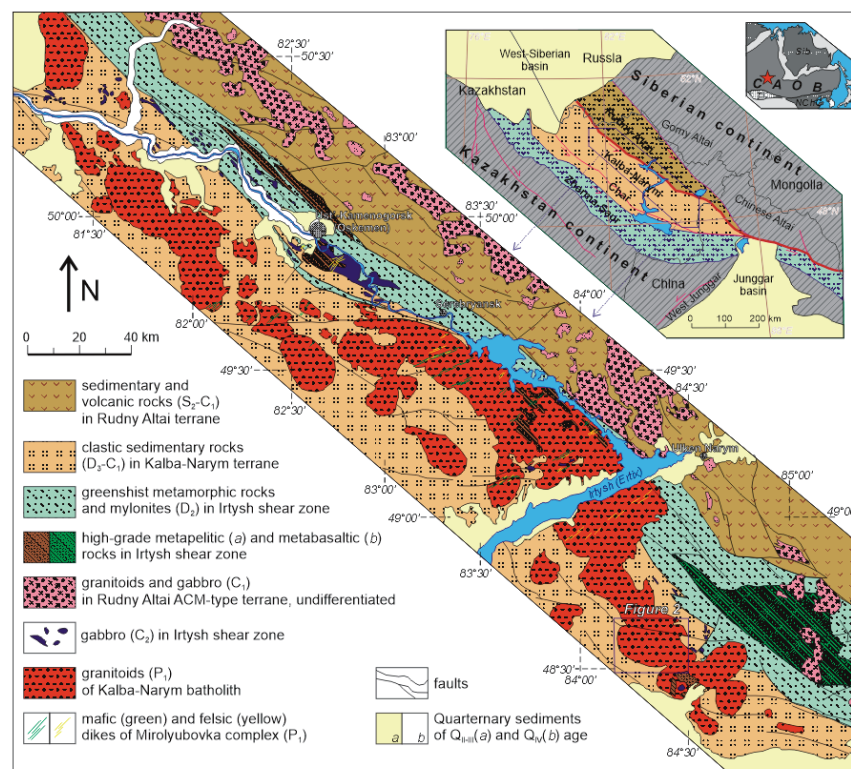


Figure 1. Geological map of the Kalba–Narym batholith in eastern Kazakhstan.

In Figure 1, the inset shows the position of batholith on a terranes map of the Late Paleozoic Altai collision system. The granitoids are from the early Permian age; they cut through Middle–Late Palaeozoic sedimentary and metamorphic rocks [18]. The formation of the Kalba batholith took place in the Early Permian (in the interval of 300–276 Ma), as follows: phase 1, biotite medium, coarse-grained porphyritic granites and, rarely, biotite granodiorites; phase 2, sub-phase 1, medium-grained, fine- and medium-grained biotite muscovitized granites; sub-phase 2, biotite and biotite-muscovite fine-grained granites; and phase 2, bastard granites, aplites, granitaplite, aplite-pegmatites, pegmatites, and quartz veins. The survey area in this paper is within the southern part of the Kalba–Narym batholith. A significant share of the territory is occupied by the Narym pluton, which combines several large granite-rock masses. The subject of our research is the territory of the Burabay rock mass located south of the Kurchum River (Figure 2).

According to the geological-mapping data [18], the Burabay rock mass has a concentric zonal structure. It is shape by rocks of the following three intrusive phases:

- (1) biotite medium- and coarse-grained granites and granodiorites;
- (2) biotite medium-grained granites; and
- (3) biotite-muscovite fine-grained granites of granite-porphyry, aplite, and pegmatite veins.

Regarding the sedimentary rocks, the geological structure of the territory involves stratified Carboniferous stages. The rocks form an alternation of gray, medium- and fine-grained, quartz-feldspathic, polymictic, sometimes initially low-in-lime sandstones, and black carbonaceous–argillaceous siltstones.

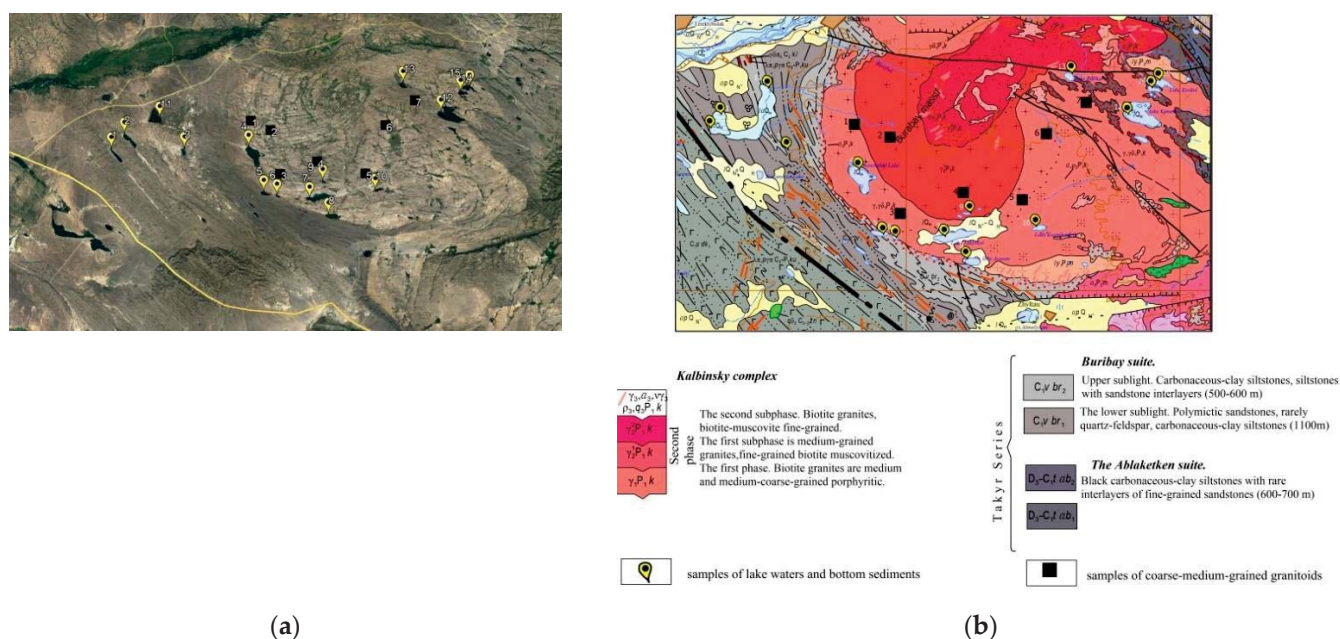


Figure 2. Burabay rock-mass district: (a)—relief and location of the analyzed lakes; (b)—geologic map (according to V.P. Solyannik).

The region relief is complex, spanning low-mountain and high-mountain terrain. The absolute elevation varies from 700–800 up to 1500 m. The planation surfaces within the relief are developed on granitoid intrusions. The true altitude falls in the range of 600–900 m; the relative altitude is 50–60 m (rarely achieving 100 m) [34]. Morphologically, the relief type is a more or less oriented system of slightly elongated, highly deplanated hills; less commonly, it is represented by ridges with smooth (5–80) bare slopes and degradations, with bottoms that are either occupied by lakes or covered with a layer of gruss–sand material. As a rule, the relative hill elevations are 20–30 m. Due to weathering, various bizarre forms are present on the hills, as well as niches and depressions of various sizes [35]. A satellite image of the research area is shown in Figure 2a; the layout of the drainless lakes on the geological map is shown in Figure 2b.

The area features a unique climate and relief, as well as a significant number of small lakes with various mineralization degrees, all of which make it an attractive location in which to study the processes of the formation of macro- and microcomponent compositions [36]. The conditions for the formation of the chemical compositions of water bodies depend on many natural factors (i.e., climate patterns, relief features, water-exchange intensity, the nature of the geochemical environment, etc.).

The region within the Burabay rock mass is characterized by a good and uniformly developed hydrographic system with numerous lakes and marshes. During field studies in 2020, the hydrochemical state of the water bodies was assessed. In the course of the research, 15 lakes were identified in the survey area. They were taken as the basis to analyze both the content and changes in the key parameters and components determining the geochemical outlook of the survey area. The formation of the hydrochemical composition of the surface water took place in the survey area under the influence of natural and climatic conditions [37].

A number of the features of the region's hydrography should be mentioned. Watershed swampiness contributes to the accumulation of a wide range of organic substances in surface water, which are the products of the incomplete decomposition of plant litter. Therefore, the presence of intermediate decomposition products of plant biomass in the natural water determines a weak acid reaction of the environment, which bodes well for an increase in the mobility of a range of metals in the composition of organo-mineral complexes.

Our research purpose is to study the chemical composition of lake water and bottom deposits to identify the mineralization of rare metals, as well as other types of mineral. For this purpose, we carried out field studies to geometrize the lakes and obtained samples of the water and bottom deposits; we then performed a chemical analysis using high-resolution and supersensitive methods (inductively coupled plasma mass spectrometry). Finally, we tried to evaluate the possibility of using water and salt-brine development for the exploration of rare metals.

2. Materials and Methods

This paper is based on the results of hydrogeochemical sampling of small lakes in the area of Burabay rock mass (Figure 2a) conducted in 2020–2022. The sampling was carried out during the driest summer period, which helped exclude influence of dilution processes through atmospheric precipitation. The studies included selection of 15 water samples (1–15) and 15 bottom-deposit samples (B1–B15). To identify the source of salt in lake water and deposits, the chemical compositions of the rocks of Burabay rock mass were analyzed in similar ways. Figure 2b demonstrates position of the sampling points. Seven samples of coarse-grained and porphyritic granites were collected.

During the field studies, geographical reference of the sampling points was made by means of special software, FieldMove Clino.

To geometrize lakes and determine water-surface area, the field studies involved aerial photography [38]. Unmanned aerial vehicle DJI Mavic was used for the purpose. The DJI Mavic quadcopter is a small but high-tech unmanned aerial vehicle with 24 high-capacity computing cores, state-of-the-art system of signal transmission for a distance of up to 7 km, five video transmitters, and 4K camera stabilized by a 3-axis mechanical gimbal. This made it possible to obtain geo-referenced high-quality aerial photographs. The georeferenced aerial photographs were taken using the Agisoft PhotoScan program.

The water was sampled according to the standard method [39]. Clean-polymer, single-use 1.5-L bottles were applied. Walls of the containers were previously moistened with a solution of nitric acid (10%) and left for 2 h, thoroughly washed with clean water, neutralized with a solution of sodium bicarbonate (2%) and, finally, washed with distilled water. Water for chemical analysis was sampled at depths of 30–50 cm at a distance from the lakeside with the help of a sterile 200-milliliter sampler. To prepare the selected sample for storage, we conserved water and loaded it into a cooling box to transport the samples. Water samples were delivered to the laboratory within 24 h [40,41].

The set of bottom-deposit samples obtained with a MPK G01 N 1/02 sampler contained a water-uptake tank, a load, and a cable. Bottom deposits were sampled at depths of 10–15 cm and weighed up to 2.0 kg; they involved the destructed soil composition. Excess water was drained; the samples were packed into plastic buckets and transported to the laboratory. After drying at a 23–25 °C temperature, the samples were quartered by standard methods.

The granite samples were prepared in the sample-preparation sector of the regional university's engineering laboratory, 'IRGETAS', by means of a fine crushing area. The procedure featured two stages: a ShD 6 jaw-breaker crushed samples to 1-mm fractions, after which they were bucked down to 0.07 mm using vibratory pulverator IV-4.

Tests with water and bottom-deposit samples were carried out in the laboratory of the Engineering Center for Advanced Development, 'VERITAS', at D. Serikbayev East Kazakhstan Technical University. The ICP-MS spectrometry methods were applied. The samples were dried in a draft chamber and the sediment was ground. A 200-mg sub-sample was taken and dissolved in concentrated hydrofluoric, nitric, and hydrochloric acids. The resulting solution was analyzed by means of a mass spectrometer for following elements: Ag, As, Ba, Be, Bi, Cd, Co, Cr, Cu, Ga, Ge, In, La, Li, Mn, Mo, Nb, Ni, P, Pb, Sb, Sc, Sn, Sr, Ta, Te, Ti, Tl, V, W, Zn, Zr. The minimum detectable concentration of elements was up to 10^{-9} g/dm³ in liquid objects and up to 1 ppb in solids.

3. Results

3.1. Digital Relief Model

In order to obtain the most detailed information about the relief of the survey area, a digital relief model was needed. Based on the georeferenced aerial photographs, a digital relief model was developed and an altitude map was constructed using the Agisoft Metashape Professional software product. Georeferenced dense clouds of points, textured polygonal and tile models, digital relief models, and orthophotomaps were created based on overlapping digital images and information about geographic coordinates. Based on the calculated image positions, a depth map was compiled. Using the developed 3D polygonal model, we managed to obtain a color reproduction of the graphic properties of objects in the form of a raster with a set resolution. From a dense cloud of points, depth maps and a polygonal model, a digital relief model was constructed. This was a surface model in the form of a regular grid of height values. Table 1 shows the data from the wells of the Burabay granitoid-rock mass.

Table 1. Summary on the wells of Burabay granitoid-rock mass.

Lake Number	Coordinates	Altitude, m	Water-Surface Area, km ²
1	48°34'1.03" 84°1'36.61"	488	0.37
2	48°34'48.32" 84°2'42.98"	498	0.6
3	48°34'12.76" 84°6'56.38"	519	0.36
4	48°34'5.53" 84°12'31.52"	641	1.83
5	48°32'9.19" 84°13'22.77"	657	0.26
6	48°32'1.54" 84°14'21.84"	659	0.12
7	48°32'0.39" 84°17'35.76"	660	1.05
8	48°31'1.67" 84°18'40.04"	679	0.43
9	48°32'48.29" 84°17'58.01"	688	0.05
10	48°32'24.49" 84°22'12.29"	686	0.17
11	48°36'5.56" 84° 4'40.95"	534	1.5
12	48°36'24.53" 84°27'39.28"	851	2.07
13	48°37'50.81" 84°24'2.92"	914	0.25
14	48°37'31.03" 84°28'39.29"	867	0.26
15	48°37'47.23" 84°29'7.39"	869	0.46

For the photofixation and determination of the survey-site location with the use of the aforementioned Agisoft PhotoScan program and the application of georeferenced point clouds from the photographs obtained through the UAV, digital relief models of the lakes in Burabay District were developed. It was possible to obtain a relief profile using the features of the Agisoft PhotoScan program (Figure 3).

The study objects within Burabay District were classified, with small lakes being the most numerous forms of negative surface relief. The digital model and the obtained lake relief profile helped to study the redistribution and allocation of the bottom-forming material. The model analysis helped us to establish that the maximum concentration of bottom-forming material was at the lowest levels of the water collection. However, it is not possible to suggest regular patterns of the element-concentration distribution due to the insufficient study of the seasonal changes in chemical composition of the water while considering the changes in the levels of the water collection.

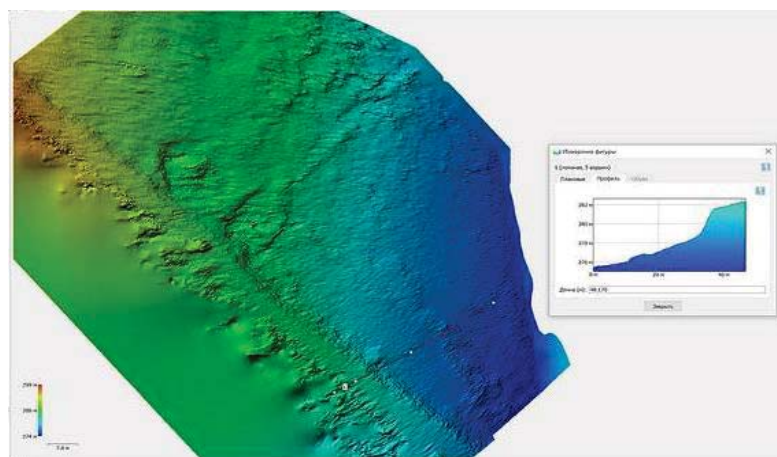


Figure 3. Relief profile using the Agisoft PhotoScan program.

The study of the distribution and deposition of bottom-forming materials in small lakes can have a range of practical applications. For example, understanding how sediments are distributed within lakes can help manage water quality or restore degraded ecosystems. Additionally, understanding the formation and characteristics of small lakes in a region can provide valuable information for land-use planning and management. At the same time, it is important to understand the distribution of bottom-forming material in water bodies, as it can affect water quality and ecosystem health. In this specific case, the study suggests that the maximum concentration of such materials was found at the lowest water-collection levels. However, the lack of studies on seasonal changes in water-chemical composition and water-collection levels made it difficult to determine regular patterns in the distribution of this material. Further research in this area may be required to gain a more comprehensive understanding of how these factors influence the bottom-forming-material distribution.

3.2. Geochemical Characteristics of Burabay Granites

The Burabay rock mass is located in the southern part of the Kalba–Narum batholiths (see Figure 1). In the course of field works in the Burabay rock mass, seven samples of medium-grained porphyritic granites from the first phase of the Kalba complex (Figure 4) were selected. Table 2 demonstrates data on the composition of the granites.



Figure 4. Porphyritic granites from phase 1 of Kalba complex (sample #3 of coarse-grained and porphyritic granites).

Table 2. Summary of the wells of Burabay granitoid-rock mass (wt%).

Sample	1	2	3	4	5	6	7
SiO ₂	69.54	67.32	70.80	65.18	62.29	74.74	68.15
TiO ₂	0.50	0.83	0.25	0.68	0.93	0.10	0.48
Al ₂ O ₃	15.22	14.84	15.28	16.52	16.71	13.88	13.79
Fe ₂ O ₃	3.26	5.59	2.68	5.53	6.46	1.93	3.01
MnO	0.04	0.08	0.03	0.07	0.10	0.07	0.05
MgO	0.68	1.50	0.69	1.56	1.87	0.21	0.75
CaO	1.19	1.84	2.34	2.75	3.07	0.58	2.37
Na ₂ O	3.24	3.55	4.50	3.43	3.57	3.63	3.24
K ₂ O	4.62	3.17	1.39	3.33	3.48	4.37	4.25
P ₂ O ₅	0.21	0.17	0.09	0.18	0.23	0.22	0.35
Rb	149	101	43	96	136	165	93
Sr	137	348	445	263	214	72	264
Y	17.1	31	5.3	56	44	14.7	32
Zr	239	417	105	318	389	41	197
Nb	14.1	10.9	2.1	12.6	16.6	10.2	13.2
Cs	4.3	3.7	1.38	7.1	13.9	14.2	8.4
Ba	535	900	233	655	469	219	216
La	44	44	9.7	28	49	7.0	36
Ce	90	90	18.7	58	96	14.7	87
Pr	12.2	11.8	2.5	7.6	12.6	1.85	11.8
Nd	44	42	8.3	28	46	6.6	24
Sm	8.3	7.2	1.44	6.0	8.9	1.70	2.56
Eu	1.09	1.76	0.49	1.25	1.09	0.33	0.25
Gd	6.3	6.4	1.27	6.8	8.4	1.69	7.32
Tb	0.86	0.95	0.18	1.27	1.30	0.35	1.34
Dy	3.4	4.8	0.84	7.9	7.1	2.2	6.58
Ho	0.48	0.97	0.14	1.72	1.37	0.43	1.12
Er	1.20	2.6	0.42	4.9	3.9	1.20	4.2
Tm	0.16	0.42	0.060	0.77	0.62	0.19	0.57
Yb	1.02	2.6	0.39	4.6	3.9	1.18	3.38
Lu	0.16	0.40	0.058	0.70	0.58	0.18	0.49
Hf	6.7	10.0	2.9	8.4	10.6	1.51	9.78
Ta	1.07	0.75	0.21	0.87	1.38	1.73	1.32
Th	16.3	9.8	2.3	8.9	21	3.2	11.2
U	3.9	2.6	1.00	2.5	2.6	1.84	1.95

Phase 1 is represented by medium-grained porphyric granites (Figure 4). There are gradations among them. With some minor exceptions, the granitoids always contained xenoliths from the granitized sedimentary rocks, varying from a millionth of a centimeter up to 10×15 cm, with rare examples measuring up to 30×50 cm. The xenoliths were of a discoid–ellipsoid shape. In terms of their composition, they were composed of 20–40% plagioclase; 15–37% opotash feldspar; 30–35% quartz; 7–11 (up to 12–15)% biotite; and

1–1.9% accessory minerals. The plagioclase included three generations: zonal, knotty and zonal, and polysynthetically twinned nonzonal one. The quartz took the form of isometric xenomorphic grains or, sometimes, idiomorphic crystals. The biotite is distributed evenly within the rock; occasionally, it formed clusters. The muscovite, clinkstone, and epidote were accessory minerals.

The obtained data on the chemical composition helped to draw the conclusion that the formations of phase 1 of the Kalbinsk complex belonged to potassium–sodium granite series, i.e., rather highly aluminous acid plutonic rocks, normally of an alkaline suborder. The conclusion was made on the basis of determining the specific types and characteristics of the studied rocks in terms of their chemical composition.

The hydrochemical water composition was determined in terms of more than 20 key indicators, including: pH; mineralization; the content of potassium, sodium, magnesium, ammonium ions, nitrites, nitrates, phosphates, silicon, aluminum, copper, iron, lead, zinc, nickel, cadmium, and manganese; and rare metals [42]. Relying upon data from [42], relevant indicators were selected to identify the hydrogeochemical water composition. Table 3 represents the results.

Table 3. Content of macrocomponents and mineralization (M) of lakes within Burabay rock mass.

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
pH	9.08	8.17	8.14	8.93	8.93	9.09	8.14	9.24	9.24	9.23	8.21	9.1	9.23	9.25	8.74
HCO ₃ [−]	mg-equ/L	4.1	6.2	6.4	14.7	12.7	20.6	6.4	10.6	11	9.9	6.4	19.4	9.3	11.1
	% equ	63	79	79	84	79	41	94	48	49	45	93	40	31	35
	mg/L	250.1	378.2	390.4	896.7	774.7	1256.6	390.4	646.6	671	603.9	390.4	1183.4	567.3	677.1
CO ₃ ^{2−}	mg-equ/L	0.6	0.12	0.12	0.49	1.24	2.86	0.12	2.49	2.24	2.87	0.12	3.36	2.24	2.41
	% equ	7	1	1	2	6	5	1	9	8	10	1	5	6	6
	mg/L	29	6	6	23.95	59.8	137.9	6	120	108	138	6	162	108	116
SO ₄ ^{2−}	mg-equ/L	2.11	1.77	1.79	1.94	1.86	24.55	0.24	9.55	9.57	9.62	0.31	24.48	20.61	20.64
	% equ	26	18	17	9	9	39	3	34	34	35	4	40	55	51
	mg/L	101.8	85.3	86.1	93.5	89.5	1180.5	11.6	459.5	460.5	462.6	15.1	1177.3	990.9	992.4
Cl [−]	mg-equ/L	4	3.38	3.72	15.9	15.14	128.56	1.74	35.1	34.88	35.08	2.31	128.16	42.49	42.52
	% equ	4	2	3	5	5	15	1	9	9	9	2	15	8	8
	mg/L	14.2	12	13.2	56.4	53.7	455.9	6.2	124.5	123.7	124.4	8.2	454.5	150.7	150.8
Ca ₂ ⁺	mg-equ/L	0.99	2.09	2.34	1.09	1.04	1.04	2.87	1.5	1.74	1.74	2.24	1.04	1.24	1.24
	% equ	13	26	30	4	4	1	28	3	4	15	24	1	2	2
	mg/L	20.04	42.08	47.09	22.04	21.04	21.04	57.62	30.1	35.07	35.07	45.09	21.04	25.05	25.05
Mg ₂ ⁺	mg-equ/L	3.69	3.19	2.99	2.74	3.14	3.59	2.74	10.73	10.11	9.98	2.74	3.64	4.99	5.24
	% equ	30	24	23	7	8	2	16	14	12	51	18	1	5	5
	mg/L	44.96	38.88	36.45	33.41	38.27	43.74	33.41	130.61	123.02	121.5	33.41	44.35	60.75	63.79
Na ⁺	mg-equ/L	3.26	3.27	2.94	16.8	16.87	86.76	3.74	27.54	31.23	3.09	3.32	117.91	41.9	45.14
	% equ	50	47	43	79	78	92	42	70	72	30	41	90	82	83
	mg/L	75.14	75.22	67.6	386.4	387.98	1994.66	86.19	633.12	718.08	71.21	76.37	2710.62	963.32	1037.71
K ⁺	mg-equ/L	0.28	0.14	0.14	1.26	1.29	2.53	0.72	2.92	2.95	0.24	0.77	6.43	3.04	3.1
	% equ	7	3	4	10	10	5	14	13	12	4	16	8	10	10
	mg/L	11.1	5.5	5.55	49.39	50.44	99.16	28.31	114.23	115.37	9.63	30.12	251.45	119.04	121.1
M	mg/L	529	639	733	1896	1420	5059	616	2.147	2253	1548	601	5849	2881	3074

According to the classification in [43], there were four water groups:

- (1) fresh water with total dissolved solids (TDSs) < 1 g/L;
- (2) 1–10 g/L brackish water;
- (3) 10–50 g/L saline water;
- (4) >50 g/L brine water.

Accordingly, according to the total dissolved solids, the studied lakes can be divided into two groups: fresh-water lakes (## 1–3, 7, 11) and brackish-water lakes (## 4–6, 8–10, 12–15) (Table 3). The lakes are located in an arid zone, where, due to the prevalence of evaporation over precipitation, Ca is deposited in the form of minerals in the bottom

sediment, while Mg remains in solution (calcite, dolomite, gypsum), similar to the Khakassi salt lakes [44].

In terms of the pH level, the water can be divided into several types, depending upon acid-base conditions [45]. The water in lakes 2, 3, 7, and 11 was weakly alkaline; and the water in lakes 1, 4–6, 10, and 12–15 was alkaline. The minimum pH level was 8.14, in lake 3, and the maximum pH level was 9.24, in lake 14. Table 4 a, b explains the chemical composition of the water and bottom deposits from the lakes within the Burabay rock mass.

Table 4. (a). Chemical composition of lake water within Burabay Rock mass (ppm). (b) Chemical composition of bottom deposits from the lakes within Burabay Rock mass (ppm).

(a)															
Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Ag	0.228	0.168	0.313	0.108	0.138	0.096	0.12	0.525	0.944	0.649	0.09	0.313	0.144	0.307	0.162
As	0.56	0.99	1.23	1.45	2.11	0.69	0.78	0.95	0.92	0.96	0.94	1.02	1.36	1.25	1.11
Ba	162.2	158.5	170	165	145.3	149.5	170.3	133.9	145.5	153.2	191.5	174.1	163.5	179.4	183.6
Be	1.26	1.26	2.51	1.26	1.26	1.89	1.89	2.51	2.51	5.03	0.63	0.63	2.51	1.89	1.66
Bi	1.52	1.49	0.69	0.15	0.46	0.3	0.5	0.42	0.76	7.43	1.41	0.34	1.72	0.19	0.95
Cd	0.113	0.072	0.105	0.064	0.048	0.024	0.024	0.056	0.032	0.346	0.1	0.056	0.201	0.53	0.297
Co	9.06	10.5	11.58	6.96	6.18	4.86	7.14	5.28	7.14	17.58	4.14	16.56	11.52	23.88	22.32
Cr	89.23	65.43	65.96	63.06	52.66	58.91	176.6	48.38	54.16	71.5	57.21	67.23	66.74	96.72	134.8
Cu	256.8	174.6	204.7	173.4	220.3	120	140.3	146.6	122.9	259.3	97.85	276.4	767.8	1172	3668
Ga	20.95	25.35	29.76	23.08	21.61	20.81	28.96	12.4	15.34	30.56	26.56	24.42	25.35	28.56	32.31
Ge	0.27	0.3	0.55	0.45	0.2	0.08	0.4	0.18	0.18	0.2	0.28	0.53	0.3	0.53	0.65
In	0.08	0.11	0.04	0.01	0.01	0	0.02	0.01	0.01	0.83	0.01	0.02	0.01	0.01	0.01
La	29.38	34.12	37.26	18.7	24.98	19.13	30.14	16.98	27.46	21.08	16.83	24.02	22.3	27.08	33.81
Li	6.84	12.68	15.7	9.26	14.49	11.47	10.87	8.45	11.07	19.32	9.06	13.28	10.87	15.4	16.1
Mn	690	546	742	455.3	501.5	262.1	411.85	439.1	706	334.05	196	758	455.05	836	814
Mo	4.47	5.14	4.26	4.45	3.76	5.14	3.97	4.72	4.93	4	5.55	4.77	4.22	3.65	5.07
Nb	9.88	11.19	25.36	5.93	9.31	7.02	9.13	4.24	6.46	6.65	4.06	8.78	6.53	11.38	16.97
Ni	60.03	71.69	71.57	69.63	55.55	65.94	54.68	59.87	66.38	56.38	71.37	71.61	64.67	57.05	77.6
P	1121	1398	1351	1070	1046	813	884	881	823	867	759	870	644	1212	1121
Pb	259.2	64.85	62.63	65.54	82	60.95	83.92	108.4	80.96	78.01	52.87	60.76	128.88	82.16	149.36
Sb	1.33	0.03	0.1	0.13	0.28	0.13	0.35	0.64	0.23	0.1	0.07	0.09	0.42	0.03	0.63
Sc	2.6	3.04	2.14	3.97	3.16	4.8	4.01	1.7	1.83	4.66	4.5	3.85	5	3.45	8.67
Sn	1.63	1.28	1.08	0.61	1.01	0.81	0.69	0.79	0.87	0.92	1.03	0.74	1.01	0.61	0.99
Sr	135.6	82.93	93.03	68.29	95.02	51.36	63.6	145.4	215.9	69.86	57.23	100.7	81.49	208.7	96.11
Ta	1.33	1.26	1.15	0.58	0.71	1.09	1.08	0.67	1.02	0.66	0.63	0.47	0.63	0.43	0.77
Te	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Ti	1230	1069	2096.7	969	1230	1189	3112.9	2031	1410	1326	1269	3402	1256	2115.4	3809.6
Tl	0.112	0.23	0.132	0.072	0.066	0.099	0.145	0.053	0.092	1.257	0.171	0.046	0.099	0.059	0.092
V	26.94	22.57	27.76	16.38	18.32	7.27	21.62	15.53	23.29	20.31	4.92	64.17	16.38	53.97	48.06
W	0.83	2.99	1.36	0.68	0.98	0.61	0.98	0.57	0.68	0.76	0.64	1.02	0.91	0.57	0.95
Zn	81.17	41.44	48.57	42.39	61	32.42	45.8	63.77	60.27	50.8	35.21	47.91	277.9	368.4	344.3
Zr	91.34	44.24	57.3	22.98	41.68	47.04	24.94	47.08	77.1	39.8	28.18	69.5	41	62.16	63.14
(b)															
Sample	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15
Ag	0.253	0.234	0.168	0.138	0.168	0.661	0.152	0.141	0.159	0.248	0.257	0.129	0.137	0.158	0.449
As	0.98	0.68	0.99	0.87	0.58	0.96	0.89	0.65	0.89	0.74	0.48	0.94	0.45	0.95	0.82
Ba	182.9	201.5	178.8	217.8	198.4	169.6	126.8	154.3	169.3	211.7	154.8	179.2	158.5	164.2	172.6
Be	41671	29281	28157	14642	25263	42767	45232	31837	24139	12451	19784	45232	42401	19025	44958
Bi	0.38	0.08	0.53	43101	0.38	0.38	0.65	0.05	0.45	45261	0.35	0.35	0.45	0.04	0.42

Table 4. Cont.

(b)															
Sample	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15
Cd	0.330	0.225	0.330	0.193	0.305	0.088	0.195	0.224	0.336	0.159	0.325	0.332	0.336	0.551	0.225
Co	27.9	15.48	34.32	17.34	25.08	28.74	23.35	12.61	35.26	15.89	15.62	25.64	35.68	15.48	11.38
Cr	103	99.7	112.7	113.3	97.4	119.8	94.62	95.23	110.25	100.4	96.12	100.13	114.5	100.3	92.13
Cu	1015	374.7	533.1	387.6	413.6	278.1	378.1	375	433	387	513.6	915	387.6	513.9	285.3
Ga	23.90	28.30	28.44	30.78	30.91	45042	24.65	25.62	27.45	29.98	28.75	22.92	21.35	28.87	27.58
Ge	0.60	0.75	0.82	0.48	0.69	0.94	0.65	0.74	0.81	0.75	0.35	0.62	0.89	0.54	0.98
In	0.00	0.00	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.00	0.01	0.01	0.01
La	26.39	25.47	38.25	30.83	46.90	47.43	45.26	24.56	32.56	29.85	42.38	22.36	41.23	21.35	30.21
Li	17.21	16.81	45134	18.52	21.33	22.74	21.36	15.26	25.36	15.17	20.36	16.25	21.58	15.64	21520
Mn	790.5	443.2	1277.5	950	1753.5	1574	1468.2	445.2	112.6	875.9	1654.3	769.3	1462.1	658.2	652.1
Mo	4.81	3.77	4.78	4.53	4.08	4.23	4.28	3.75	4.75	4.67	4	4.85	2.16	3.85	4.69
Nb	19664	31229	18.27	45093	20.78	20.69	21.34	35947	17.25	45153	21.31	13119	12724	7059.00	16.57
Ni	69.1	55	70.1	59.1	58	67.95	59.48	45.85	62.35	54.68	59.54	68.2	65.28	62.13	61.25
P	1117	1155	1249	931	1100	1496	1501	1152	1325	936	1101	1116	1214	1154	1025
Pb	97.36	68.34	97.12	93.52	68.79	101.76	95.3	89.3	69.2	75.9	98.65	65.4	65.8	102.3	98.55
Sb	0.20	0.23	0.38	0.42	0.22	0.58	0.54	0.26	0.32	0.45	0.21	0.21	0.12	0.48	0.49
Sc	19176	30042	28369	45209	12145	46174	23498	32568	29068	42248	16497	19876	46143	36192	31229
Sn	0.81	0.86	0.82	0.82	44927	0.94	0.99	0.85	0.82	0.79	0.98	0.75	0.78	0.74	0.65
Sr	203.9	76.46	186.1	95.11	90.42	129.8	132.5	74.65	168.12	84.6	96.5	195.6	187.2	89.2	97.6
Ta	0.43	0.29	0.51	0.67	0.90	0.57	0.48	0.28	0.52	0.59	0.85	0.45	0.39	0.12	0.48
Te	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Ti	3553.4	1205	3975.6	7380.1	2759	4230	3568.7	1126.5	3598.7	2351.2	1596.4	3659.1	4597.3	3698.4	1158.5
Tl	0.086	0.086	0.086	0.151	0.125	0.033	0.034	0.085	75.000	0.148	0.112	0.087	0.087	0.082	0.025
V	74.01	53.61	122.82	74.01	78	117.18	110.2	54.06	120.4	75.2	79.5	75.02	78.6	114.7	69.2
W	1.13	0.98	1.48	1.06	1.29	0.72	1.28	0.95	1.45	1.03	1.05	1.12	0.75	0.28	0.58
Zn	287.8	153.7	155.1	118.5	153.5	104.9	98.96	154.2	146.3	110.4	147.3	259.14	95.87	114.2	239.58
Zr	89.3	57.76	110.48	82.18	87.48	103.68	99.87	56.68	111.98	83.25	85.69	84.2	81.29	85.46	95.23

The ion composition of the studied lakes varied greatly. Lakes 1–5, 7, and 11 were of the hydrocarbonate type. Lakes 6 and 8–10 were of the hydrocarbonate-sulfate type; however, they differed in their cationic composition, in which sodium prevailed. The sulfate type included lakes 12–15. They were also notable for their increased water mineralization (Table 5).

The increased mineralization in the analyzed lakes changed the share of the basic ions. If mineralization was low, then hydrocarbonate ions predominated over anions. Along with the increase in mineralization, the sulfate-ion fraction increased. It should be mentioned that in the majority of the lakes, Na⁺ was the prevailing cation, except for in lake 10. The lowest mineralization level was in lake 1 (0.51 g/L); the highest level was in lake 15 (9.0 g/L). The fresh water was in the fresh lakes (#1–3, 7, and 11); the water-mineralization range was 0.5–0.7 g/L. The brackish lakes demonstrated 1.4–9.0 g/L of mineralization, and the pH value was 8.14 up to 9.08.

On a logarithmic scale, the graphs of microcomponent-content distribution within the water and bottom deposits of the studied lakes clearly displayed maximal Cu, Pb, Zn, Ba, Sr, Mn, Ti, and P, and minimal Ag, As, W, Cd, Tl, and In (Figure 5a,b).

Table 5. Hydrochemical classes of lakes of Burabay District.

Sample	Ion Composition of Lake, g/L	Hydrochemical Class of Lake
1	M 0.5	Hydrocarbonate class of sodium–magnesium group
2	M 0.6	Hydrocarbonate class of sodium–calcium group
3	M 0.7	Hydrocarbonate class of sodium–calcium group
4	M 1.9	Hydrocarbonate class of sodium group
5	M 1.4	Hydrocarbonate class of sodium group
6	M 5.0	Hydrocarbonate-sulfate class of sodium group
7	M 0.6	Hydrocarbonate class of sodium–calcium group
8	M 2.1	Hydrocarbonate-sulfate class of sodium group
9	M 2.3	Hydrocarbonate-sulfate class of sodium group
10	M 1.5	Hydrocarbonate-sulfate class of magnesium–sodium group
11	M 0.6	Hydrocarbonate class of sodium–calcium group
12	M 5.8	Hydrocarbonate-sulfate class of sodium group
13	M 2.9	Sulfate class of sodium group
14	M 3.1	Sulfate class of sodium group
15	M 9.0	Sulfate class of sodium group

Higher levels of some microcomponents in the lake water and bottom deposits were noted. These included Cu (97.85–3668.00 ppm; 278–1015.0 ppm); Pb (52.87–259.2; 65.4–102.3 ppm); Zn (35.21–368.4; 95.87–287.8 ppm); Ba (133.9–191.5; 164.2–217.8 ppm); Sr (51.36–215.9; 76.46–203.9 ppm); Mn (196.0–836.0; 112.6–1574.0 ppm); Ti (969.0–3809.6; 1126.5–7380 ppm); P (644.0–1398.0; 931.0–1496 ppm); and Li (8.5–16.1; 12.6–21.5).

The graph of the distribution of elements in the granitoids in the Burabay rock mass (Figure 5c) demonstrate the following microcomponent contents (ppm): Cu (4.0–4.6); Pb (2.8–5.6); Zn (4.0–8.5); Ba (18.0–30.0); Sr (18.0–20.0); Mn (10.0–49.5); Ti (25.0–260.0); P (50.0–60.0); and Li (0.98).

Recently, increased interest has been expressed in the analysis of the behavior of rare-earth elements in lake water. Due to their significantly reduced migration abilities and coordinated chemical behavior, REEs are widely used while studying geological processes (the study of the genesis of igneous rocks and evolution of the Earth's crust and magma). The interest in the behavior of the elements in natural surface water results from their potential use as indicators of geochemical processes, as well as from the determination of the migration features and fractionation laws of certain rare-earth elements.

The amount of REEs in lake water ranged from 79.16 to 197.92 ppm; the average value was 128.18 ppm (Table 6). The maximum amounts of REEs in lakes 2, 3, and 15 were 168.4 and 197.92 ppm, respectively. At the same time, the concentration of light REEs was several times higher than the concentration of heavy REEs, which is coherent with the nature of their distribution in the geosphere in general. The hydrospheric comparison of the REE content with the Clarke content in the lakes showed that the former were slightly higher than the sea- and fresh-water Clarke number. Nevertheless, the geochemical-environment standard for lake water (i.e., alkaline pH value and high mineralization) is unfavorable for REE accumulation and migration in water [46–51].

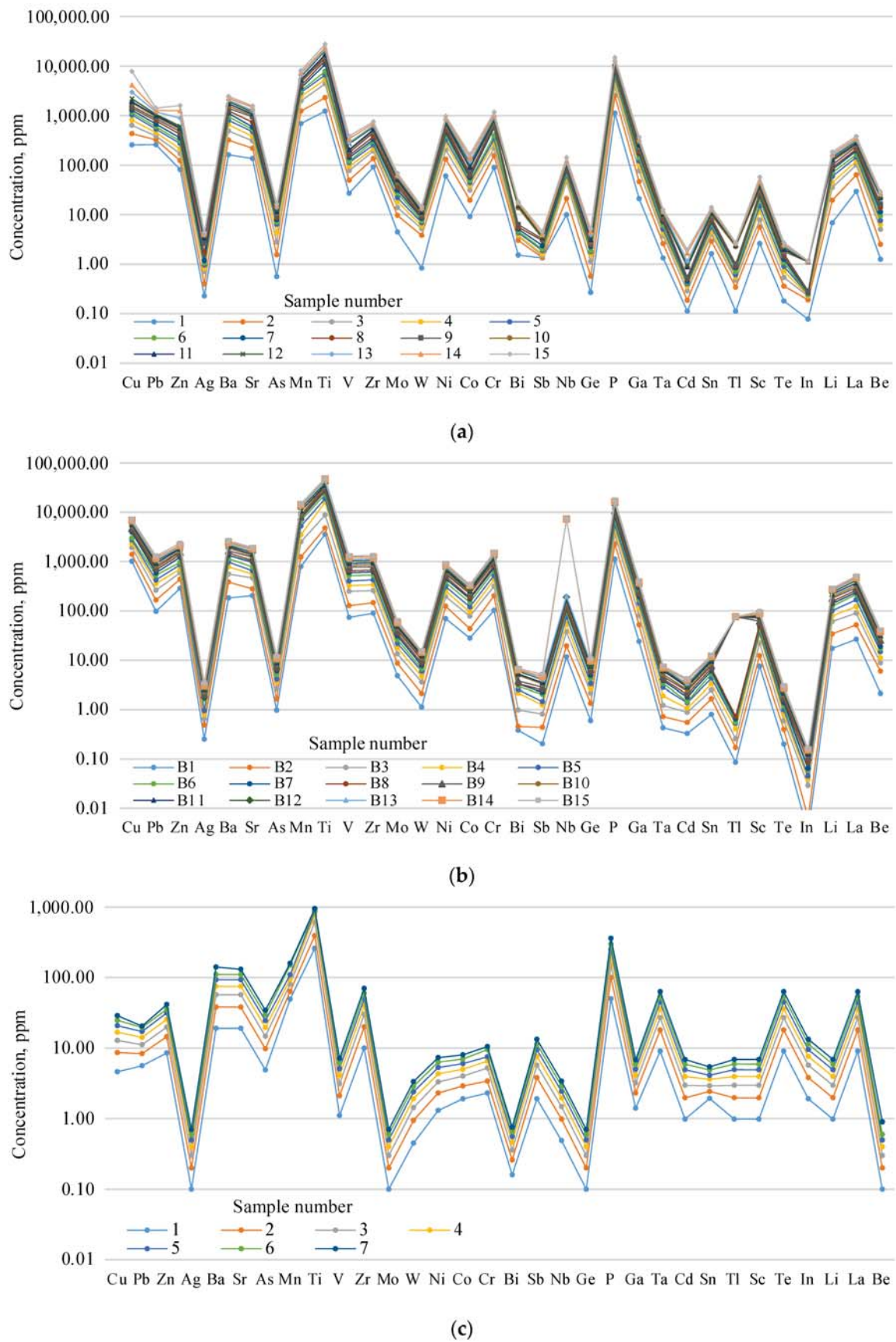


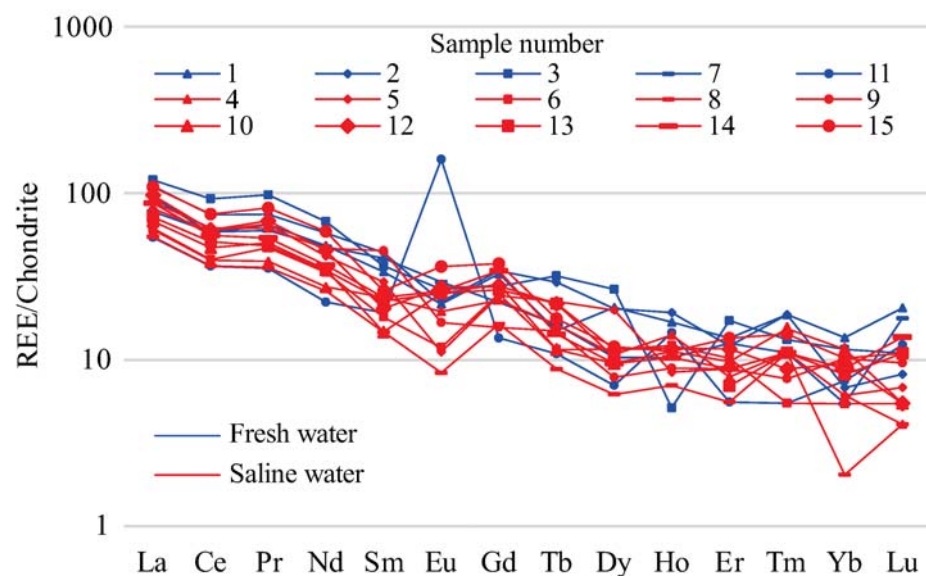
Figure 5. Distribution of microcomponents within Burabay rock mass: (a)—in water (15 samples, lakes); (b)—in the bottom sediments (15 samples, B1–B15); (c)—in granites (7 samples).

Table 6. Contents of rare-earth elements in lake water of Burabay District.

№	Type of REE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
La	Light rare-earth elements (µg/L)	29.38	34.12	37.26	18.7	24.98	19.13	30.14	16.98	27.46	21.08	16.83	24.02	22.3	27.08	33.81
Ce		46.71	59.91	74.76	31.96	48.1	32.27	48.65	29.56	49.98	38.1	29.4	47.3	41.44	45.07	60.51
Pr		7.9	9.09	11.92	4.77	7.97	5.75	8.34	4.36	7.49	6.13	4.32	7.29	5.89	6.57	9.95
Nd		29.04	34.6	40.52	16.46	25.16	20.16	27.2	15.53	27.94	20.91	13.32	28.67	20.72	22.19	35.33
Sm		6.6	8.59	7.13	4.62	5.72	3.52	3.96	2.86	8.81	2.86	3.74	7.93	4.4	4.62	5.06
Eu	Heavy rare earth elements (µg/L)	1.59	1.64	1.95	1.43	0.82	0.87	2	0.61	1.23	1.85	11.74	2.15	1.85	1.9	2.66
Gd		8.49	8.86	7.18	5.91	6.27	6.46	7.2	4.24	4.06	7.38	3.51	5.72	6.83	8.86	9.78
Tb		0.71	1.38	1.51	0.77	1.06	0.55	1.03	0.42	0.71	0.55	0.51	0.77	1.03	0.68	0.84
Dy		6.66	6.52	8.52	3.46	6.39	3.73	3.73	2	2.53	3.06	2.26	3.33	3.33	3.06	3.86
Ho		1.21	1.38	0.37	1.01	0.61	0.87	0.84	0.5	0.64	0.81	1.04	0.74	0	0.74	0.81
Er		2.83	2.54	3.61	1.66	1.85	2.15	2.44	1.17	1.85	2.05	1.17	2.64	1.46	1.85	2.83
Tm		0.61	0.61	0.43	0.36	0.36	0.18	0.29	0.36	0.25	0.5	0.18	0.36	0.36	0.36	0.46
Yb		2.84	1.42	2.42	1.28	1.28	1.14	1.99	0.43	2.13	2.42	1.57	1.14	1.71	1.85	2.13
Lu		0.66	0.26	0.35	0.13	0.22	0.18	0.18	0.13	0.31	0.18	0.4	0.57	0.35	0.44	0.35
ΣREE µg/L		145.23	170.92	197.92	92.52	130.78	96.96	137.99	79.16	135.38	107.86	89.99	132.62	111.66	125.28	168.4

Figures 6–8 show the distribution graphs of the REEs in the lake water within the Burabay District (the chondrite is normalized according to [52]), the distribution profile of the rare-earth elements in the lake water within the Burabay rock mass (the river-water Clarke is normalized according to [53]), and the distribution profile of the rare-earth elements in the lake water within the Burabay rock mass.

The concentrations of commercial microelements (i.e., Li, Sr, Rb, B, U) in the lake water and bottom deposits were analyzed (Table 7). Higher B and U contents in the lake bottom deposit ($2.2\text{--}12.7 \cdot 10^{-3}$ and $0.2\text{--}0.5 \cdot 10^{-3}$) were also noted in comparison to the Clarke numbers of the elements in the sea water ($0.4\text{--}0.46 \cdot 10^{-3}$ and $0.2\text{--}0.3 \cdot 10^{-6}$).

**Figure 6.** Spectra of REEs in lake water within Burabay District (chondrite is normalized).

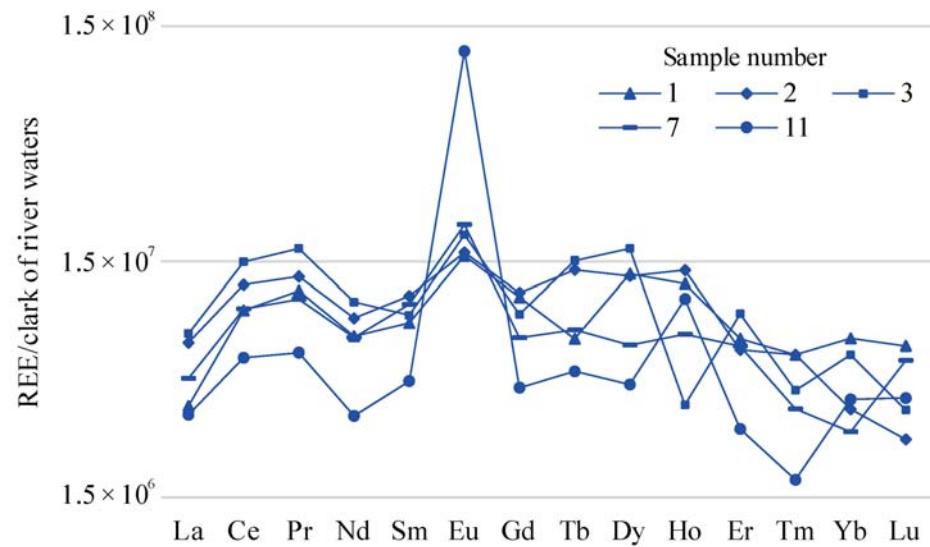


Figure 7. Distribution profile of rare-earth elements in lake water within Burabay rock mass (river-water Clarke is normalized).

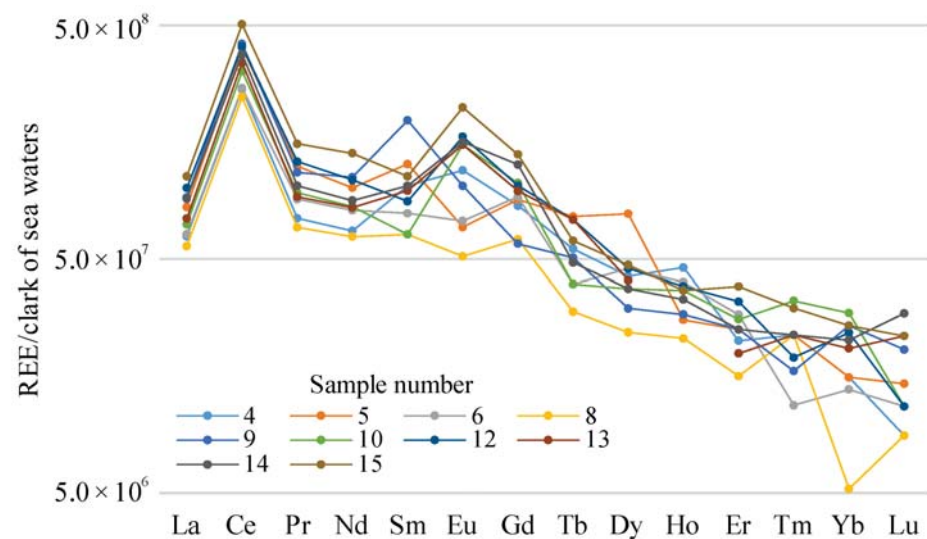


Figure 8. Distribution profile of rare-earth elements in lake water within Burabay rock mass (sea water Clarke is normalized).

Table 7. Results of study of the composition of lake water and bottom deposits in Burabay rock mass, depending upon the content of commercial microelements (mg/kg).

Rare Elements	Lake Waters	Bottom Deposit	Clarks of Elements in Sea Waters	Clarks of Elements in Sedimentary Rocks	Clarks of Elements in Granites
Li	$0.6\text{--}1.9 \cdot 10^{-3}$	$1.7\text{--}2.7 \cdot 10^{-3}$	$1.5\text{--}2 \cdot 10^{-3}$	$7.8\text{--}7.4 \cdot 10^{-3}$	$3.7 \cdot 10^{-3}$
Sr	$13.56 \cdot 10^{-3}$	$7.6\text{--}20.3 \cdot 10^{-3}$	$0.8 \cdot 10^{-3}$	$2\text{--}4 \cdot 10^{-3}$	$15 \cdot 10^{-3}$
Rb	$19.6 \cdot 10^{-3}$	$15.7\text{--}22.4 \cdot 10^{-3}$	$0.012 \cdot 10^{-3}$	$5\text{--}15 \cdot 10^{-3}$	$18 \cdot 10^{-3}$
B	$0.5\text{--}0.9 \cdot 10^{-3}$	$9.2\text{--}12.7 \cdot 10^{-3}$	$46 \cdot 10^{-3}$	$10\text{--}25 \cdot 10^{-3}$	-
U	$0.1\text{--}0.3 \cdot 10^{-3}$	$0.2\text{--}0.48 \cdot 10^{-3}$	$0.0003 \cdot 10^{-3}$	$0.13\text{--}0.37 \cdot 10^{-3}$	$0.39 \cdot 10^{-3}$
Th	$0.4\text{--}0.9 \cdot 10^{-3}$	$0.3\text{--}0.7 \cdot 10^{-3}$	$0.7 \cdot 10^{-7}$	$1.2 \cdot 10^{-3}$	$1.8 \cdot 10^{-3}$

4. Discussion

Over the past decades, Kalba–Narym batholith granites were studied by many researchers [54–61]. Their interest was mainly caused by the availability of large granite–pegmatite deposits with Li, Ta, Cs, Nb, and Be mineralization in the northern and central parts of the batholith [62,63]. In the southern part of the batholiths, Cherdoyak deposits associated with granitoids from the Narym Sn–W rock mass are present [64–68].

The Kalba–Narym batholith is mainly composed of Kalba-complex granites. According to the data from previous geochemical studies [60,61], the granitoids in the Kalba complex contain 63–77% wt of SiO₂ and 2–7% wt of K₂O; in addition, they belong to high-potassium calcium–alkali series. Furthermore, LREEs prevail over HREEs; in the majority of the analyzed samples, there was a negative Eu anomaly (Eu/Eu* from 0.7 to 0.3). The multielement diagrams showed negative Ba, Sr, Eu, and Ti anomalies, as well as positive Th and P anomalies with multidirectional U and Ta behavior. The set of petrogeochemical data allows the suggestion that Kalba-complex granitoids are similar to S-granites.

The geochemical characteristics of the Burabay rock-mass granites corresponded to those of the Kalba-complex granites. The behavior of the rare-earth and rare elements was also similar to that of Kalyubin granites. The four analyses of the granites in terms of the behavior of the rare-earth elements showed that these were fully consistent with those of Kalba granites. Two analyses of granites (#3 and #6 in Table 2) showed reduced concentrations of LREEs. In analysis #3, the HREE concentrations were also reduced. This phenomenon can be explained by local manifestations of the post-magmatic alteration of granites.

Compared to Central Kalba, the granitoid mass within the Narym ore district was formed under Quarternary tectonic conditions, which resulted in the lesser development of intra-intrusive fractures, fault structures, and vein fields, a weaker manifestation of metasomatic processes, pegmatite veins with simpler compositions, and lower ore contents. Separate ore manifestations of block microcline and quartz–albite–muscovite pegmatites with no practical significance were established in the study area [69–72].

A geological survey within Burabay rock mass identified rare-metal specialization, including three complex halos. The largest of these, with an area of about 20 km² [61], is located in the central part of the rock mass. The rocks are characterized by lithium content of 0.3–0.9 ppm. Two other complex halos, with 0.5 ppm of tin content, 4 ppm of copper content, less than 0.5 ppm of molybdenum content, and 0.1 ppm of silver content, of smaller sizes (up to 1 km²), are located in the eastern part of the studied area.

According to the data from another geological survey [1], two complex rare-metal anomalies were found in the territory of the Burabay rock mass: one northern (about 12 km²) and one southern (about 5 km²). The former is characterized by 0.0008–0.002% niobium content, 0.0002–0.0005% bismuth content, 0.0005–0.0008% beryllium content, 0.0015–0.002% lithium content, and 0.001–0.0015% tin content. The latter consists of three local halos, containing 0.0005% beryllium, 0.001–0.0012% tin, and 0.002–0.008% lithium; they are united by a 0.0003–0.0004% beryllium halo [73].

Considering the findings of previous studies [1], which include the rather significant saturation of the area with small (but low-in-contrast) halos, as well as its localization within a field with several points of tantalite–columbite, tin ore, and beryl (Pridorozhny section) mineralization, in addition to the proximity of Cherdoyak tin–tungsten deposits, the study of the chemical lake composition is of practical interest [74].

A comparison of the graphs concerning the distribution of the microcomponents in the lake water and bottom deposits within the bedrock of the Burabay rock mass (Tables 2–4; Figures 5–8) showed that the general tendency is preserved in their content by the main maxima and minima. Along with this similar general tendency in the content according to the graphs, there were certain differences in the nature of the microcomponents. For example, the following were higher in the bottom deposits (bottom deposits; water, ppm): V (up to 120.4; up to 64.17); Ti (up to 4597.3; 3800.6); Ge (up to 0.82; up to 0.6); Ta (up to 0.90; up to 1.3); Cd (0.551); and Co (35.68 23. 88). However, the following substances were

significantly (i.e., up to the first tens) reduced (bottom deposit; water, ppm): In (0.02; 0.8) and Sb (0.54; 1.3).

It can be concluded from the analysis of the graphs in Figure 5a–c that the contents of the microcomponents in the lake water and bottom deposits were tens and hundreds of times higher than those in the bedrock (except for Ti and P, which were almost equal). On the other hand, the aqueous solutions and bottom deposits have sharply reduced Ta, Cd, Sn, and In contents. This can be explained by the different solubility levels of the microcomponents in different types of water, as well as by the different sedimentation rates in the lakes.

The elevated REE concentrations in the lake waters may have resulted from the presence of erosion and the passage of the migration flow in the zone of influence of the geochemical anomalies established by [72]. This scientific source proposes many possible reasons for the occurrence of anomalies in various rare-earth elements.

To study the behavior of the rare-earth elements, distribution graphs of rare-earth elements in the analyzed water were constructed, with chondrite-content specification in terms of the rock standards (Figure 6). To take into consideration behavioral features of the elements in the solutions, the REE content in the fresh water was specified for lakes 1, 2, 3, 7, and 11 (river-water Clarke) (Figure 7). In the salt water (lakes 4–6, 8–10, and 12–15), the sea-water Clarke was used as the gauge (Figure 8) [53].

The graphs of the REE distribution standardized by the chondrite (Figure 6), as well as by the sea-water Clarks (Figure 8), demonstrate clearly that the content of the light REEs prevailed over that of the heavy REEs. For the fresh water, the distribution of HREE and LREE was roughly the same. In the salt-lake water, prominent Ce maxima were seen; in the fresh water, prominent positive La, Ce, and Pr anomalies were seen. At the same time, the content value of the elements in the fresh water was dozens of times lower. In the graphs of the REE content in the salt water, slightly positive Sm anomalies were shown. There was a clear positive europium anomaly in both the fresh and the salt water; this was especially apparent in the fresh alkaline water from lake 11.

The study of the chemical compositions of the samples showed that the Li contents in the lake-bottom deposits were $1.7\text{--}2.7 \cdot 10^{-3}$ wt%, and they were 0.6 to $1.9 \cdot 10^{-3}$ wt% in the lake water. The obtained values are comparable to the Li content in sea water ($1.5\text{--}2.0 \cdot 10^{-3}$), or slightly higher; nevertheless, they were lower than the Li Clarke in the sedimentary rocks ($7.0\text{--}7.4 \cdot 10^{-3}$). The proportions of Sr and Rb in the bottom deposits were $7.7\text{--}20.6 \cdot 10^{-3}$ and $15.7\text{--}22.4 \cdot 10^{-3}$ wt%, respectively, exceeding the Clarks of the elements in the sedimentary rocks ($7.5\text{--}15.3 \cdot 10^{-3}$) and sea water ($0.7\text{--}8.4 \cdot 10^{-3}$). Similar shares were seen in the lake water for the Sr ($10.7\text{--}13.6 \cdot 10^{-3}$) and Rb ($9.5\text{--}19.6 \cdot 10^{-3}$ wt%).

The comparison of the REE contents in the lakes with the Clarke contents in the hydrosphere (Figure 6) demonstrated that they were slightly higher than the Clarks of the sea and fresh water, although the geochemical-environment standard for lake water (alkaline pH value, and high mineralization) is unfavorable for REE accumulation and migration in water [46,47,49,51,75–78].

It should be noted that interpretation of the REE behavior in natural water is complicated by such processes as the generation conditions and the hydrodynamic regime of water complexes, the prevailing form of element migration in water, ion exchange, and adsorption by host-rock complexes which, apparently, leads to the fractionation of these elements in aqueous solutions compared to source rocks. However, the data in this study are very important for identifying the direction of migration flows and determining the areas of microelement subtraction. The possibility of using the lake water within the Burabay rock mass as a source of hydromineral resources has been defined (Table 7). The Sr, Rb, Th, and U contents are tens or even hundreds times higher (Th, U) than their respective Clarke contents in seawater and sedimentary rocks.

The results of the comparative analysis of the mineralization and macro-component composition of the lake water of the Burabay rock mass for fresh and salty water showed different correlations between the mineralization indicators and the levels of Na, Mg, Ca,

and Cl accumulation. There was practically no correlation with fresh water (Figure 9a). As expected, the Na content increased for the salty water, along with an increase in the mineralization indicator (Figure 9b).

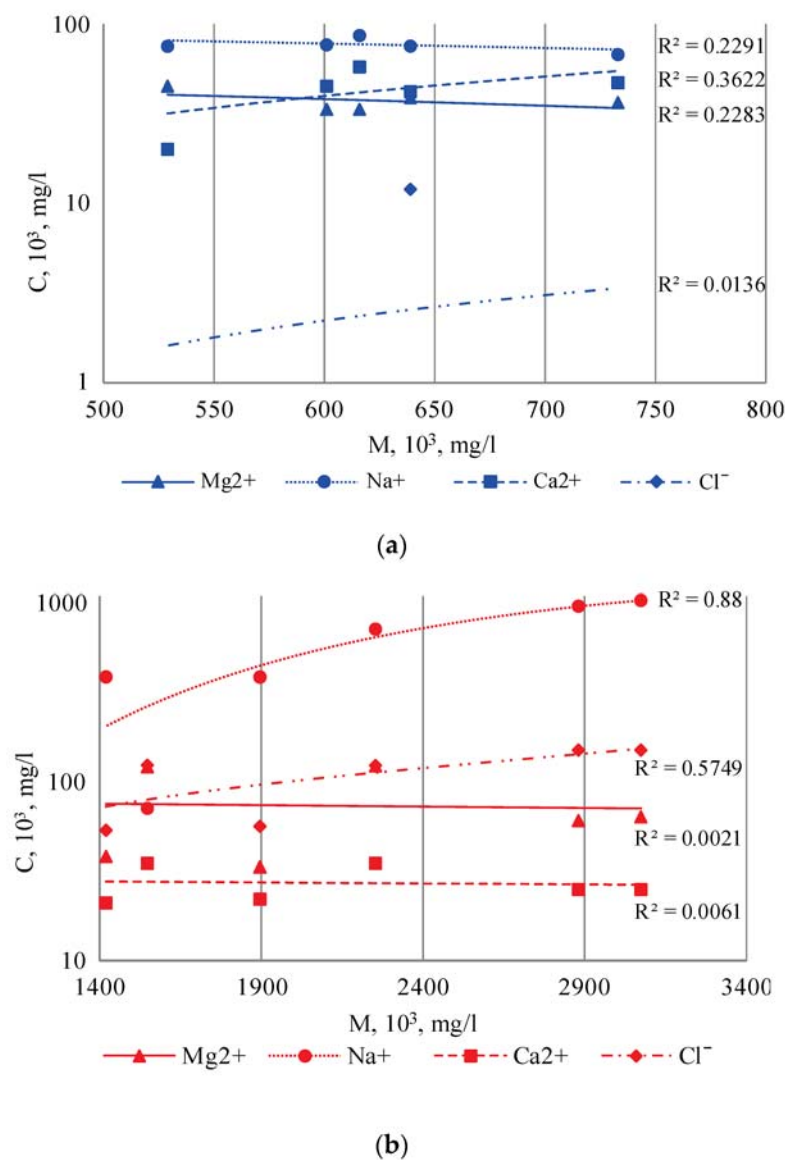


Figure 9. Correlation between mineralization (M) and concentration of macrocomponents (Na, Mg, Ca, and Cl) in lake water of Burabay rock mass: (a)—fresh water; and (b)—salty water.

The Cl content showed a weak correlation with the mineralization; in turn, the Ca and Mg demonstrated no correlation. The fact that the correlation was high for the Na and medium for the Cl supports the idea that the Na originated from the surface-water runoff. The Na also potentially originated from the alkaline granites of the Burabay granitic rock mass, as their most soluble component.

A positive correlation was also established between the water mineralization and the contents of some of the rare elements. In the fresh lakes of the Burabay rock mass, the Li shows a high correlation ($R^2 = 0.957$), the Th showed a moderate correlation ($R^2 = 0.543$), and the Rb showed a rather poor positive correlation ($R^2 = 0.337$). There was a negative content correlation for U ($R^2 = 0.607$), and there was no correlation for Sr ($R^2 = 0.12$) (Figure 10a). These correlations were not expressed in the salty lakes (Figure 10b). It is quite possible that the Li and Na were leached from the same mineral within the sur-

rounding granitic rocks. The area is also of interest owing to the demonstrated correlation between the parent rocks of the enclosing formation and the lake-water composition.

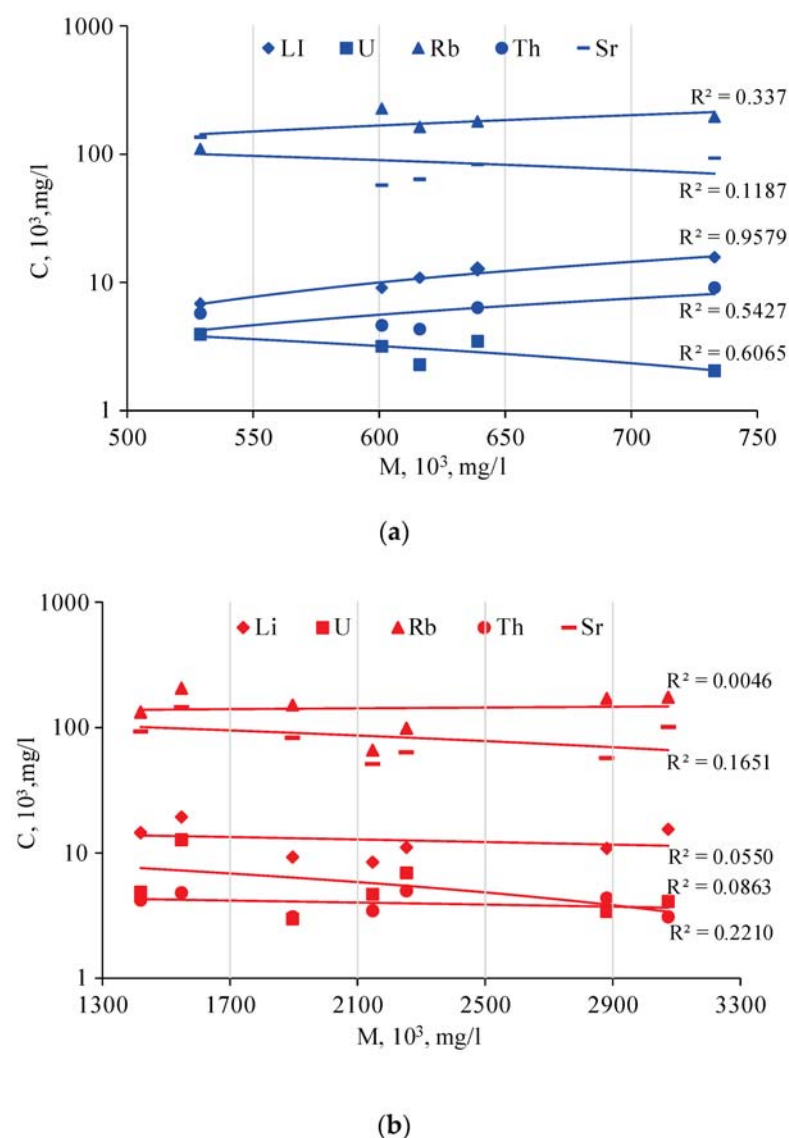


Figure 10. Graphs with relationship between mineralization (M) and concentration (C) of microcomponents (Li, Sr, Rb, Th, and U) in lake water of Burabay rock mass: (a)—fresh water; and (b)—salty water.

The interpretation of the analytical data from within the area helped to establish the relationship between the water mineralization and the weathering products of the parent rock mass; moreover, the influence on the ultimate composition of the studied lake water was observed. This may have resulted from areal losses.

It was identified that the lake water accumulated elevated concentrations of commercial components (Sr, Rb, and U), which may become the basis for specific studies of the small lakes within the area. It is possible to apply the findings of this study for future geological prospecting activities and operations within the promising sites identified.

The main sources of rare-alkaline elements are rare-metal and rare-earth-mineral occurrences, which are associated with Permian granites in the eastern Kazakhstan region. During the orogenic (post-collisional) stage of the Hercynian cycle, the survey area experienced extremely high mobility, which is reflected in the occurrence of powerful granite magmatism. In this regard, the following promising survey areas are distinguished. In these areas, we plan to conduct further research on the chemical composition of the lake

waters, salt brines, and bittern and bottom sediments to identify the mineralization of rare metals and other types of mineral:

- (1) Delbegeteysky area (the lakes in the north-west of the Delbegeteysky massif);
- (2) Shagan–Charyn area (between the Shagan and Charyn rivers);
- (3) Kaskabulak area (near the Maksut field), where there is a fault zone in which an intrusion and a Suurly tungsten deposit are known to the south of the lakes.

Large-scale granite outcrops on the daylight surface of the Kalba complex (P1) were noted in the identified survey areas. These are genetically related to the rare-metal type of mineralization. Quartz-veined-greisen and quartz-veined tin, tin–tungsten, and tungsten formations are also widely evident. Given the intense geochemical migration ability of rare-alkaline elements in the thickness of loose deposits as a result of intense geodynamic processes in the eastern Kazakhstan region, we can assume the possibility of their migration to the upper horizons and their accumulation in salt lakes localized within the area of the development of Permian granite intrusions and associated deep tectonic faults.

The planned scientific research makes a certain scientific contribution to the problem of modeling rare-metal ore-forming systems and improving prediction methods in order to create a modern scientific base for the further development of the mineral and raw-materials sector in the world economy.

5. Conclusions

The results of the study of the granitoid rocks, bottom sediments, and water in small lakes within the Burabay granitoid-rock mass showed a specific relationship between the concentrations of macro- and microcomponents, as well as rare elements in the water and bottom sediments of 15 lakes at the Burabay site, and the composition of the granitoids in the Burabay rock mass.

The study of the macro- and microcomponent composition of the water and bottom sediment of the lakes at the Burabay site showed that the sharply continental arid climate of the territory, the hydrodynamic regime of permanent and temporary surface watercourses, the terrain, and the presence of drainage basins all played leading roles in their formation. The source of the substances entering these lakes as a result of the flushing of the products of physical and chemical weathering are granitoids in the Burabay rock mass from the Permian age, as well as soils with elevated contents of a number of elements within the identified geochemical anomalies in the area of the Burabay granitoid-rock mass.

It was established that high concentrations of useful components (Sr, Rb, U, and Th) accumulate in the water and bottom sediments of the lakes, and that the U and Th contents are hundreds of times higher than their Clarke values in the sea water and comparable to their contents in the igneous rocks. This may be considered as the basis for the specialized study of the small lakes in the region. The use of modern technologies to extract radioactive elements from water sources, as well as from a large number of lakes, significantly increase the region's prospects for hydromineral-raw-material extraction.

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Article

In Vitro Assessment of Salinity Stress Impact on Early Growth in Ten Certified Palestinian Barley Cultivars (*Hordeum vulgare* L.) Potentially Suitable for Cultivation on Former Quarry Substrates

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Abstract: Salinity is a major constraint for crop health and productivity, particularly on arid, semiarid, and otherwise marginal soils, such as quarry residue. Quarries are a main pillar of national income in Palestine but have a long-lasting toll on the environment. We examined barley (*Hordeum vulgare* L.), another pillar of the Palestinian economy and one of the most important crops in the world, in this regard for its tolerance to salinity stress. This study is the first to evaluate the impact of salinity (50, 85, 120, and 175 mM NaCl) on seed germination, early growth stage, and morpho-anatomy on ten pre-selected certified Palestinian barley cultivars (Baladi, Improved Baladi, Rihan, ICARDA 1, ICARDA 15, ACSAD 68, ACSAD 176, ACSAD 1417, ACSAD 1732, and ACSAD 1744) to assess their potential for a successful growth start under adverse saline conditions. In addition, soil samples from quarries in Hebron governorate were randomly selected and tested for salinity level, electrical conductivity, and total of soluble salts for a first rough overview of options for applying our results, since local data are often scarce or outdated. The examined soil samples reached electrical conductivity (EC) ranges of 1.81×10^{-4} – 9.071×10^{-4} dS m⁻¹, which are below the normal EC (11 – 57×10^{-4} dS m⁻¹). This result may contraindicate the hypothesis that quarry lands always suffer from salinity stress. Cultivars such as ACSAD 68 and Icarda 15 proved very sensitive to higher salinity stress with high G₅₀ (time point when 50% of seeds have germinated) at 4.4 d, with 120 mM NaCl (ACSAD 68) or incalculable amounts (Icarda 15) and just 50 and 20% total germination, respectively. Concentrations of 175 mM NaCl were found in ACSAD 176 and Improved Baladi (no G₅₀, 37 and 30% germination, respectively). Some cultivars showed a moderate to high resilience to salinity, such as ICARDA I, ACSAD 1417, and ACSAD 1744, which reached > 80% seed germination at 120 mM NaCl and >60% at 175 mM NaCl, and G₅₀ within 1.5–2.2 days; the most resilient was ACSAD 1732 with G₅₀ < 2 days and germination still >80% at 175 mM NaCl. This is strongly supported by the monitored growth parameters. In conclusion, ACSAD1732 and Icarda 1 cultivars are highly recommended for cultivation in areas of low precipitation and high salt accumulation. In addition, the land and/or soil of quarries, their landfills, and nearby areas in Palestine may be fit for barley cultivation with recommended cultivars regarding salinity stress.

Keywords: abiotic stress; electrical conductivity (EC); barley; quarries; salinity stress; shoot system

1. Introduction

Salts are essential for plant growth at compatible levels. However, salinity stress is the second-biggest abiotic factor, accounting for major global problems that negatively affect agricultural productivity by disturbing numerous physiological, biochemical, and molecular processes [1,2]. High salinity is mostly due to high concentrations of Na⁺ and

Cl^- in the soil, which produce hyperosmotic and hypertonic solutions that stop water and nutrient uptake by plants [2]. The sources of soil salinity are rainfall, weathering of rocks, flooding of seashores, urbanization, and irrigation with brackish water [3–5]. In addition, the reuse of wastewater causes considerable salinization of groundwater [6], which in turn is used for irrigation. The most important mineral ions in soil–water extracts are Na^+ , Cl^- , Ca^{++} , SO_4^- , HCO_3^- , K^+ , Mg^{++} , and NO_3^- [7,8].

Increased sodium and magnesium ion levels can destroy soil structure. However, calcium carbonate can improve soil structure, forming calcareous alkaline soil and increasing soil pH. On highly saline soil, visible salt crystals often occur on the soil surface, making it vulnerable to erosion [5]. High salts levels in soil can also positively affect soil physical properties by causing fine particles to bind together in a process known as flocculation; this can have benefits in soil aeration, root penetration, and root growth [9].

Soil salt content is usually determined for different soil layers and at different depths, based on the plant species root growth [10]. The electrical conductivity of a soil sample is affected by the concentration and composition of dissolved salts, which increase the solution's ability to conduct an electrical current [11,12]. In this context, water-soluble salts in the soil act as strong electrolytes that have electrical conductivity (EC), which is defined as the ability of a material to conduct electrical current. Within a certain concentration range, the salt content in the soil is positively related to the electrical conductivity. Recently, a simple and quick approach has emerged that uses electrical conductivity to directly represent the total salt content in the soil. The SI unit of electrical conductivity is siemens per meter (S m^{-1}) [10].

The effects of salinity on plants are recognized as water stress, cytotoxicity that is caused by the excessive uptake of ions, and nutritional imbalance [13,14]. Increasing salinity stress can also induce oxidative damage to the plant cells, which can affect germination and the characteristics of the seedling [15]. This stress negatively affects seed germination by means of osmotic stress and ion toxicity [16–18]. The ion toxicity results from the accumulation of salt ions (Na^+ and Cl^-) in the seed. This inhibits the metabolism needed for seed germination, and in some cases will eventually lead to seed death. In addition, the plant will reduce its cell rigidity, the number of the roots, their length, the rigidity, the length of the shoot, and the crop yield [19,20]. Moreover, an excess of some ions can cause an imbalance and reduce the ability of plant to take up nutrients; i.e., high levels of calcium may inhibit the uptake of iron (lime-induced chlorosis), and high sodium may frustrate potassium uptake [5,21]. In addition, ion excess can decrease the uptake of phosphorus due to the precipitation of phosphate ions in the presence of Ca ions. Some elements, such as sodium, chlorine, and boron, have specific toxic effects on plants [22]. Symptoms of damage emerging from soil salts are similar to other plant diseases and can include browning leaf edges, chlorosis, wilting, leaf drop, etc., which makes diagnosis complex.

Plants firstly respond to the salts by a shoot-ion-independent reaction that is related to the detection of Na^+ and the signaling process. This causes the closure of the stomata in the leaves and inhibits the expansion of the leaf due to low water activity. The second phase is a salt-dependent response to the accumulation of toxins in the leaves that causes a premature leaves senescence. Another mechanism is genetic control by several genes that can control the salinity tolerance [20,23,24]. Moreover, the impact of salinity on plant is salt-specific in regards to bioactive compound production. For example, in one study, the highest polyphenol concentrations were obtained with Na_2SO_4 variants, while in another, the highest flavonoid content was obtained with salt mixtures of NaCl and Na_2SO_4 (100% higher than control) [25,26].

Barley (*Hordeum vulgare* L.) is a valuable grain crop that has ranked fourth among the cereal crops [27] and as the second-most economically important cereal after wheat in the world and Palestine as well [28]. It is commonly used in breads, soups, food, alcoholic beverages, and health products, as well as for animal fodder [20,29,30]. Barley is an annual plant that belongs to the Poaceae family. It is adaptable to a great range of climates and does best in growing seasons of at least 90 days; in Palestine, it is mainly cultivated in autumn. It

grows with greater resistance to dry heat than other small grains and thrives in near-desert areas. In addition, it shows a wide range of responses to salinity stress depending on the phylogenic of the cultivars [31]. Salinization is a problem that results from quarry operations. There are almost 300 quarries in Palestine, and 142 of them are within the Hebron governorate. Quarries, their landfill, and their nearby areas have deleterious effects on the environment, resulting in areas of poor substrate [24–26]. However, they are considered essential pillars of national economic development in Palestine. As of now, little research has been conducted on the consequences of quarries in terms of environmental and climate change [32–34]. Therefore, screening for salt-tolerant crop cultivars is a prerequisite to mitigate the quarries' negative impact on otherwise agriculturally usable land.

This study therefore aimed to identify barley cultivar(s) showing salinity resilience during the stages of seed germination and early seedling growth. The ultimate goal was the assessment of physiological and morphological features that assist the plant in tolerating salinity stress throughout its growth period. In addition, the study aimed to establish an initial, current overview of the salt content in the soil of quarries at Hebron governorate to enable recommendations for suitable cultivars as a novel approach to rehabilitating quarries, their landfills, and nearby areas.

2. Materials and Methods

2.1. Materials

The experiments were carried out *in vitro* from 2019 to 2020 at the Applied Biology Department and Palestine–Korea Biotechnology Center in Palestine Polytechnic University. Seeds of ten certified barley cultivars growing in Palestine were kindly provided by National Agriculture Research Center (NARC)/Palestine. The barley cultivars were Rihan, Icarda1, Icarda15, Baladi, Improved Baladi, ACSAD176, ACSAD1732, ACSAD68, ACSAD1417, and ACSAD1744.

2.2. Area of Study and Soil Sampling

The study area was four regions in the Hebron governorate, which is located in the south of Palestine at latitude 31.31° north and longitude 35.8° east, 36 kilometers south of Jerusalem. The mean average of precipitation in the Hebron governorate is 595.6 mm [32], which has a semi-arid climate. The four regions we studied were Bani Naim, AlShyoukh, Taffouh, and Sier. The soil sampling was carried out via the quadrature method, in which grids of 10 m × 10 m were constructed and random selection was conducted. Substrate samples were taken from the surface and a depth of 20 cm and collected in sealed polyethylene plastic bags. EC was measured, and soluble salt content was calculated according to [10].

2.3. Methods

2.3.1. Plant Seed Disinfection and Germination

We selected 120 healthy and viable seeds with similar size and shape for each cultivar. The seeds were surface-sterilized by soaking in 1% (*v/v*) sodium hypochlorite solution for 20 minutes with the aid of Tween 20. After applying 70% ethanol, the seeds were washed with sterile distilled water three times [19]. *In vitro* germination was performed in 9 cm Petri dishes containing water–agar medium (0.8%) supplemented with 0 mM, 50 mM, 85 mM, 120 mM, and 175 mM NaCl for 10 days. The pH of the medium was adjusted to 5.8 with NaOH. The medium was autoclaved for 20 minutes at 121 °C and 1 atmosphere (Tuttnauer AC 2540E). Under aseptic condition, ten seeds of each barley cultivar were placed in each Petri dish in a triplicate form for each concentration. The plates were incubated in a plant growth room under fluorescent cool light with a 16 h photoperiod at 24 ± 2 °C.

During the seed germination stage, the number of germinated seeds (defined as the sprouting of the seeds after a period of dormancy, based on the emergence of radicle) was recorded daily for 10 days. The G_{50} , which is defined as time (in days) required for

germination of 50% of the seeds, was calculated according to [19]; G_{50} was determined after daily monitoring from the point-slope formula, Formula (1):

$$y - y_1 = m(x - x_1) \quad (1)$$

where y = day when 50% of seeds germinated; y_1 = day before y ; x = total number of germinated seeds at day of y ; x_1 = total number of germinated seeds at day of y_1 . The slope m represents G_{50} .

For morphological analysis, seedlings of ten days' growth were harvested. The roots and shoots were separated, and their lengths were measured by a regular caliper. The fresh roots and shoots were dried in an oven at 70 °C until reaching constant weight [33]. The dry biomass and total water content of constituent barley parts were measured (TWC calculation: fresh constituent barley part mass—dry constituent barley part mass/fresh constituent barley part mass $\times$ 100%) according to Cappelletti [34].

2.3.2. Electrical Conductivity (EC) and Salinity Contents of the Soil

Soil samples of 100 g were air-dried, sieved in a 1 mm sieve, and extracted by 500 mL of CO₂-free distilled water (5:1; distilled water: soil). The extraction was performed on a hotplate with the aid of air-pump filtration and a Buchner funnel. Then, 25 mL of the sample solution was used to determine the electrical conductivity (μ S) and total soluble salt concentration according to Bado et al. [10].

2.3.3. Statistical Analysis

The data analysis for this paper was conducted using the Real Statistics Resource Pack software (Release 8.5), Copyright (2013–2023), Charles Zaiontz (www.real-statistics.com, accessed last 26 February 2023). Abbreviations used: analysis of variance, ANOVA; standard deviation, SD; standard error of the mean, SEM; compact letter display, CDL. Differences in means of anatomical and morphological variables between cultivars under the salinity treatments were assessed by one-way ANOVA due to its robustness with unequal sample sizes, followed by Tukey–Kramer test with Bonferroni correction for post-hoc comparisons and classical Cohen's D for effect size estimation. Since comparisons between salinity treatment levels were, with 2 exceptions, all significant, in this paper, we focus on reporting differences between the cultivars within each treatment level.

3. Results

3.1. Effect of Salinity Stress on Seed Germination of Barley

Salinity stress delayed seed germination, illustrated by G_{50} (see Table 1), and reduced germination percentage of all cultivars (see Figure 1). The results reveal that ACSAD 1732 proved to be the most resistant cultivar during germination and reached $80 \pm 1\%$ seed germination at 175 mM NaCl. ACSAD 1744, ACSAD 1417, and Icarda 1 were at the second order for salinity stress resilience, since they reached lower germination percentages than ACSAD 1732 under the effect of 175 mM NaCl (Figure 1).

The most sensitive cultivar was Icarda 15, which possessed the lowest percentage of germinated seeds at all tested salt concentrations. Rihan, Baladi, and Improved Baladi cultivars revealed a high germination percentage at 120 mM NaCl ($67\% \pm 1.5$; $70\% \pm 1$; $77\% \pm 2.08$, respectively) and a dramatical reduction in seed germination percentage ($40\% \pm 1$; $37\% \pm 1.15$; and $30\% \pm 1.53$, respectively) only at the highest concentration of 175 mM NaCl. The remaining cultivars such as ACSAD 176 and ACSAD 68 showed stronger decline over increasing salinity levels and can be considered moderately to weakly resilient.

Table 1. The average time [d] of G_{50} for the ten certified Palestinian barley cultivars grown under salinity stress followed by SEM where applicable, calculated from the point-slope formula (see Formula (1)).

	Baladi	Rihan	ACSAD 176	Icarda 1	ACSAD 1417	Improved Baladi	ACSAD 1744	ACSAD 68	ACSAD 1732	Icarda 15
0 mM NaCl	3.0 ± 0.11	1.1 ± 0.11	1.9 ± 0.02	1.5 ± 0.03	1.5 ± 0	0.2 ± 0.72	1.5 ± 0	1.8 ± 0	1.3 ± 0	N/A
50 mM NaCl	2.3 ± 0.08	1.2 ± 0.05	2.3 ± 0.13	1.6 ± 0.09	1.8 ± 0.03	0.2	1.1 ± 0	4.1 ± 0.13	1.5 ± 0.12	N/A
85 mM NaCl	3.4 ± 0.31	1.3 ± 0.07	N/A	1.6 ± 0.05	1.6 ± 0.03	0.3	1.6 ± 0.01	2.2 ± 0.13	1.8 ± 0	N/A
120 mM NaCl	1.6 ± 0.49	2.6 ± 0.06	N/A	1.8 ± 0.08	1.8 ± 0.03	2.2	2.0 ± 0.06	4.4	1.2 ± 0.01	N/A
175 mM NaCl	N/A	N/A	N/A	2.1	4.4 ± 0.83	N/A	3.9 ± 0.54	N/A	1.8 ± 0.05	N/A

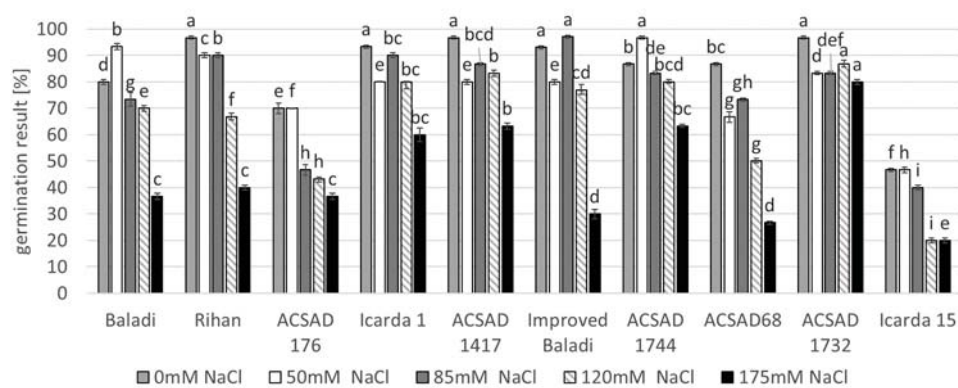


Figure 1. Seed germination mean [%] ± SEM of Palestinian barley cultivars under different salt concentrations. Comparisons between cultivars within each treatment (same-colored bars) visualized by compact letter display (CDL) visualized by letters a,b,c,d; shared letters between plotted result bars of one treatment mean no significant differences between those results at the level of $p < 0.05$.

The Baladi cultivar revealed a higher germination percentage at 50 mM NaCl than its control. In addition, Icarda 1, ACSAD 1417, and ACSAD 68 revealed a higher seed germination percentage in 85 mM NaCl than in 50 mM NaCl but less than in control, while ACSAD 1732 possessed a slightly higher percentage at 120 mM NaCl than in 85 mM NaCl.

The G_{50} is illustrated in Table 1. In this context, the best cultivars were ACSAD 1732 and Icarda 1, which possessed the lowest G_{50} . The G_{50} of ACSAD 1732 was 1.3 days in control and 1.87 days in 175 mM NaCl. Thus, we observed narrow fluctuations under high salt concentration. Icarda 1 behaved in a similar way under the same salt concentrations. ACSAD 1744, ACSAD 1417, and Rihan cultivars possessed moderate values of G_{50} . Baladi, ACSAD 68, ACSAD 176, and Icarda 15 were among the least efficient, with the highest or non-computable values of G_{50} at 120 and 175 mM NaCl.

Regarding the morphological data collected at day 10 after sowing and the early growth stage, the total seedling height of all cultivars increased with time, but growth decreased inversely with salinity (see Figures 2–4). Increasing salinity caused a reduction in plant height, stem length, and root length. However, no significant effects on the number of the fibrous roots under the effect of salinity stress were observed. ACSAD 1417 showed the highest length of shoot system (2.5 cm) at 175 mM NaCl, followed by Icarda 1 (1.7 cm). However, Icarda 1 showed better growth at all other salt concentrations (see Figure 3). Moreover, Rihan and Improved Baladi cultivars did not grow at all at a salinity level of 175 mM NaCl.



Figure 2. Photograph of 10-day-old seedlings of ACSAD 1732 illustrate its morphology under different NaCl concentrations. Scale bar = 1 cm.

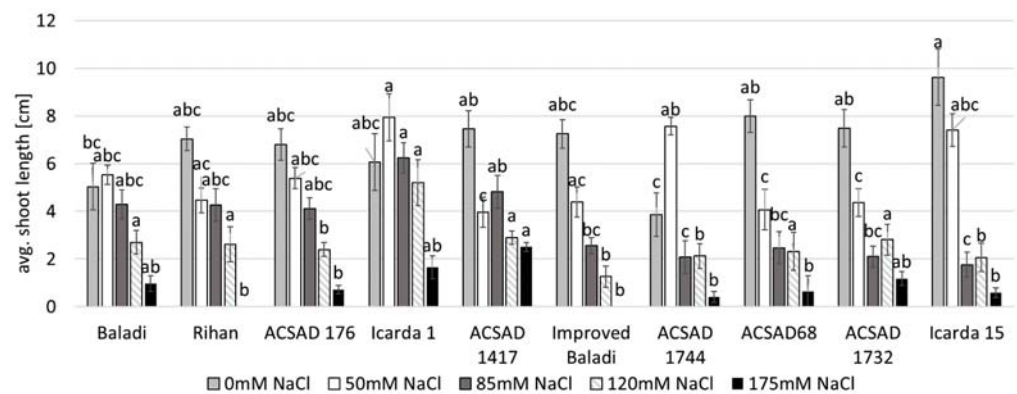


Figure 3. Average shoot system length [cm] $\pm$ SEM for the ten certified Palestinian barley cultivars grown under salinity stress during early growth stage (10 days from seed germination); comparisons between cultivars within each treatment (same-colored bars) visualized by compact letter display (CDL) visualized by letters a,b,c,d; shared letters between plotted result bars of one treatment mean no significant differences between those results at the level of $p < 0.05$.

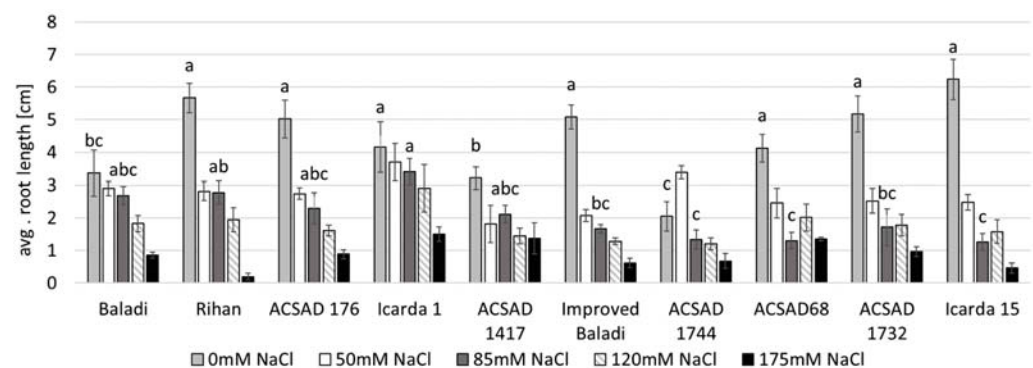


Figure 4. The average root-system length [cm] $\pm$ SEM for the ten certified Palestinian barley cultivars grown under salinity stress during early growth stage (10 days from seed germination); comparisons between cultivars within each treatment (same-colored bars) visualized by compact letter display (CDL) visualized by letters a,b,c,d; shared letters between plotted result bars of one treatment mean no significant differences between those results at the level of $p < 0.05$.

The average root lengths of the barley cultivars showed significant reduction under the effect of salinity stress in comparison to the 0 mM controls (see Figure 4). Icarda 1 and ACSAD1417 cultivars revealed the least fluctuation in root-system length and still possessed the longest roots of 1.5 cm and 1.4 cm, respectively, at 175 mM NaCl. Meanwhile, Rihan, Improved Baladi, and Icarda 15 possessed the lowest root-system length at higher NaCl concentrations.

3.2. Effect of Salinity Stress on Water Content and Biomass

Water content and biomass are parameters that indicate productive plant growth and biochemical allocation in plant tissues. The results revealed that the shoot water content percentage was affected by salt stress (see Figure 5A). The total water content was semi-constant for most cultivars. However, it increased significantly in ACSAD 1744, ACSAD 68, and ACSAD 1732, mainly at 175 mM NaCl. The roots also expressed semi-constant total water content for most cultivars, but it increased significantly in ACSAD 1732, ACSAD 1417, and Icarda 1 (see Figure 5B). In addition, ACSAD 176, ACSAD 1417, ACSAD 1744, ACSAD 68, and Icarda 15 possessed higher water content at 175 mM NaCl than in their controls (see Figure 5B).

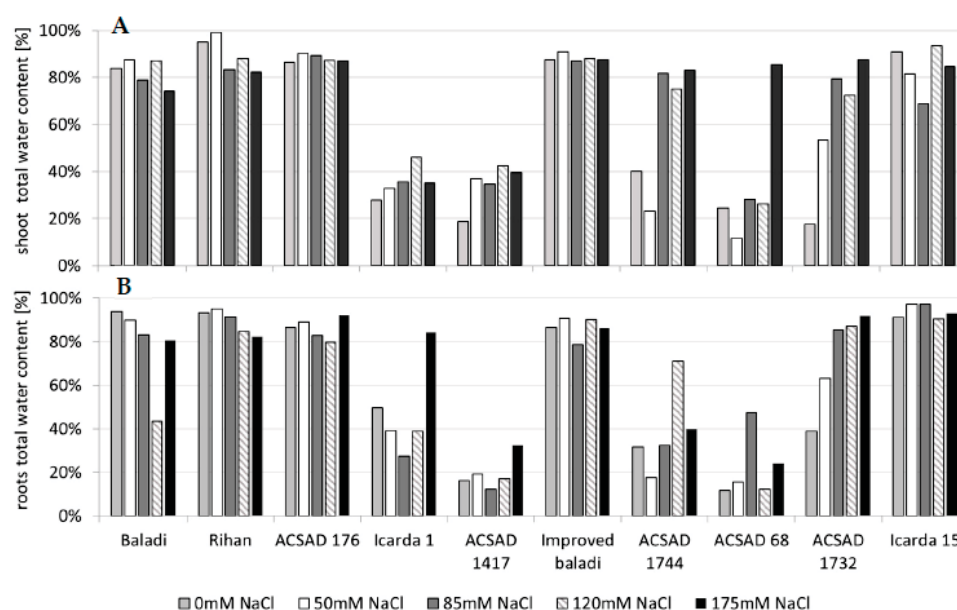


Figure 5. The average total water content [%] of the shoot system (A) and of the root system (B) for the ten certified Palestinian barley cultivars grown under salinity stress during early growth stage (10 days from seed germination). Plant parts were weighed in bulk for higher precision to report per total biomass, measured according to Cappelletti [34].

The effect of salinity stress on biomass of barley during the early growth stage was evident; it was reflected in the calculations of water content, where dry weight percentage and water content percentage form 100% (see Figure 5). Shoot dry weight/water content was semi-constant for most cultivars except for ACSAD 1744, ACSAD 68, and ACSAD 1732, where it increased with salinity level. Root water content was also semi-constant for most cultivars except for ACSAD 1732, and comparably much lower for Icarda 1, ACSAD 1417, ACSAD 1744, and ACSAD 68.

3.3. Electrical Conductivity for Quarry Substrate

Electrical conductivity is a parameter that relates to the ions in a sample with a direct relation between them. The electrical conductivity was measured for substrate samples collected from quarry land at different depths and distance in Hebron governorate (see Table 2). The results revealed that Seir Jamal Nassar samples possessed the highest EC

values, while EC from samples collected from a quarry of Taffouh were lowest. Overall, the Bani Naim region possessed the high EC values, and the other regions were variable in EC values. For those regions, EC decreased toward the core of the stones in the samples that were directly taken from the cutting machines (samples number 2, 3, 7, 9, and 16). EC of the soil near quarries was at times higher than in the quarries themselves. There was no significant difference in the EC values at different temperatures. TSS was calculated from EC values and in moderate range. Overall, samplings showed less pronounced salinity/soluble salt concentrations than expected.

Table 2. Electrical conductivity for sixteen soil samples collected based on the quadrat method from quarries at different depths and distances located in the Hebron governorate.

Soil Sample	Region in Hebron Governorate	Measured Temperature (°C)	Measured Conductivity of Soil/Water Mix (5:1) [$\mu\text{S}/\text{cm}$]	EC _t Calculated for Soil [$\mu\text{S}/\text{cm}$]	EC ₂₅ Calculated for 25 °C [dS m^{-1}]	TSS–Total Soluble Salts (ppm)
1. Red soil, middle of stones, north-west Hebron	Bani Naim 31°30′57.1″ N 35°10′58.5″ E	23.1	702	667	6.923×10^{-4}	0.443
2. Bani Naim Ashour 1	Bani Naim	24	344	309	3.152×10^{-4}	0.097
3. Bani Naim 1, center of quarry	Bani Naim	23.6	417	382	3.927×10^{-4}	0.150
4. Bani Naim Ashour 2	Bani Naim	22.8	493	458	4.782×10^{-4}	0.219
5. Bani Naim sample 3	Bani Naim	23.8	550	515	5.274×10^{-4}	0.272
6. Side of quarry, 2 cm depth	AlShyoukh	24	348	313	3.193×10^{-4}	0.099
7. Light soil, 15 cm depth	AlShyoukh	25.8	219	184	1.81×10^{-4}	0.0333
8. Red stones, middle of quarry	AlShyoukh	26.4	546	511	4.967×10^{-4}	0.254
9. Light soil under the cutting machine	AlShyoukh	24.8	403	368	3.695×10^{-4}	0.140
10. Abu Bassam, white stone	Seir 30°11′10.2″ N 35°19′05.7″ E	26.2	356	330	3.221×10^{-4}	0.106
11. Seir Jamal Nassar 220 cm depth	Seir	23.4	914	879	9.071×10^{-4}	0.797
12. White, soft road of quarry	Seir	22.6	278	243	2.547×10^{-4}	0.0619
13. Light red, Jamal Nassar, 15 cm above stone	Seir	26.1	543	508	4.968×10^{-4}	0.252
14. Red stone, Jamal Nassar, from surface of quarry	Seir	25.9	839	804	7.895×10^{-4}	0.635
15. Quarry road, Taffouh	Taffouh 31°32′20.7″ N 35°03′09.5″ E	30	461	448.6	4.037×10^{-4}	0.181
16. Quarry, Taffouh	Taffouh	30.8	295	282.6	2.498×10^{-4}	0.071

4. Discussion

Seeds are dormant embryos, adapted to endure harsh, unsuitable environmental conditions that endanger the vegetative structures of plants and will only germinate well under favorable conditions. The germination event starts by imbibition of water, which activates the hydrolytic enzymes that break down the stored nutrients, which are used for the development of new below- and aboveground tissue [19]. These processes are coordinated and controlled by several hormones, brassinosteroids, gibberellins, abscisic acid, and ethylene, and they can be hampered by excessive salinity [35–37]. Salinity stress is one of the major abiotic stresses limiting crop production in arid and semi-arid regions [38]

as well as the quarries and their landfills. According to our results, salinity stress caused a delay in the seed germination, especially at 120 and 175 mM NaCl. This coincides with observations in sunflower [39] and Palestinian tomato that showed deep decreasing rates at the 100 mM level [19].

The differences in G_{50} values (germination rate) under salt stress conditions exhibited by the cultivars (Table 1) could be interpreted as a consequence of differences in ion plasma lamella extrusion pumps. Therefore, the ACSAD 1732 cultivar may harbor a larger number of such transporters than the other cultivars. In addition, it may also have more efficient mechanisms for salt compartmentalization into the vacuoles. The reduced number of toxic ions due to the action of these mechanisms of ion translocation in turn exerts less toxic effect on the metabolic enzymes, thereby allowing seed germination processes to occur [17,19,21,40].

In the presented results, the early growth stage showed a decline in both shoot and root systems with increased salinity. Comparable results were reported for barley genotypes in Iran [41]. A high sodium accumulation in the cells causing osmotic imbalance and ion toxicity has been proposed as underlying cause [42,43] due to a shortage in water supply. The plant will compromise under such conditions by suppressing growth hormones [23]. Stomata close as a defense mechanism against salinity stress to prevent the loss of their limited amount of water [44]. This leads to photosynthesis reduction because of the reduction in the CO_2 supply to photosynthetic mesophyll cells [19] and subsequently results in overall hampered performance.

Our findings indicate that the ACSAD 1732 and Icarda 1 cultivars show less reduction in root and shoot sizes compared to other cultivars in 120 and 175 mM NaCl (Tables 1 and 2). This is probably due to the lesser toxic effect imposed by ions in these cultivars due to their extrusion by active transport in the roots. The reduced root volume and/or root-to-shoot ratio may improve salinity tolerance by restricting the flux of toxic ions to the shoot, leading to a delay in the onset of the tolerance [19,45]. In addition, salinity stress negatively affects the root numbers of barley; i.e., the root number decreases with increased salinity stress. This occurs in order to reduce the saltwater uptake by roots, which results in a reduction of the efflux of toxic ions to the tissues in the shoot system, mainly the leaves.

Salinity stress affects the total water content percentage and dry weight percentage of barley. Our results revealed that the root and shoot development of all tested cultivars decreased due to salinity stress in comparison to corresponding controls. Such decrease in barley cultivar physiological features, e.g., gas-exchange-related traits as well as impacts on root and shoot biomass, is well-documented in barley genotypes in Iran and elsewhere [41]. Barley cultivars such as ACSAD 1732 and Icarda 1, with improved resistance during seed germination, also possess a higher percentage of total water content in their shoot and root system when they grow at higher levels of salinity than the respective controls. Other cultivars such as ACSAD 1417, ACSAD 1744, and ACSAD 68, try to resist the high salinity pressure through accumulation of water in their shoot and root system during the early growth stage. In general, the accumulation of solutes in the cytoplasm of the plant cell will increase its osmotic pressure. Thus, a plant increases its affinity to take up and accumulate water in the cell central vacuole, compelled by the demand for biological activity. This also leads to succulence in plant tissues, which is an important adaptive strategy to accumulate excessive salt and conserve water in saline-growing plants (i.e., halophytes). Succulence occurs also in glycophytes in order to overcome such uncomfortable osmotic stress [19,27,46].

Based on their response to high levels of salinity, plants can be grouped into two broad categories. First, halophytes are plants that grow and complete their life cycle in environments of high salt concentration [47–49]. Second, glycophytes ('sweet plants') are plants that are sensitive to salt and cannot tolerate salt to the same level as halophytes [50,51]. Crop plants vary in their sensitivity to salt levels in soil. For example, corn, bean, lettuce, onion, and citrus plants are considered highly sensitive to salt. In contrast, sugar beet and date palm trees are highly tolerant. Crop plants like cotton, barley, and some tomato

cultivars are considered moderately tolerant plants. However, the present study emphasizes that some Palestinian barley cultivars might be considered halophytes, since they can start growth under salt concentration of 175 mM NaCl. These cultivars include ACSAD 1732, ACSAD 1744, ACSAD 1417, and Icarda 1. Moreover, the biochemical, physiological, morphological features of the adaptation mechanisms of other crop plants, as well as barley cultivars, against salinity stress are genotype-specific [1–6,9]. The implications for the further life cycle need to be assessed in detail for the most promising barley cultivars identified here to ensure productivity until harvest.

Soil salt content is critical for plants through their life span. The characteristics of saline soil areas include micro-topography, complicated soil types, and significant differences in local soil conditions and depths based on the plant species root growth [10]. In the present study, soil samples were collected from quarries at different depths and different distances (see Table 2), which corresponded to a basic knowledge of salt distribution [10]. Electrical conductivity in soil is a function of the concentration of charged ions in the soil solution, which are assessed by conducted current. The soil EC values for most samples in this study were close to each other, because all the samples were taken from quarry lands with relatively similar conditions. However, the EC value for each sample was below the normal range of 1100–5700 μScm^{-1} ($11\text{--}57 \times 10^{-4} \text{ dS m}^{-1}$) of conductivity [10]. This result might contraindicate the hypothesis that quarry land always suffers from salinity stress.

Many factors besides salt content can also affect the EC. Substrates with continuous pore spaces have a higher conductivity due to the continuous water column in the water-filled pores. Therefore, soils with high clay content usually conduct better than sandy soils. An increased water content with more dissolved electrolytes and high cation exchange capacity also increases EC; with increasing depth and decreasing temperature, EC decreases too [52]. The optimal EC levels in the soil for plant growth are 110–570 milliSiemens per meter (mS m^{-1}) [53]. EC is an important indicator for nutrient availability in soil, while, e.g., sandy soils express low EC due to low organic matter and nutrient content, as opposed to higher quality agricultural substrates with high clay content [54]. In this context, quarry substrates are not highly affected by salts but more by seasonal and climatic conditions. This is obvious, since the samples collected directly from the cutting machine had low amounts of solutes and EC. However, the samples collected from the road and/or periphery of the quarries had higher EC and TSS, since their dust and soil mixed with the topsoil surface via vehicles, animals, and winds. Moreover, quarry substrates tend to be sandy rather than high in clay, and dry rather than moist. Therefore, quarry soils showed lower EC values than expected. Further characterization of the local quarry residues in higher spatial resolution is necessary on the large expansions of former quarry lands to decide on the best approach in each case. One of the most common abiotic stresses aside from salinity is drought, affecting large marginal areas of low rainfall that depend on rain-fed water in Palestine. Locally adapted cultivars (landraces), as screened here, would be a valuable solution, since such landraces possess fitting genetic material for required resilience not only against salinity, but other local challenges. Further clarification of the underlying mechanistic will facilitate usage of more marginal areas in the future [1,28].

5. Conclusions

We highly recommend ACSAD1732 cultivation in areas of low precipitation and high soil salt concentration that is at or below 175 mM NaCl. We also recommend the cultivation of the identified resilient barley cultivars in quarries, their landfill, and nearby areas as a means of rehabilitation. Further research is necessary to investigate the homogeneity, salinity, and alkalinity of quarry land substrates and the possible consequences on crop growth and productivity. The capacity and key adaptation features of such resilient cultivars must also be assessed to successfully germinate and grow them in such poor substrates, since the demand for the agricultural use of such areas will increase.

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Article

Effect of an Organic Fertilizer of *Ganoderma lucidum* Residue on the Physical and Chemical Properties and Microbial Communities of Saline Alkaline Soil

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Abstract: Saline-alkali land is the main reserve soil resource. The amount of arable farmland soil can be increased through improvement and utilization of saline-alkali land. Bio-organic fertilizer is an effective saline-alkali soil conditioner, but there are few studies on the improvement of saline-alkali soil with traditional Chinese medicine residues (TCMRs). In this study, an organic fertilizer made from *Ganoderma lucidum* residue (GLR) was mixed with saline-alkali soil at different proportions; physicochemical properties, enzyme activity, and microbial community characteristics of the soil were investigated. The results showed that the soil pH, as well as bulk density and electrical conductivity were significantly reduced, while the soil moisture content and porosity were significantly increased after the GLR organic fertilizer incorporation. Soil invertase and soil amylase activities significantly increased, as well as the diversity and richness of the soil microbial community structure. The abundance of the dominant phyla, Bacteroidota, Actinobacteriota, Chloroflexi, Firmicutes, and Basidiomycota, increased, while the abundance of the dominant Proteobacteria and Ascomycota phyla decreased. The best improvement effect is obtained when the application ratio of GLR organic fertilizer is 25%. The findings showed that TCMRs have positive application prospects in saline-alkali soil improvement.

Keywords: saline-alkali soil; high-throughput sequencing; soil physical and chemical properties; soil enzyme activity; bacterial community

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1. Introduction

Improvements of saline-alkali soil are aimed at increasing the area of arable land and increasing crop yield [1]. However, the existing methods of saline-alkali land treatment have the problem of “treating the symptoms but not its cause”. This will lead to the alternation of “desalting” and “returning salt”, which will cause much interference with the farmland soil ecology (microbial community) [2]. Advancement of science and technology has aided our understanding of saline-alkali soil remediation. At the same time, biological soil improvement methods, such as the use of organic fertilizers, have received widespread attention [3]. Bio-organic fertilizers (microbial organic fertilizers) have the advantages of traditional organic fertilizers and are enriched with added bacterial agents. As such, these soil amendments contain a large amount of organic matter together with beneficial soil microorganisms. Traditional Chinese medicine residues (TCMRs) are rich in cellulose, polysaccharide, and soil nutrients, such as organic carbon, nitrogen, and phosphorus [4,5]. They can be used as raw material for producing bio-organic fertilizer. The bacteria and toxic substances contained in fresh residue can be completely eliminated by high-temperature aerobic fermentation. In this way, the harmless treatment of TCMRs can be realized [6].

Studies have shown that biosolids play a positive role in improving soil properties, promoting the healthy growth of plants, and increasing the diversity of beneficial microorganisms [7,8]. Some studies have shown that TCMRs have beneficial effects on saline-alkali soil improvement. Through the application of Mailuoning TCMRs in combination with inorganic fertilizer and biological bacterial fertilizer, the soil enzyme activity was improved, the formation of granular structure in raw soil was promoted, and the raw soil was rapidly matured. The effect is better than that of chicken manure [9]. Bai et al. [10] applied Chinese medicinal residues, such as *Sophora japonica*, to the arid and abandoned saline-alkali soil in Ningxia, and found that the numbers of bacteria, fungi, and actinomycetes in the saline-alkali soil after the residue application were significantly higher than those in the control. The activity of alkaline phosphatase and catalase was significantly promoted. Bai et al. [11] conducted a black soil fertilizer application experiment and found that the application of organic fertilizer increased the microbial biomass carbon/nitrogen and the number of fungi and bacteria. Li et al. [12] studied the relationship between bio-organic fertilizers and nutrients in saline-alkali soil and rhizosphere microorganisms. The results showed that the content of available phosphorus and potassium in the saline-alkali soil after the fertilization treatment increased to varying degrees, and the microbial biomass of the plant roots increased. Ma et al. [13] found that organic fertilizer from TCMRs improved the soil fertility, especially in terms of organic matter, nitrogen, and phosphorus. The application rates (0.2–0.6%) were beneficial for improving the physiological parameters of maize seedlings. However, there is very limited research on the improvement of saline-alkali soil by organic fertilizers derived from GLR.

This study researched the use of GLR to (i) explore the effect of the organic fertilizer of GLR on the physical and chemical properties, enzyme activity and microbial community structure of saline-alkali soil, (ii) provide a theoretical basis for the improvement of saline-alkali soil with organic fertilizers from TCMRs, and (iii) open up a new way for the resource utilization of TCMRs. The results of this experiment can provide reference for the development and utilization of saline-alkali soil in arid and semi-arid areas, and the high-value utilization of organic solid wastes, such as TCMRs.

2. Materials and Methods

2.1. Experimental Materials

GLR: GLR was provided by the Baotou Traditional Chinese Medicine Co., Ltd. (Baotou, China).

GLR organic fertilizer: After the GLR was naturally dried in the shade and pulverized, the carbon-nitrogen ratio was 35/1, and the water content was adjusted to 65%. The nano-compost covering film was naturally fermented at room temperature for 42 days. The physical and chemical parameters of compost products were determined in the Environmental Biotechnology Laboratory of Inner Mongolia University of Science and Technology. Total humus (HS) was 37.56%, organic matter content was 79.84%, pH was 4.79, moisture content was 46.12%, and electrical conductance was 1.25 $\mu\text{S}/\text{cm}$.

Saline-alkali soil: Soil samples were collected from Dabusutai Village in the town of Haya Hutong, Jiuyuan District, Baotou City, Inner Mongolia (109°26′22.22″ E–109°26′24.78″ E, 40°31′57.33″ N–40°31′58.3″ N). Soil samples from the 0–20 cm layer of treated sample plots were dried in the shade and passed through a 3 mm sieve for analysis.

2.2. Experimental Method

2.2.1. Experimental Design

The experiment of improving saline-alkali soil with GLR organic fertilizer was carried out by indoor pot planting. A total of 6 treatments were set up by adding a GLR organic fertilizer in the following proportions: 0% (FSF), 8.3% (FSE), 10% (FSD), 12.5% (FSC), 16.7% (FSB), and 25% (FSA). Each treatment was repeated 5 times for a total of 30 pots. The plastic flowerpots were 22 cm in diameter and 28 cm in height.

2.2.2. Determination of Soil Physical and Chemical Properties

Soil physical and chemical properties were determined according to Lu (2000) [14]. The main measured indicators were soil bulk density, soil particle density, soil porosity, moisture content, pH, electrical conductance, organic matter content, effective phosphorus content, ammonium nitrogen, hydrolyzed nitrogen. The $\text{pH}_{(1:5)}$ value was determined using a calibrated pH meter (PHSJ-4F, Leici, Shanghai, China). Electrical conductance was determined using a conductivity meter (DDSJ-318T, Leici, Shanghai, China).

2.2.3. Determination of Soil Enzyme Activity

The 3,5-dinitrosalicylic acid colorimetric method was used to determine invertase activity and amylase activity [15]. The sodium phenate-sodium hypochlorite titration colorimetric method was used to determine urease activity [16]. Catalase activity was determined by potassium permanganate colorimetric titration [17]. Acid phosphomonoesterase activity was determined by the disodium phenylphosphate colorimetric method [18].

2.2.4. Determination of Soil Microbial Community Structure

Microbial community analysis was performed by the Shanghai Meiji Biomedical Technology Co., Ltd. (Shanghai, China). Sequencing of the V4–V5 region of the 16S rRNA gene of bacteria and ITS1 + ITS2 region of fungi was done on an Illumina MiSeq platform. Corresponding regions of primers, 16SV4 + V5 region primers (515F and 806R), were used to identify the bacterial diversity, and ITS1 + ITS2 region primers (ITS5-1737F and ITS2-2043R) were used to identify fungal diversity.

2.2.5. Data Analysis

Qiime1.9.1 sequencing was used to analyze microbial-community-related indicators. The experimental data were processed and analyzed with Excel and SPSS Statistics 23.0 (IBM, Armonk, New York, NY, USA). The parameters between different treatments were analyzed using a one-way analysis of variance (ANOVA) with Tukey's post hoc test at the level of $p < 0.05$. The relationships between the main phylum of the fungal and bacterial communities and environmental factors were analyzed by redundancy analysis (RDA).

3. Results and Discussion

3.1. Effects of the GLR Organic Fertilizer on the Physicochemical Properties and Enzyme Activity of Saline-Alkali Soil

3.1.1. Changes in Physicochemical Properties of Saline-Alkali Soil

Soil bulk density, porosity, and particle density are important indicators of soil physical properties. Their values can better reflect soil texture, permeability, water-holding capacity, and erosion resistance [10]. Table 1A shows that the addition of the GLR organic fertilizer significantly increased the water content and porosity of the saline-alkali soil and decreased the soil bulk density and soil particle density. Among them, the water content and porosity of the FSA treatment were higher than those of the other treatments, which were significantly higher than those of the FSF treatment. The soil particle density and bulk density were significantly lower than those of the FSF treatment.

The pH value can reflect the pH value of the soil, and the electrical conductance usually reflects the soluble salt content of the soil. Organic matter is also the main source of soil nutrients [19]. Table 1B shows that the addition of the GLR organic fertilizer significantly increased the contents of available phosphorus, alkali-hydrolysable nitrogen, organic matter, and ammonium nitrogen in the saline-alkali soil and reduced the pH value and electrical conductance of the saline-alkali soil. Among them, the effect of FSA and FSB treatment is the most significant.

Table 1. Physical (A) and chemical (B) properties of saline-alkali soil improved by adding a GLR organic fertilizer in different proportions. For each row, the means $\pm$ SD with different letters were significantly different between treatments ($p < 0.05$, using the HSD test).

(A)	Sample					
	FSA (25%)	FSB (16.7%)	FSC (12.5%)	FSD (10%)	FSE (8%)	FSF (0%)
ρ_b (g/cm ³)	0.449 $\pm$ 0.006 d	0.579 $\pm$ 0.005 cd	0.582 $\pm$ 0.012 cd	0.736 $\pm$ 0.017 bc	0.891 $\pm$ 0.013 b	1.434 $\pm$ 0.154 a
W (%)	25.164 $\pm$ 1.834 a	20.772 $\pm$ 0.401 ab	18.140 $\pm$ 0.397 bc	17.011 $\pm$ 0.571 c	11.667 $\pm$ 0.457 d	6.464 $\pm$ 0.057 e
ρ_s (g/cm ³)	1.813 $\pm$ 0.779 c	2.022 $\pm$ 0.082 bc	2.085 $\pm$ 0.060 b	2.452 $\pm$ 0.054 a	2.539 $\pm$ 0.042 a	2.562 $\pm$ 0.054 a
f	0.751 $\pm$ 0.014 a	0.713 $\pm$ 0.011 ab	0.720 $\pm$ 0.011 ab	0.699 $\pm$ 0.007 ab	0.648 $\pm$ 0.007 b	0.440 $\pm$ 0.058 c
(B)						
	FSA (25%)	FSB (16.7%)	FSC (12.5%)	FSD (10%)	FSE (8%)	FSF (0%)
P (mg/kg)	36.86 $\pm$ 0.04 a	28.78 $\pm$ 0.04 b	21.51 $\pm$ 0.03 c	19.78 $\pm$ 0.03 d	18.38 $\pm$ 0.03 e	15.15 $\pm$ 0.05 f
AHN (g/kg)	11.70 $\pm$ 0.62 a	7.90 $\pm$ 0.23 b	7.466 $\pm$ 0.84 b	6.5 $\pm$ 0.84 bc	4.9 $\pm$ 0.70 c	1.63 $\pm$ 0.47 d
C (g/kg)	43.24 $\pm$ 0.41 a	39.26 $\pm$ 0.37 b	28.43 $\pm$ 0.47 c	26.68 $\pm$ 0.60 d	13.79 $\pm$ 1.76 e	5.42 $\pm$ 0.37 f
AN (mg/kg)	10.66 $\pm$ 0.05 a	10.08 $\pm$ 0.08 a	8.82 $\pm$ 0.31 b	6.99 $\pm$ 0.27 c	6.93 $\pm$ 0.38 c	4.86 $\pm$ 0.08 d
pH	7.51 $\pm$ 0.02 f	7.78 $\pm$ 0.02 e	7.86 $\pm$ 0.03 d	8.11 $\pm$ 0.02 c	8.23 $\pm$ 0.01 b	8.98 $\pm$ 0.02 a
EC (mS/cm)	6.55 $\pm$ 0.02 d	7.37 $\pm$ 0.07 c	7.38 $\pm$ 0.01 c	7.5 $\pm$ 0.03 bc	7.52 $\pm$ 0.02 b	7.68 $\pm$ 0.05 a

Note: ρ_b —bulk density; ρ_s —soil particle density; W —moisture content; f —porosity; P—available phosphorous; AHN—alkali-hydrolysable nitrogen; C—organic matter; AN—ammonium nitrogen; EC—electrical conductance. FSA, FSB, FSC, FSD, FSE, and FSF represent saline-alkali soil samples with GLR organic fertilizer addition ratio of 25%, 16.7%, 12.5%, 10%, 8.3%, and 0%, respectively.

After application of the GLR organic fertilizer on arid saline-alkali land, the physical and chemical properties of the soil significantly improved. Compared with the FSF treatment, the bulk density, electrical conductivity, and pH of the saline-alkali soil treated with the GLR organic fertilizer were significantly reduced, the soil moisture content and porosity significantly increased. The FSA treatment showed the best improvement effect. The reason may be that after the addition of the GLR organic fertilizer, the structure of the soil improved. Soil porosity, moisture, and permeability increased, and salt leaching was promoted, which is beneficial for the reduction of soil salinity. On the other hand, the reason may be that the organic acid produced after the decomposition of GLR organic fertilizer can reduce the soil pH, buffer the saline-alkali soil, and finally improve soil structure and reduce soil salinity.

3.1.2. Changes of Enzyme Activities in Saline-Alkali Soil

Soil enzymes are sensitive parameters for evaluating soil remediation effects. The enzyme activity is related to soil nutrients, soil types, vegetation characteristics, soil microorganisms, soil moisture, temperature, bulk density, and the properties of the enzymes themselves [20]. As shown in Table 2, the addition of the GLR organic fertilizer significantly increased the activity of invertase, amylase, urease, catalase, and acid phosphomonoesterase. The soil enzyme activity in the FSA and FAB treatments was the highest.

Table 2. Enzyme activity of saline-alkali soil improved by addition of different amounts of GLR organic fertilizer. For each row, the means $\pm$ SD with different letters were significantly different between treatments ($p < 0.05$, using the HSD test).

Sample	FSA (25%)	FSB (16.7%)	FSC (12.5%)	FSD (10%)	FSE (8%)	FSF (0%)
INV (mg/(g·24 h))	8.71 $\pm$ 0.11 a	6.69 $\pm$ 0.21 b	3.56 $\pm$ 0.15 c	3.33 $\pm$ 0.11 c	2.62 $\pm$ 0.16 d	0.51 $\pm$ 0.13 e
AMS (mg/(g·24 h))	7.44 $\pm$ 0.43 a	7.38 $\pm$ 0.47 a	2.09 $\pm$ 0.58 b	1.61 $\pm$ 0.51 bc	1.39 $\pm$ 0.54 bc	0.4 $\pm$ 0.05 c
URE (mg/(g·24 h))	26.32 $\pm$ 0.02 bc	26.69 $\pm$ 0.24 ab	26.63 $\pm$ 0.04 ab	26.69 $\pm$ 0.05 ab	26.82 $\pm$ 0.07 a	26.23 $\pm$ 0.01 c
CAT (mg/(g·24 h))	35.05 $\pm$ 1.79 a	35.86 $\pm$ 2.22 a	34.48 $\pm$ 0.18 a	32.95 $\pm$ 1.45 a	25.61 $\pm$ 1.35 b	18.21 $\pm$ 2.15 c
ACP (mg/(g·24 h))	32.84 $\pm$ 0.03 a	32.74 $\pm$ 0.06 a	32.75 $\pm$ 0.07 a	32.75 $\pm$ 0.07 a	32.62 $\pm$ 0.05 a	32.13 $\pm$ 0.12 b

Note: INV—invertase activity; URE—urease activity; CAT—catalase activity; ACP—acid phosphomonoesterase activity; AMS—amylase activity.

3.1.3. Correlation between the Amount of the GLR Organic Fertilizer and Soil Physicochemical Properties and Enzyme Activity

Soil organic matter is a comprehensive indicator reflecting soil fertility and quality, and is an especially important source of N and P elements [21]. As further indicated by Figure 1A, the addition of the GLR organic fertilizer was significantly related to soil organic matter. Available phosphorus, ammonium nitrogen, and alkali-hydrolysable nitrogen were all significantly positively correlated, indicating that the organic fertilizer of GLR significantly increased the content of soil nutrient elements, and the effect of the FSA treatment (addition amount of 25%) was the most obvious. This was consistent with the findings of other researchers. For example, Zhang et al. [22] found that the application of biochar and organic fertilizer could effectively improve the physical structure of the saline-alkali soil, and the higher the amount of fertilizer applied, the more it is conducive to the storage of carbon and nitrogen. Compound fertilizers and bio-organic fertilizers could significantly increase the content of available phosphorus, available potassium, and alkali-hydrolyzed nitrogen, reduce the total salt content, and increase the soil fertility of typical saline-alkali soils [23].

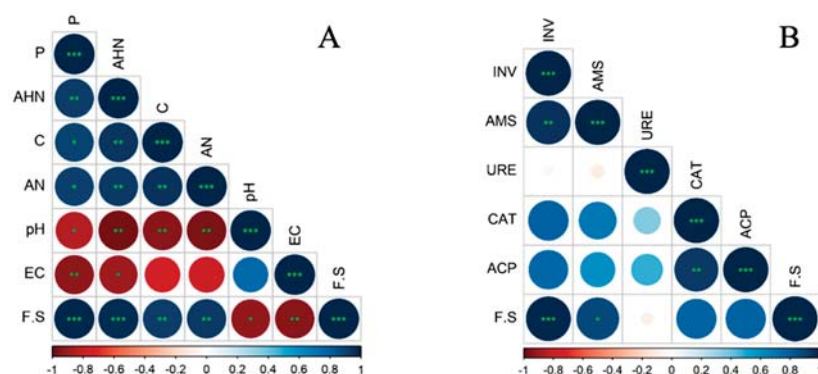


Figure 1. Heatmap of the correlation between the application amount of GLR organic fertilizer and soil physicochemical properties and enzyme activity. Note: (A) correlation between the application amount of GLR organic fertilizer and soil physicochemical properties; (B) correlation between the application amount of GLR organic fertilizer and enzyme activity; P—available phosphorous; AHN—alkali-hydrolysable nitrogen; C—organic matter; AN—ammonium nitrogen; EC—electrical conductance; F. S—addition of GLR organic fertilizer; INV—invertase activity; URE—urease activity; CAT—catalase activity; ACP—acid phosphomonoesterase activity; AMS—amylase activity; Pearson analysis * ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$). Positive correlation is displayed in blue, and negative correlation is displayed in red. The color intensity and the size of the circle are proportional to the correlation coefficient.

Soil enzyme activity can reflect the strength and intensity of various biochemical processes in soil. Relevant studies have shown that soil enzyme activity can represent important indicators such as soil fertility, quality, and microbial activity, etc. [24]. In this study, most of the enzyme activity in saline-alkali soils supplemented with the GLR organic fertilizer was found to be significantly higher than that in the control group (FSF) (Figure 1B). Studies have shown that soil organic matter is the storage place of enzyme sources. N, P, K, and other elements in soil are substrates and products of enzyme action [25]. The results showed that GLR organic fertilizer increases the organic matter content of saline-alkali soil and promotes soil enzyme activity.

3.2. Effects of the GLR Organic Fertilizer on the Microbial Community Structure in Saline-Alkali Soil

A total of 771,397 16S rRNA sequences were obtained from the six soil samples by pyrosequencing of bacterial 16S rRNA genes. Cluster analysis was performed based on a similarity of 97%, and 3986 operational taxonomic units (OTUs) were obtained. A total of

1,363,553 valid sequences were obtained from the six soil samples by pyrosequencing of fungal ITS genes, and 1133 OTUs were obtained by a cluster analysis based on a similarity of 97%. Figure 2 shows that the rarefaction curves of soil bacterial and fungal alpha diversity in the different treatments tended to be flat, indicating that sequencing had become saturated [26].

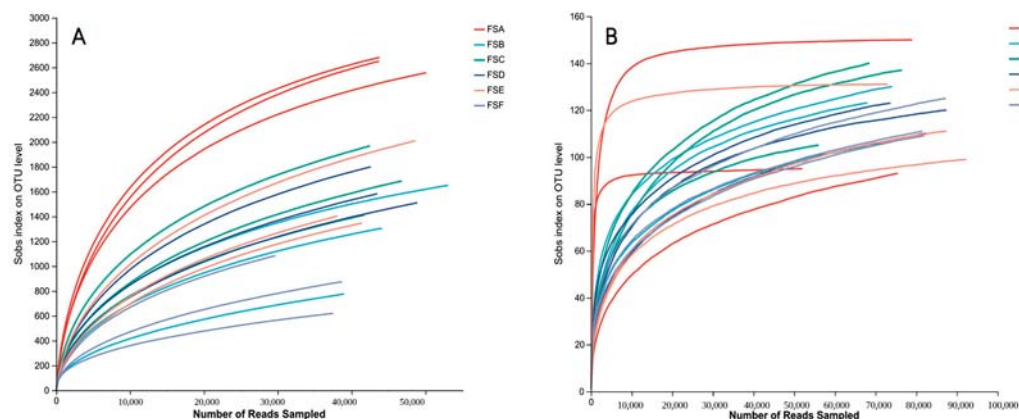


Figure 2. Bacterial and fungal rarefaction curves of different soil treatments. Note: (A) rarefaction curve of bacterial community; (B) rarefaction curve of fungal community. FSA, FSB, FSC, FSD, FSE, and FSF represent saline-alkali soil samples with GLR organic fertilizer addition ratio of 25%, 16.7%, 12.5%, 10%, 8.3%, and 0%, respectively.

3.2.1. Variation of Microbial Community Structure Diversity Index in Saline-Alkali Soil

Alpha diversity reflects the microbial richness and diversity of soil bacteria and fungi (97% similarity). The data in Table 3 show that the organic fertilizer of GLR significantly improved the richness and diversity of the bacterial community structure in the saline-alkali soil but had no significant effect on the diversity of the fungal community structure. The Sobs, Chao1, and Shannon indices of the soil bacterial community in the FSA treatment were significantly higher than those of the other treatment groups.

Table 3. Alpha diversity index of the microbial community in saline-alkali soil improved by different treatments. For each row, the means $\pm$ SD with different letters were significantly different between treatments ($p < 0.05$, using the HSD test).

		FSA (25%)	FSB (16.7%)	FSC (12.5%)	FSD (10%)	FSE (8%)	FSF (0%)
Bacteria	Sobs	2628.33 $\pm$ 36.84 a	1242.67 $\pm$ 254.61 bc	1686.67 $\pm$ 161.09 b	1629.67 $\pm$ 86.77 b	1585.67 $\pm$ 212.28 b	857.00 $\pm$ 133.87 c
	Shannon	6.00 $\pm$ 0.12 a	4.50 $\pm$ 0.28 bc	4.85 $\pm$ 0.13 b	4.97 $\pm$ 0.12 b	4.48 $\pm$ 0.22 bc	4.2 $\pm$ 0.05 c
	Simpson	0.01 $\pm$ 0.003 b	0.04 $\pm$ 0.082 a	0.03 $\pm$ 0.003 ab	0.02 $\pm$ 0.006 ab	0.05 $\pm$ 0.009 a	0.04 $\pm$ 0.006 a
	Chao1	3073.44 $\pm$ 43.17 a	1849.98 $\pm$ 266.71 bc	2429.51 $\pm$ 196.88 ab	2358.54 $\pm$ 57.18 b	2287.85 $\pm$ 247.25 b	1366.89 $\pm$ 185.38 bc
Fungi	Sobs	112.67 $\pm$ 18.676 a	119.67 $\pm$ 7.129 a	127.00 $\pm$ 11.200 a	117.67 $\pm$ 3.929 a	113.67 $\pm$ 9.333 a	117.67 $\pm$ 3.772 a
	Shannon	2.53 $\pm$ 0.66 a	1.99 $\pm$ 0.178 a	1.89 $\pm$ 0.045 a	1.81 $\pm$ 0.114 a	2.15 $\pm$ 0.637 a	1.74 $\pm$ 0.066 a
	Simpson	0.18 $\pm$ 0.094 a	0.23 $\pm$ 0.037 a	0.25 $\pm$ 0.008 a	0.26 $\pm$ 0.018 a	0.25 $\pm$ 0.081 a	0.28 $\pm$ 0.012 a
	Chao1	122.68 $\pm$ 15.733 a	141.59 $\pm$ 5.880 a	140.62 $\pm$ 13.984 a	134.65 $\pm$ 1.368 a	120.94 $\pm$ 7.839 a	139.47 $\pm$ 5.474 a

3.2.2. Variation of Dominant Bacteria in Microbial Communities in Saline-Alkali Soils Dominant Phyla of Soil Microbial Communities

Figure 3 shows the composition of microbial communities with species abundance higher than 5% at the phylum level in the improved saline-alkali soil with different treatments. The dominant phyla under the FSF treatment were only Proteobacteria. The dominant phyla under the FSB treatment were Proteobacteria and Bacteroidota. The dominant bacterial phyla under the FSC, FSD, and FSE treatments were Proteobacteria, Bacteroidota, and Firmicutes. Proteobacteria, Actinobacteriota, Firmicutes, and Bacteroidota were the dominant phyla under the FSA treatment. The above results indicated that the application of the GLR organic fertilizer increased the number of dominant bacterial phyla in the saline-alkali soil, increased the abundance of the dominant bacterial phyla Bacteroidota,

Firmicutes, Actinobacteriota, and Chloroflexi, and decreased the abundance of the dominant bacterial phylum Proteobacteria. The dominant phylum in the fungal community of the six soil treatments was Ascomycota. The addition of the GLR organic fertilizer had no significant effect on the number and abundance of the dominant phylum in the fungal community in the saline-alkali soil.

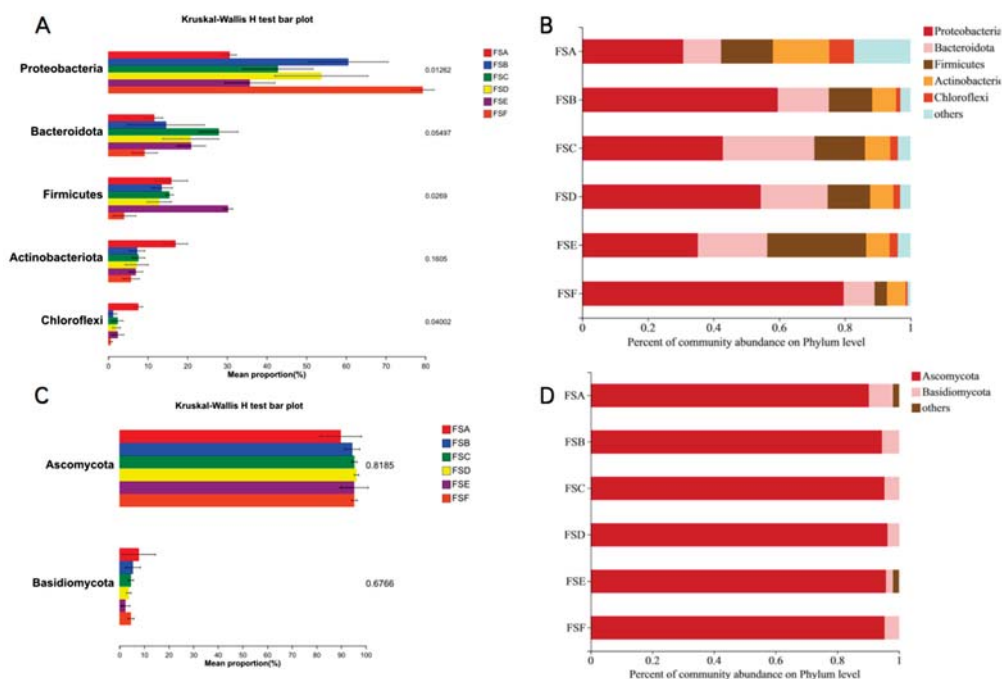


Figure 3. Relative abundance at the phylum level of microbial communities in soils with different treatments. Note: (A) differences in relative abundance of bacterial communities; (B) relative abundance of bacterial communities; (C) differences in relative abundance of fungal communities; (D) relative abundance of fungal communities.

Figure 4 shows the correlation analysis between the application amount of the GLR organic fertilizer and the relative abundance of the dominant phyla. The results showed that with the increase in the added amount of the GLR organic fertilizer, the types of bacteria in each treatment gradually increased, and the FSA treatment had the highest number of species. From an abundance perspective, the added GLR organic fertilizer treatment reduced the soil salinity, increased the abundance of Bacteroidota, Actinobacteriota, Chloroflexi, and Firmicutes, and decreased only the Proteobacteria.

Figure 5 shows the correlation analysis between the relative abundance of the dominant phyla and the soil physical and chemical properties. Some studies have found that Proteobacteria have a good salt tolerance and belong to the group of moderately halophilic bacteria [27]). In this study, Proteobacteria were found to be positively correlated with soil conductivity and pH, and negatively correlated with the addition of the GLR organic fertilizer (Figure 5A). This result shows that Proteobacteria have the characteristics of halophilic bacteria, which is consistent with the findings of Canfora et al. [28]. They also found that the dominant bacteria in saline-alkali soil also contain Proteobacteria, and the abundance of Proteobacteria is positively correlated with soil salinity. The abundance of Firmicutes was negatively correlated with soil salinity, and the abundance of Bacteroidota in saline-alkali soil increases after autumn irrigation [29]. Bacteroidota is a tolerant bacteria group [11]. In this study, Bacteroidota is the dominant bacteria group. Keshri et al. [30] also found that Bacteroidota is one of the dominant bacteria species in saline-alkali soil. Chloroflexi have a strong dependence on soil organic matter content [28]. Actinobacteriota are aerobic microorganisms suitable for growth in environments with high oxygen content. Actinobacteriota and Firmicutes have a relatively high tricalcium phosphate solubilizing

activity [31]. In this experiment, after adding the GLR organic fertilizer to improve saline-alkali soil, the content of organic matter and available phosphorus in the saline-alkali soil significantly increased, the soil structure improved, the soil porosity increased, and the soil particle density decreased (Table 1). Thus, the abundance of Chloroflexi, which are highly dependent on organic matter, and the abundance of Firmicutes with tricalcium phosphate solubilizing activity will increase.

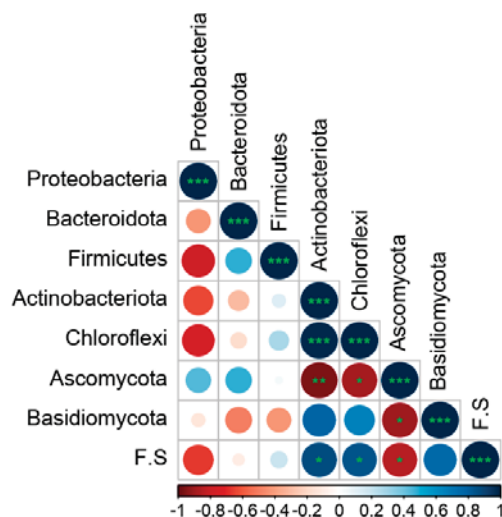


Figure 4. Heatmap of the correlation analysis between the application amount of GLR organic fertilizer and the dominant phyla of bacteria and fungi. Note: F. S—addition amount of GLR organic fertilizer; Pearson analysis * ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$). Positive correlation is displayed in blue, and negative correlation is displayed in red. The color intensity and the size of the circle are proportional to the correlation coefficient.

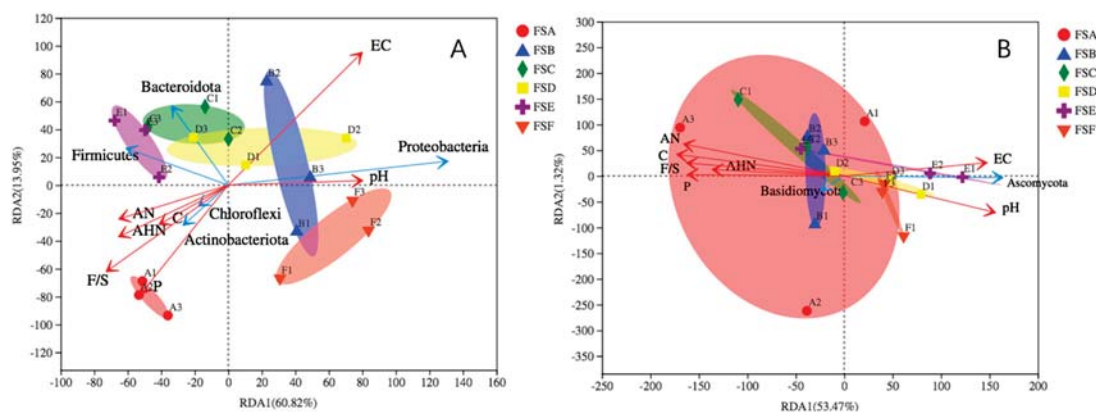


Figure 5. Correlation analysis between dominant microbial communities and environmental factors under different treatments. Note: (A) correlation between dominant bacterial phyla and environmental factors; (B) correlation between dominant fungal phyla and environmental factors; P—available phosphorus; AHN—alkali-hydrolysable nitrogen; C—organic matter; AN—ammonium nitrogen; EC—electrical conductance; F/S—addition amount of GLR organic fertilizer. The blue arrow shows species. The red arrow indicates environmental factors. The length of the arrow of environmental factors represents the degree of influence of environmental factors on species data. The angle between the arrows represents positive and negative correlation (acute angle—positive correlation; obtuse angle—negative correlation; right angle—no correlation).

As the increase of soil porosity improves the permeability of soil, it increases the abundance of aerobic Actinobacteria. Dai et al. [32] found that Firmicutes in the saline soil of

Yinbei were positively correlated with conductivity, and the abundance of Actinobacteriota and Bacteroidota was negatively correlated with soil pH.

The most abundant fungi were Ascomycota and Basidiomycota. Ascomycota play an important role in the terrestrial cycle of ecosystems and decompose organic matter in the nutrient cycle. They also form a symbiotic relationship with other organisms, such as plants [33]. Basidiomycota are the main driving force for restoring soil aggregate stability [34]. In this experiment, the addition of GLR organic fertilizer increased the abundance of Basidiomycota.

Dominant Genera of Soil Microbial Communities

Figure 6 shows the composition of bacterial and fungal communities with a genus-level abundance higher than 5% in soils under different treatments. As shown in Figure 6A, genera having sums of bacterial species abundance $\geq 10\%$ were considered dominant genera. The dominant genera in the soil bacterial community in the FSA treatment were *Bacillus* and *Halomonas*. The dominant genera in the FSE, FSD, FSC, and FSB treatments were all *Halomonas*, and the dominant genus in the FSF treatment was *Stenotrophomonas*. The organic fertilizer of GLR significantly increased the abundance of the dominant genera *Bacillus*, *Salinimicrobium*, *Saiegentibacter*, and *Alkalibacterium* and decreased the relative abundance of *Pseudomonas* and *Stenotrophomonas* in the saline-alkali soil. As shown in Figure 6D, the dominant genera of the soil fungal communities in the six treatments were *Aspergillus* and *Talaromyces*. Addition of the GLR organic fertilizer increased the abundance of *Thermomyces* and *Alternaria* (except for unclassified species).

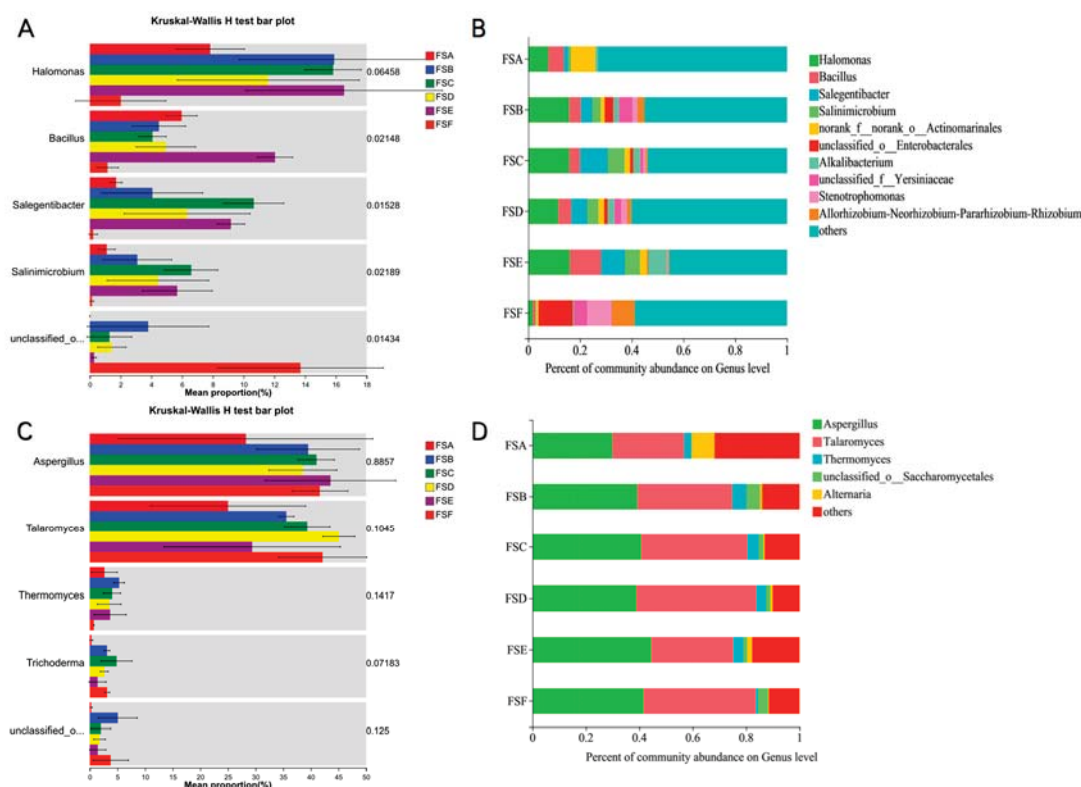


Figure 6. Relative abundance of microbial communities at the genus level in different treatments. Note: (A) differences in relative abundance of bacterial communities; (B) relative abundance of bacterial community; (C) differences in relative abundance of fungal communities; (D) relative abundance of fungal community.

From the bacterial genus level, after adding GLR organic fertilizer, the number of dominant genera species is only 1–2, and there is no obvious change. From the perspective of the abundance of the dominant genera, after the addition of GLR organic fertilizer,

the abundance of *Salegentibacter* and *Pseudomonas* significantly decreased. Some studies found that *Salegentibacter* and *Pseudomonas* were moderately halophilic bacteria [35,36]. Peng et al. [37] explored the effect of land use on the saline-alkali bacterial community. They found that *Bacillus* had a strong salt tolerance and participated in the nitrogen cycle. This microorganism can be used for bioremediation of saline-alkali soil. Shi found that *Bacillus* and *Stenotrophomonas* were the main bacterial species in Anda saline-alkali soil [38]. Thus, the studies above indicate that *Salegentibacter* and *Pseudomonas* may be used as indicator species for improving the salinity level of the studied areas. *Bacillus* can be used as an indicator species for the restoration of saline-alkali land. In the fungal community, there was no difference in the species and abundance of the dominant genera. The dominant genera were *Aspergillus* and *Talaromyces* with higher abundance values in the treated soils. *Aspergillus* can secrete acids, such as formic acid, which can convert insoluble phosphate into soluble phosphate and reduce soil pH value [39]. *Trichoderma* is a promising strain that can induce plant resistance under salt stress conditions and reduce the impact of salt damage on plants. Some studies have found that *Trichoderma harzianum* has a strong salt tolerance [40]. In conclusion, the addition of GLR organic fertilizer improved the soil quality and increased the abundance of salt-alkali tolerant bacteria in the short term. It may be that some elements in GLR organic fertilizer are beneficial to promote the increase of salt-alkali-tolerant bacteria. At the same time, it also promoted the abundance of fungi with the characteristics of acid production, alkali reduction, and increased plant resistance.

4. Conclusions

The results showed that GLR organic fertilizer could improve saline-alkali soil by reducing pH, conductivity, bulk density, and density of saline-alkali soil, increasing porosity and organic matter, improving soil enzyme activity, and regulating soil microbial community structure. Among them, the effect of GLR organic fertilizer application ratio of 25% (FSA) is the most significant. Overall, GLR can be used for saline-alkali soil improvement. The findings can provide a theoretical basis for improving saline-alkali soils, rational utilization of TCMRs, and promoting sustainable development of modern agriculture.

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Article

Dissolved Nitrous Oxide in Shallow-Water Ecosystems under Saline-Alkali Environment

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Abstract: The problem of global warming is becoming more and more serious. N_2O is a potent greenhouse gas. Most current studies on dissolved N_2O concentration have focused on inland freshwater and seawater while paying less attention to coastal agricultural catchment areas. The coastal agricultural catchment area is the link between the farmland ecosystem and the aquatic ecosystem, which is shallow in water depth. Moreover, due to the high salt content and obvious periodic change, it is highly sensitive to environmental changes and human activities and has strong potential for N_2O emission. Therefore, it is of great significance to understand the characteristics of the changes in the dissolved N_2O concentration in the shallow-water ecosystem under the saline-alkali environment of the coastal reclamation area and to identify the main controlling factors. The soil of Yudong reclamation area in Rudong County, Jiangsu Province was collected to carry out the submerged cultivation experiment. In order to simulate the saline-alkali situation of the coastal reclamation area, four salt gradients (S1–S4), four alkali gradients (A1–A4), and three levels of exogenous nitrogen concentration (N1–N3). In addition, the experiment set a control treatment (CK) without salt and alkali addition. After 2 weeks of cultivation in a shallow water layer of about 5 cm, the dissolved N_2O concentration and its influencing factors were measured and analyzed by collecting the overlying water sample and sediment after 24 h of fertilization. The results showed that changes in the saline-alkali environment in shallow-water ecosystems significantly affected the changes in dissolved N_2O concentration. The saline-alkali indicators (EC and pH of the overlying water and sediment), DO of the overlying water, and the microbial genes *nirS*, *nirK*, and *nosZ* were the key influencing factors of N_2O production in shallow-water systems. The correlation between *nirS* gene abundance and the dissolved N_2O concentration was the highest. The BP neural network model can be used to simulate and predict the dissolved N_2O concentration in overlying water under saline-alkali environment. Based on the experimental results, this study can provide a scientific basis for understanding the nitrogen cycling process in shallow-water ecosystems in the coastal reclamation area, improving the absorption of non-point-source nitrogen and reducing N_2O emissions in shallow-water wetlands.

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Keywords: saline-alkali; N_2O concentration; exogenous nitrogen; microbial functional gene

1. Introduction

Coastal saline-alkali land is an important land resource. However, due to poor structure and low fertility of the saline-alkali soil, the use of fertilizer in agricultural production is usually excessive. Traditional flood irrigation can accelerate the loss of soil nutrient, especially activated nitrogen, which enters the atmosphere and water through various ways [1]. The increasing N load and the acceleration of N cycling in the river of agricultural catchment area not only aggravate the water eutrophication but also promote the production and release of N_2O . The coastal agricultural catchment area is a significant emission source of N_2O in the atmosphere [2].

The mechanism of N_2O production in different types of water bodies is complex. The rate of N_2O emission is closely related to the N transformation and main driving factors

of dissolved N_2O [3]. Numerous studies have been carried out to show that dissolved N_2O in water bodies is mainly generated from the nitrification of water bodies themselves, denitrification of sediments, dissimilatory reduction of nitrate nitrogen, and absorption and fixation of nitrogen by algae [4]. The dissolved N_2O in water bodies is mainly related to DO , NH_4^+ , NO_3^- , Eh , pH , temperature, and so on [3]. Most current studies on dissolved N_2O concentration have focused on inland freshwater and seawater while paying less attention to coastal agricultural catchment area. The agricultural catchment area is the link between farmland ecosystem and aquatic ecosystem, different from rivers, lakes, and seas, which is small in area and shallow in water depth. It is concluded that shallow water is conducive to the growth of aquatic plants and algal reproduction, which can provide rich carbon sources for microorganisms in the sedimentary layer and promote the production and rapid transport of N_2O to the surface for release [5,6].

In addition, due to the high salt content and obvious periodic change, the coastal agricultural catchment area is highly sensitive to environmental changes and human activities and has strong potential for N_2O emission [5,7]. Salinity can inhibit the activity of N_2O reductase, which leads to the increase in cumulative N_2O emission [8–10]. Wen found that the increase in saline-alkali degree can gradually improve the contribution of N_2O emission in the nitrification process [11]. Therefore, the hypothesis of the study is that the effect of soil salinity and alkalinity through biotic and abiotic factors may be crucial to explain the mechanism of N_2O production processes in the coastal agricultural catchment area.

N_2O production and consumption mainly occur in the nitrogen cycle. It has been found that there are four main pathways of N_2O production in the aquatic environment: nitrification, denitrification, nitrifier denitrification, and dissimilatory nitrate reduction to ammonium [12]. There are two main pathways of N_2O consumption: denitrification and nitrifier denitrification [13,14]. N_2O is mainly formed through biological and abiotic pathways. Previous studies have shown that microorganisms are the main driving force of N_2O production and consumption [15]. In this study, the characteristics and main controlling factors of dissolved N_2O concentration in shallow-water ecosystems under salt-alkali environment in coastal reclamation areas were explored through submerged cultivation experiments, which provided a scientific basis for understanding the nitrogen cycling process at the water-soil interface of coastal wetland ecosystems, improving the absorption of non-point-source nitrogen and reducing N_2O emission in shallow-water wetlands.

2. Materials and Methods

2.1. Materials

The tested soils were taken from Yudong reclamation area in Liuzong Village ($32^\circ 12' \text{ N}$, $120^\circ 42' \text{ E}$), Juegang Town, Rudong County, Jiangsu Province (Figure 1). This area is mainly used for agricultural, which accounts for about 70% of the total area. The main embankment of the reclamation area is 1335 m long, and the reclamation area is about 2067 hm^2 . The region is subtropical maritime monsoon climate, with an average annual temperature of 15°C , an average annual precipitation of 1044.7 mm, an average annual evaporation of 1367.9 mm, an annual frost-free period of 223 d, and an average annual sunshine of 2421.6 h. The tested soil had a silt loam texture (13.7% sand, 81.3% silt, and 5.0% clay). The initial soil electrical conductivity ($\text{EC}_{1:5}$) was $4.0 \text{ dS}\cdot\text{m}^{-1}$, the total nitrogen was $5.9 \text{ g}\cdot\text{kg}^{-1}$, and the chloride ion content was $1.44 \text{ g}\cdot\text{kg}^{-1}$ [16,17].

2.2. Experimental Design

The submerged culture experiment was conducted in the Water-saving Park of Jiangning Campus of Hohai University from October to November 2020. There were three factors set in the experiment, including salinity, alkalinity and exogenous nitrogen concentration. Four salt gradients (S1–S4: 1‰, 3‰, 8‰, and 15‰ of soil mass), four alkali gradients (A1–A4: 0.5‰, 1‰, 3‰, and 8‰ of soil mass), and three levels of exogenous nitrogen concentration (N1–N3: 0.05, 0.10, and $0.15 \text{ g}\cdot\text{kg}^{-1}$ soil). In addition, the experiment set a

control treatment (CK) without salt and alkali addition. Therefore, there were 27 treatments in total, with three replicates per treatment. Different salt gradients were obtained by adding sodium chloride (NaCl), and different alkali gradients were obtained by adding sodium bicarbonate (NaHCO_3). Analytically pure urea ($\text{CO}(\text{NH}_2)_2$, nitrogen content 46%) was used as nitrogen source. In this experiment, glucose ($\text{C}_6\text{H}_{12}\text{O}_6$) was used as a carbon source to ensure microbial activity.

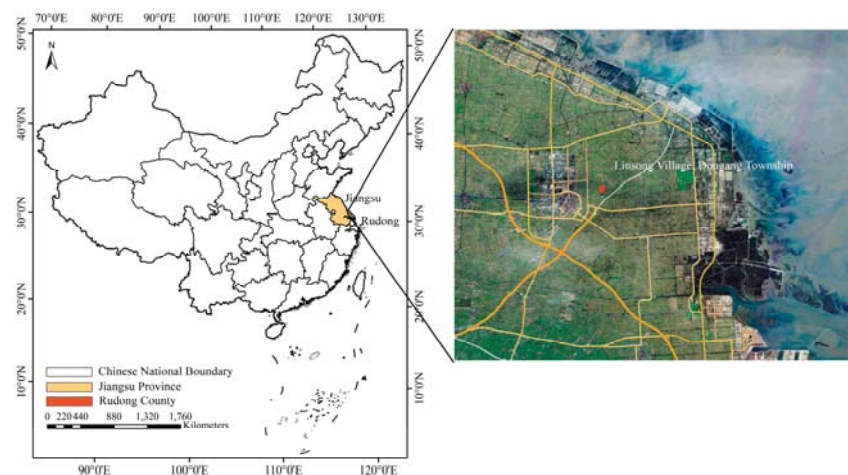


Figure 1. The location of the studied coastal reclamation area in Liuzong Village, Juegang town, Rudong County, Jiangsu Province, China.

The soil samples collected in the field were fully washed with distilled water to keep the salinity in the soil at a low level (all below 0.2‰). The sampled soils were natural air-dried and sieved to 2 mm. According to the experimental design, the soil samples were gently sprayed with NaCl or NaHCO_3 solutions of different concentrations for several times to mix well so as to avoid the influence of uneven salt distribution on the test results. The treated soil samples were naturally air-dried and filled into the incubators (PVC, 5 mm thickness, $340 \times 270 \times 130$ mm internal size), and each incubator was filled with 8 kg of soil. In order to ensure the same sunlight and temperature conditions, the incubators were randomly arranged in the greenhouse, incubated with deionized water and sufficient organic carbon source (glucose, 1.2 g/pot), and kept in shallow-water of about 5 cm for 2 weeks until the soil properties became stable. Subsequently, three concentrations of urea solution were added into each incubator. The overlying water and sediment samples were collected after 24 h of fertilization by the use of an undisturbed sediment sampler.

2.3. Determination of N_2O Dissolved Concentration and Its Influencing Factors

The concentration of N_2O was determined by headspace sampling gas chromatography. First of all, a 20 mL vacuum headspace vial (SVF-20, Nichiden-Rika Glass Co, Ltd., Kobe, Japan) was prepared. Secondly, 5 mL of the water sample was injected into the vial with a medical syringe and supplemented with 15 mL of air as equilibrium gas to balance with atmospheric pressure. Finally, the sample was manually shaken evenly. At the same time, 4 glass vials with only air injection and no water sample injection were prepared as blank samples and put in the refrigerator at 4 °C. After 24 h, when the N_2O in the water reached the balance with the air, about 4mL of gas was extracted from the upper part of the glass vials with a syringe and then injected into the gas chromatograph (Agilent 7890, Agilent Technologies, Inc., Wilmington, NC, USA) to determine the concentration of N_2O in the gas.

Referring to the method recommended by Terry et al., the equation for calculating the N_2O concentration in the overlying water is as follows:

$$N_2O_s = \frac{N_2O_h - N_2O_a \times H_{vol} + \alpha \times N_2O_h \times W_{vol}}{W_{vol}} \quad (1)$$

where N_2O_s represents N_2O concentration in the water sample; N_2O_h represents the N_2O concentration of the air in the vacuum glass vial after equilibrium; N_2O_a represents N_2O concentration in the equilibrium gas, which is obtained by measuring the concentration of N_2O in the blank sample vial; H_{vol} represents the volume of air in the glass vial after adding the water sample, which is 15 mL; α is the Benson absorption coefficient of N_2O at 4 °C, which is 1.12896; W_{vol} represents the volume of water sample added to the glass, which is 5 mL.

After 24 h of fertilization, samples of the overlying water (100 mL each) and bottom mud (0–5 cm layer, about 20 g) were collected to measure environmental factor parameters. The contents of ammonia nitrogen (NH_4^+ -N) and nitrate nitrogen (NO_3^- -N) in the overlying water and sediment extract (15 g soil sample mixed with 50 mL 2 mol·L⁻¹ KCl solution) after filtration (0.7 µm Whatman GF/F filter) were determined by Flow Injection Analyzer (Skalar Analytical, Breda, The Netherlands). EC and pH values of the overlying water and sediment were respectively determined by the DDS307 conductivity meter and PHSJ-4F pH meter (Shanghai Precision Scientific Instruments Co., Ltd., Shanghai, China). The soil EC_{1:5} is measured by 1:5 soil/water ratio soil extraction method. The content of dissolved oxygen (DO) in the overlying water were determined by the portable multi-parameter detector (Hach Company, Loveland, CO, USA). The concentration of DOC in the overlying water was determined by Multi N/C 3000 analyzer (Jena Analytical, Jena, Germany). The denitrification gene abundance was determined by collecting the sediment samples immediately from the surface layer of the overlying water-sediment interface at a depth of 5 mm for cryopreservation to quantitative analysis of denitrifying gene abundance. According to the manufacturer's instructions, total genomic deoxyribonucleic acid (DNA) samples were extracted from frozen sediment subsamples using an Ultra Clean Soil DNA Isolation kit (MoBio Laboratory, Carlsbad, CA, USA).

2.4. Statistical Analysis

All the data were initially sort out and standardized using Excel. Next, Pearson correlation coefficient analysis was carried out using SPSS25. Based on the grey correlation degree analysis [18], the dissolved N_2O concentration was used as the reference sequence and its 13 related impact factors were used as the comparison sequence in the same grey system for correlation degree analysis. The specific calculation of the correlation degree was carried out by the use of Python. The correlation degree reflects the closeness between the comparison sequence and the reference sequence of the system. The greater the correlation degree, the closer the relationship between the comparison sequence and the reference sequence is so as to determine the weight of each factor. The calculation formula is as follows:

(1) Dimensionless variable:

$$X'_i(k) = \frac{x_i(k)}{x_i(1)}, X_i(1) \neq 0 \quad (2)$$

(2) Correlation coefficient:

$$\xi_i(k) = \frac{\min_i \min_k |y(k) - x_i(k)| + \rho \max_i \max_k |y(k) - x_i(k)|}{|y(k) - x_i(k)| + \rho \min_i \min_k |y(k) - x_i(k)|} \quad (3)$$

where $\min_i \min_k |y(k) - x_i(k)|$ and $\max_i \max_k |y(k) - x_i(k)|$, respectively, represent the maximum and minimum second-order difference. ρ represents the resolution coefficient, generally $\rho = 0.5$.

(3) Correlation degree:

$$S_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k), \quad k = 1, 2, \dots, n \quad (4)$$

Dissolved N_2O concentration is nonlinear and affected by many factors, and it is difficult to obtain ideal results by using general prediction methods. In order to simulate and predict the concentration of N_2O in the overlying water more accurately, the BP neural network model was constructed by MATLAB R2020a. The BP neural network is an error-back-propagation neural network, which is usually composed of input layer, output layer, and hidden layer. The neurons between layers of BP neural network are fully interconnected through the corresponding network weight coefficient w , while the neurons in each layer are not connected. The nonlinear mapping relationship of the BP neural network has a good effect in processing variables and has obvious advantages in the model fitting, simulation of initial data and prediction ability of new data [19]. Pelliccioni et al. established a three-layer BP neural network to predict the concentrations of NO_2 and CO , and the results were in good agreement with the measured results [20]. Yang et al. constructed a BP neural network to retrieve the chlorophyll-a concentration, and the results showed that the error between the chlorophyll-a concentration output by the inversion model and the measured value was less than the result obtained by using the linear regression method [21]. The BP algorithm is composed of two processes: signal-forward propagation and error-back propagation. In the forward propagation, the input layer samples are determined by the results of grey correlation degree analysis, which enters the network from the input layers and transmits to the output layer through the hidden layers. If the actual value of the output layer is different from the target value, the error-back propagation is transferred. The output error (the difference between the target value and the actual value) is calculated by reverse propagation of the original path until reaching the input layer. The weight and threshold of neurons in each layer are constantly adjusted until the number of training reaches the preset value or the output error is reduced to the minimum. Finally, the test samples are used for network inspection.

3. Results

3.1. Characteristics of Dissolved N_2O Concentration in the Overlying Water with the Variation of Salinity and Alkalinity

With the change of salinity and alkalinity in the tested sediment, the dissolved N_2O concentration in the water was significantly different (Figure 2). The concentration of dissolved N_2O in the water increased significantly with the increase in sediment salinity, while it decreased sharply when salt gradient of the sediment was more than 8‰. Under the same salt gradient, with the input of exogenous nitrogen, the dissolved N_2O concentration in the water increased significantly. When the concentration of exogenous nitrogen is high, the variation of salinity has a more significant effect on the dissolved N_2O concentration in the water. The dissolved N_2O concentration in the N3S3 treatment was the highest (20.467 $\mu gN/L$), while the dissolved N_2O concentration in the N1CK treatment was the lowest (2.189 $\mu gN/L$).

The concentration of dissolved N_2O in the overlying water significantly decreased with the increase in sediment alkalinity. Similarly, under the same alkali gradient, the concentration of N_2O in the water increased with the input of exogenous nitrogen. The dissolved N_2O concentration in the N3-CK treatment was the highest (6.805 $\mu gN/L$), while the dissolved N_2O concentration in the N1-A4 treatment was the lowest (0.864 $\mu gN/L$). In conclusion, both saline-alkali level and exogenous nitrogen concentration have remarkable effects on the potential of N_2O emission in the shallow water, and there is an interaction between them. The higher salt content can promote N_2O emission within certain range, while the N_2O emission decreases apparently when the salinity is too high. The alkalinity can cause the inhibition of N_2O emission remarkably. The rising nitrogen content in the shallow-water system inspires the potential of N_2O emission and makes the saline-alkali effect on N_2O emission more significant.

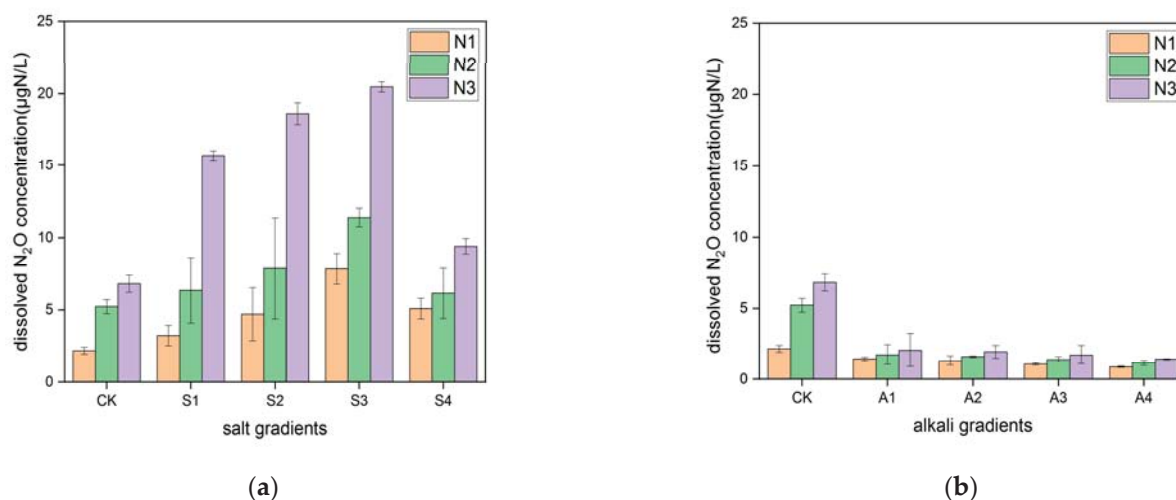


Figure 2. Dissolved N₂O concentration in the water treated with different salinity and alkalinity: (a) dissolved N₂O concentration in the water treated with different salinity ($n = 45$); (b) dissolved N₂O concentration in the water treated with different alkalinity ($n = 45$).

3.2. Correlation between Dissolved N₂O Concentrations in the Overlying Water and Water-Soil Environmental Factors

The correlation between dissolved N₂O concentrations in the overlying water and its influencing factors including water-soil environmental factors and microbial functional genes in the shallow-water ecosystem is shown in Table 1. Under salt-alkali environment, the dissolved N₂O concentrations were positively correlated with NO₃[−]-N, EC, and DO of the overlying water, EC_{1:5} of the sediment, and microbial functional genes nirK, nirS, and nosZ significantly. Moreover, the dissolved N₂O concentrations were also significantly negatively correlated with NH₄⁺-N and DOC of the overlying water and the NO₃[−]-N and pH of the sediment. The correlation between dissolved N₂O concentrations and DOC is the strongest, and its coefficient is -0.544 , which indicates that organic carbon content is one of the most important factors controlling dissolved N₂O concentrations in the water. The second was microbial gene nirS, and the correlation coefficient was 0.463 . There is also a high correlation between the pH of the sediment and the dissolved N₂O concentration in water, and the correlation coefficient is -0.459 , which proves that the alkalinity of the sediment has an important influence on the N₂O emission potential of the water.

Table 1. Correlation between dissolved N₂O concentrations and its influencing factors.

Water-soil Environmental Factors	Overlying Water						Sediment				Denitrification Genes		
	NH ₄ ⁺ -N	NO ₃ [−] -N	EC ¹	pH	DO ²	DOC ³	NH ₄ ⁺ -N	NO ₃ [−] -N	EC _{1:5}	pH	nirK	nirS	nosZ
Dissolved N ₂ O concentrations	-0.356^{**4}	0.386^{**}	0.336^{**}	-0.175	0.323^{**}	-0.544^{**}	-0.029	-0.344^{**}	0.236^{*5}	-0.459^{**}	0.339^{**}	0.463^{**}	0.255^{*}

Notes: ¹ EC represents electrical conductivity; ² DO represents dissolved oxygen; ³ DOC represents dissolved organic carbon; ⁴ ** Extremely significant at the $p < 0.01$ probability level; ⁵ * Significant at the $p < 0.05$ probability level.

3.3. Identification and Simulation of Key Factors Leading to Changes in Dissolved N₂O Concentration in the Overlying Water

The influence of water-soil environmental factors and microbial functional genes on the dissolved N₂O concentration under saline-alkali environment was analyzed by the grey correlation analysis, in which the dissolved N₂O concentration was taken as the reference index. The influencing factors of dissolved N₂O concentration are as follows: NH₄⁺-N(X1), NO₃[−]-N(X2), EC(X3), pH(X4), DO(X5), DOC(X6) of the overlying water, NH₄⁺-N(X7), NO₃[−]-N(X8), EC_{1:5}(X9), pH(X10) of the sediment, and microbial genes nirK(X11), nirS(X12), and nosZ(X13). The correlation degree between each factor and dissolved N₂O concentration is shown in Table 2.

Table 2. Analysis of correlation degree between dissolved N₂O concentration and its influencing factors.

Factors ¹	X ₁	X ₂	X ₃	X ₄	X ₅	X ₆	X ₇	X ₈	X ₉	X ₁₀	X ₁₁	X ₁₂	X ₁₃
Correlation degree	0.760	0.799	0.828	0.823	0.826	0.763	0.798	0.760	0.816	0.820	0.840	0.854	0.832
Order	12	9	4	6	5	11	10	13	8	7	2	1	3

Notes: ¹ X₁, X₂, X₃, X₄, X₅, X₆, X₇, X₈, X₉, X₁₀, X₁₁, X₁₂, X₁₃ respectively represent NH₄⁺-N, NO₃⁻-N, EC, pH, DO, DOC of the overlying water, NH₄⁺-N, NO₃⁻-N, EC_{1:5}, pH of the sediment, and microbial functional genes nirK, nirS, and nosZ.

The correlation degree between and dissolved N₂O concentration its influencing factors in descending order is X₁₂ > X₁₁ > X₁₃ > X₃ > X₅ > X₄ > X₁₀ > X₉ > X₂ > X₇ > X₆ > X₁ > X₈. Among the factors of dissolved N₂O concentration, the correlation degree of EC, pH, DO in the overlying water, EC_{1:5}, pH in sediments, and microbial genes nirS, nirK, and nosZ were all above 0.8. Among them, the correlation with microbial genes nirS, nirK, and nosZ were the highest, and their degrees were, respectively, 0.854, 0.840, and 0.832. It indicated that denitrification microbial functional genes had a great influence on the dissolved N₂O concentration, and denitrification process played a decisive role in N₂O emission in the water. The saline-alkali indexes (EC and pH of overlying water and sediment) in shallow-water systems are highly correlated with dissolved N₂O concentration (ranging from 0.816–0.828), which indicates that saline-alkali environment is of great importance to the potential of N₂O emission in the water. The correlation degree between DO and dissolved N₂O concentration ranked fifth, with a value of 0.826, which showed that dissolved oxygen also determines the production of N₂O to a large extent.

Based on the identification of the key factors leading to changes in dissolved N₂O concentration, the BP neural network model was constructed with the key factors and dissolved N₂O concentration to achieve the high-precision prediction of dissolved N₂O concentration in the overlying water. The key influencing factors that grey correlation degrees were higher than 0.8 with dissolved N₂O concentration were selected as the neurons in the input layer, including the system saline-alkali index (EC and pH of the overlying water and sediment), DO of the overlying water, and microbial genes nirS, nirK, and nosZ. The output layer is the dissolved N₂O concentration in the overlying water. In the training progress, the method of random division was adopted to divide the data into the training set, validation set, and test set so as to ensure that the predicted value is more reliable. The training set was used to determine the parameters of the BP neural network. The validation set was used to verify the accuracy of the model trained each time so that the number of iterations and learning rate were constantly adjusted to make the results on the validation set optimal. After the final training of the model was completed, the accuracy of the final model was tested with the test set. The default number of hidden layer nodes in the BP neural network model was 10. The network target error was 1×10^{-10} . The learning speed was 0.05. The number of training steps was 50,000. The BP neural network was trained according to the above settings until it met the intended target, as shown in Figure 3. R was the accuracy of the model; Target was the true value of the sample; Output was the actual output value of the model. The tested neural network converged faster and the output error was reduced to the minimum at 10 steps. The goodness of fit for the training set was 82.69%, for the validation set it was 80.62%, and for the test set it was 89.91%, which explained that the model has a good goodness of fit. The BP neural network model test the trained network with test samples by simulation Sim function. The test results were well in line with the predetermined settings. The Figure 3 showed that the overall accuracy of the model (R) was 0.810. The network training results showed that this artificial neural network can be used to predict the dissolved N₂O concentration in saline-alkali shallow-water ecosystems, and the model has a wide range of applications.

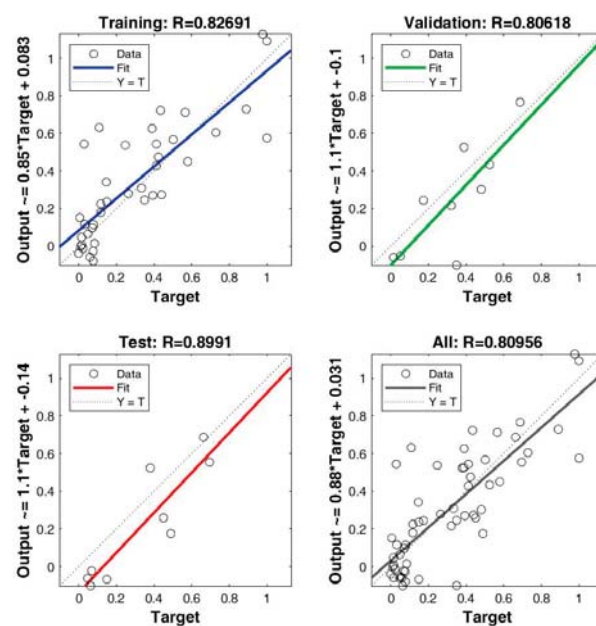


Figure 3. BP neural network regression analysis diagram.

4. Discussion

The concentration of N_2O in the overlying water varied significantly with the changes in salinity and alkalinity in the shallow-water ecosystems. The higher the salinity was, the N_2O production could be promoted. However, when the salinity exceeded a certain threshold (8‰ in this study), the N_2O production decreased sharply. With the increase in alkalinity, the dissolved N_2O concentration decreased significantly. The findings indicate that the activity of N_2O reductase could be inhibited in the moderate salinity environment inhibits, resulting in the increase in the N_2O emission [5,11]. However, higher levels of salinity and alkalinity were usually linked to lower activities of nitrification and denitrification enzymes, thus inhibiting the N_2O production [22,23]. The rising exogenous nitrogen content in the shallow-water ecosystems inspired the potential of N_2O emission and made the saline-alkali effect on N_2O production and emission more significant.

Previous studies have shown that dissolved N_2O in water mainly comes from processes such as nitrification in water and denitrification in sediment [4]. In this study, the contents of DO in the overlying water were more than $7 \text{ mg} \cdot \text{L}^{-1}$, which indicates that nitrification was the main mechanism of N_2O production in water. Pearson correlation analysis results showed that, firstly, the increase in DO concentration could raise the nitrification rate and promote N_2O production, which is consistent with the research results by Cai et al. [24]. Secondly, the more $\text{NH}_4^+ \text{-N}$ was consumed as the substrate of nitrification, the higher the N_2O concentration was, which is consistent with the results of Yoshinari et al. [25]. Thirdly, DOC provides an energy source for nitrification and denitrification, which would promote the N_2O production. Fourthly, the more $\text{NO}_3^- \text{-N}$ was consumed as the substrate of denitrification in sediment, the higher the N_2O concentration was. The results showed that the occurrence form of nitrogen has a significant impact on N_2O production, which was consistent with the results of Wang et al. [26]. What is more, the pH value in this study was about 8.0. Previous studies have shown that pH can affect and control the activity of microorganisms. Dumetre [27] and Garcia [28] showed that neutral or weakly alkaline environment is conducive to the denitrification. Bian [29] showed that when the pH value is in the range of 7.0–8.0, the microbial activity in the sediment is the highest.

In the shallow-water ecosystems, the key influencing factors of N_2O production in water included the salinity indexes (EC and pH of overlying water and sediment), DO of the overlying water, and microbial genes *nirS*, *nirK*, and *nosZ*, whose gray correlation degrees with dissolved N_2O concentration were above 0.8. The correlation degree of mi-

microbial functional genes *nirS*, *nirK*, and *nosZ* ranked as the top three, which indicates that microbial denitrification genes played a crucial role in the production and consumption of N_2O . N_2O is the intermediate product of denitrification and nitrifier denitrification, which can be further reduced to N_2 and release it into the atmosphere through the process of nitrous peroxide reduction [30,31]. Each step of the transformation process is driven by the corresponding functional microbial community. The microorganisms involved in N_2O release mainly include bacteria, archaea, and fungi, among which bacteria play a major role [15]. The enzymes involved in N_2O release in bacteria can be divided into two categories according to the source and destination of N_2O . One category is the enzymes involved in N_2O formation, including nitrate reductase, nitrite reductase, nitric oxide reductase, and hydroxylamine oxidoreductase. Another category of the enzymes reduces N_2O to form N_2 , such as nitrous oxide reductase [32]. The key functional genes in the process of biological nitrogen removal are *nirK*, *nirS*, and *nosZ*, which have different tolerance to high salt-alkali environment and can be significantly affected by available nitrogen content [33]. The abundances of *nirK* and *nirS* are of great importance to the process of nitrite reduction. In line with previous studies, it was shown that the abundances of *nirS* have stronger metabolic activity than the abundances of *nirK* in the alkaline environment [34,35]. The denitrifying bacteria of *nosZ* function in the nitrous oxide reduction process. Piao et al. reported that high salinity would inhibit the activity of denitrifying enzyme [36]. The lower the abundances of *nirK* and *nirS* were, the harder the further reduction from NO_2^- to NO was, thus inhibiting the N_2O production. On the contrary, the cumulative N_2O production could be promoted with the decrease in the abundances of *nosZ*, because *nosZ* functions in the reduction from N_2O to N_2 . Since the correlation degree of *nirS* abundances ranked the first, it explained that the denitrifying bacteria of *nirS* might be the dominant microbial community in the whole process, which is consistent with the study by Guo et al. [37]. Therefore, in general, high levels of salinity and alkalinity inhibit the production of N_2O .

The study demonstrated the structure characteristics and mechanisms of the microbial communities driving nitrogen removal processes in the saline-alkali environment, which played a key role in controlling the production and release of N_2O . The BP neural network model constructed in this study (considering the grey correlation degree) adopts the principle of random distribution to reflect the regularity of data so that the goodness of fit and modeling effect were satisfactory. In conclusion, the model could effectively predict the dissolved N_2O concentration of the overlying water, which provided scientific guidance for the control of the N_2O production in the shallow-water ecosystems under saline-alkali environment. The results could make a significant contribution to reduce greenhouse gas emissions to a certain extent.

5. Conclusions

In this study, the concentration of N_2O in the overlying water varied significantly with the changes in salinity and alkalinity in the shallow-water ecosystems. The higher the salinity in the sediment was, the N_2O production could be promoted. However, when the salinity exceeded a certain threshold (8‰ in this study), the N_2O production decreased sharply. With the increase in alkalinity, the dissolved N_2O concentration decreased significantly. The rising exogenous nitrogen content in the shallow-water ecosystems inspired the potential of N_2O emission and made the saline-alkali effect on N_2O production and emission more significant. Based on the grey correlation analysis method, the key influencing factors of N_2O production in water included the salinity indexes (EC and pH of overlying water and sediment), DO of the overlying water, and microbial genes *nirS*, *nirK*, and *nosZ*, among which the abundance of the *nirS* gene played a crucial role. These factors can be used to predict the dissolved N_2O concentration in the shallow-water ecosystems under saline-alkali environment, according to the BP neural network model simulation results.

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Article

A Study on the Dynamics of Landscape Patterns in the Yellow River Delta Region

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Abstract: The Yellow River Delta region is one of the estuarine deltas with the fastest land building speed, and it is an important region for the study of landscape pattern change due to its diverse variety of landscape types. By analyzing the dynamic degree, landscape type transfer matrix, and landscape indices of landscape types in the Yellow River Delta region in 2005, 2012, and 2018, this paper found that the area of construction land, salt fields, and breeding ponds in the Yellow River Delta region has increased to a large extent, with an increase in the aggregation degree and the utilization rate of this landscape type, and the landscape has developed toward the direction of aggregation and unification. The increase in construction land area mainly comes from the transfer of cropland area, part of which is occupied in order to adapt to urban expansion, and the salt fields and breeding ponds mainly come from the transfer of waters and mudflats, which can be seen as the main utilization direction of the water landscape. Moreover, unused land has increased with the degree of dispersion and fragmentation of development and utilization, so the exploitation and utilization of unused land still needs to be optimized. Through the analysis of the dynamic change in landscape pattern, we can explore the direction and extent of the evolution of landscape types, which has certain guiding significance for the sustainable use of land resources and the sustainable development of economy in the Yellow River Delta region.

Keywords: landscape pattern; dynamic degree; landscape type transfer matrix; landscape pattern index; dynamic change

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1. Introduction

1.1. Research Progress

The Yellow River Delta region, located at the mouth of the Yellow River, is the youngest wetland ecosystem in the country and the fastest growing area of land resources in the country and the world, making it a key area for ecological research [1,2]. The landscape types in the region are diverse, but with rapid economic development, human activities in the Yellow River Delta region have been enhanced, and the exploitation of land has led to fragmentation of the landscape pattern as well as increased dispersion of the landscape, affecting the ecological pattern, structure and function of the region, leading to a series of ecological problems such as river breakage and vegetation degradation, which pose a threat to ecological security as well as sustainable socioeconomic development [1–3]. Therefore, the dynamic change of landscape patterns has become one of the hot spots of current research. Landscape pattern refers to the arrangement of landscape patches of different sizes, which can characterize the heterogeneity of the landscape and is the result of various ecological processes acting at different scales [4]. The evolution of landscape pattern is closely related to ecological processes, which together drive the changes in landscape types [5]. Li T.Y. et al. used GIS technology and Fragstats software to obtain landscape change patterns in the Fen River Basin over a 25-year period and found that the natural

landscape was transformed into an anthropogenic landscape as urbanization accelerated [6]. Wang T. et al. constructed normalized vegetation index timeseries curves to optimize the landscape classification results and analyzed its dynamic changes using the landscape pattern index [7]. Li F. et al. combined landscape pattern evolution with ecosystem service capacity and human stress indicators to analyze the health status and change trends of ecosystems [8]. By studying the dynamic changes and drivers of landscape patterns, Cao L.H. et al. found that socioeconomic development was the main driver of landscape pattern changes, and that economic development and urban and rural population changes were the main driving factors [9]. Anthropogenic disturbance indicators can be used to evaluate the degree of influence of human activities on landscape types. The Yellow River Delta region is affected by human activities, so the landscape type clustering is reduced, the overall landscape connectivity is reduced, the shape of patches tends to be regular and simple, the disturbance of human activities such as reclamation, farming, salt tanning, construction, agricultural land reclamation, and so on, although they drive economic development, they also cause serious damage to the ecological environment [3,10,11]. Li M.D. et al. found that the spatial and temporal distribution characteristics of landscape patterns were influenced by the scale of the study, with different scales and development statuses all leading to different landscape patterns [12]. Wang D. et al. found that the impact of economic development on the landscape pattern was obvious, with the overall landscape becoming less connected and more fragmented, but the internal stability of the construction land patches increased and the shapes tended to be simpler as a result of urbanization, while other landscape types tended to be more complex and fractured [13]. By studying the evolution of the landscape pattern of Changbai Mountain over a 30-year period, Chen X.Y. et al. found that the landscape changed from small and scattered patches to large and concentrated patches during the restoration process, and the overall connectivity of the landscape decreased and developed toward homogenization [14]. The river networks are also important landscape features, which are obviously influenced by external factors such as climate, and at the same time, the river networks have the role of connectivity, which has a certain influence on the landscape pattern of the surrounding areas. The study of critical nodes of river networks is important for studying the changes in landscape patterns, understanding biodiversity, and maintaining the ecological integrity of the landscape [15,16]. Guo Y. et al. studied the effects of sand transport, sand content, and runoff on landscape changes in the Yellow River Delta region and found a significant correlation between the water and sand factors and landscape patterns [17].

1.2. Importance of Study

The Yellow River Delta region is the last large river delta to be developed in China. It is located at the combination of the Shandong Peninsula and Beijing–Tianjin–Hebei metropolitan area [18], which is the intersection of land and sea, forming a complex ecosystem and has a rich landscape type and a suitable environment for human living, which is important in regulating climate and protecting biodiversity [19]. The region is rich in reserve land resources, and it is an important food production base in China and has abundant natural resources. The development of the Yellow River Delta region began in the 1960s, and from an untouched wasteland to a development hotspot today, the development advantages and potential of the Yellow River Delta region have made it an important force in driving the development of the Bohai Sea Rim. However, with economic development, the ecology of the Yellow River Delta has been damaged by excessive reclamation and the development of salt pans and aquaculture ponds, and the original landscape type and landscape pattern have been changed.

Based on the area of landscape types in the Yellow River Delta region during 2005–2018, the transformation of landscape types within the study time period and the spatial distribution characteristics were analyzed. According to the landscape type shift matrix used to analyze the change in landscape types and the transfer direction during the study time period, the change inland use pattern and the trend of the landscape type transfer in the

study area can be inferred. Combined with the landscape pattern index, we can analyze the landscape pattern changes in different years, compare the pattern of landscape pattern changes over time from 2005 to 2018, and study the change characteristics of its landscape fragmentation degree, dominance, heterogeneity, landscape complexity, landscape density, and other characteristics, which is meaningful for studying the dynamic changes of landscape pattern as well as the evolution and direction of the landscape in the Yellow River Delta region, and provide technical and data support for the changes in the landscape types and rational use of land resources in the Yellow River Delta region. At the same time, it has a positive effect on regulating the conflicts among society, economy, and resources, and promoting the healthy and stable development of the Yellow River Delta region.

2. Study Area Overview and Data Sources

The Yellow River Delta region is where the Yellow River meets the sea, with sediment in the Bohai Sea depressions formed by the alluvial plain. Generally speaking, the “Yellow River Delta” refers to KenliNinghai as the apex, with the north to TaurEstuary as the starting point, and the south to the end of the branch ditch fan-shaped area of about 5400 km², most of which is in Dongying City, as shown in Figure 1. It is located in the mid-latitude region, in the warm temperate zone, with cold winters and hot summers, four distinct seasons, and obvious temperature differences. The soil in this area has a high salt content, the natural vegetation is mostly salt vegetation, the distribution of forest trees is limited by the soil topography, forest vegetation is less and more scarce, and herbaceous plant communities are absolutely dominant [20]. The study area is located at 37°16′~38°0′ N, 118°06′~119°18′ E, involving Dongying District, Kenli District, Hekou District, and Lijin County, and the dynamic changes of its landscape pattern were studied.



Figure 1. Overview of the study area.

The 2005, 2012, and 2018 Landsat remote sensing image data of the Yellow River Delta region used in this study were downloaded from the Geospatial Data Cloud website (<https://www.gscloud.cn/>, accessed on 5 December 2022) with a resolution of 30, and the remote sensing effects of similar study months and no clouds were selected to enhance the accuracy of the data. According to the research needs, the Landsat images were pre-processed using ENVI5.31 and the processed Landsat images were supervised and classified into eight major landscape types: grassland, cropland, construction land, woodland, waters, mudflats, salt fields and breeding ponds, and unused land. The textual information was obtained from the Dongying Statistical Yearbook and literature related to the Yellow River Delta region and the changes in landscape patterns.

3. Research Methodology

(1) Dynamic degree

The dynamic degree can reflect the way of quantitative changes of multiple landscape types such as the spatial changes of different landscape types and the way the landscape is combined over a period of time [21], and is an index that characterizes the dynamic changes of landscape types and can be used to describe the rate of change of landscape types [22]. The expression of the dynamic degree is as follows.

$$K_i = (Sit1 - Sit2)/Sit1 \times 1/(t2 - t1) \times 100\%$$

In the expression, K_i is the dynamic degree of type i landscape type in the study period; $Sit1$ and $Sit2$ are the area of type i landscape at $t1$ and $t2$; $t1$ and $t2$ are the beginning of the study period and the end of the study period.

(2) Landscape type transfer matrix

The landscape type transfer matrix can be used to describe the transfer in and out of each landscape type, to calculate the area of interconversion between different landscape types, and to describe the structural characteristics and the direction and degree of the change of landscape type conversion during the study time to express the process of landscape change [23,24]. ArcGIS software was used to intersect the landscape data and calculate the area, and an Excel pivot table was used to produce the landscape type transfer matrix. The expressions are as follows.

$$S_{ij} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix}$$

In the expression, S is the area; n is the number of different landscape types; i and j are the landscape types at the beginning and end of the study period.

(3) Landscape pattern index

The landscape index method is a more mature research method in landscape pattern research, which mainly uses the landscape pattern index to describe the pattern of the landscape and its changes [25]. The landscape pattern index reflects the structural composition and spatial pattern of the landscape, and is a high concentration of landscape information [26]. The landscape index was selected to represent the characteristics of all aspects of the landscape, and the index was not redundant to also take the index selection of other related landscapes as a reference [27,28], as shown in Table 1. In this paper, the largest patch index (LPI), edge density (ED), landscape shape index (LSI), perimeter area fractal dimension (PAFRAC), patch cohesion index (COHEOSION), patch density (PD), and aggregation index (AI) were selected as landscape pattern indices to study the landscape pattern characteristics of the study area in combination with the landscape characteristics of the Yellow River Delta region, in order to reflect the landscape pattern characteristics of the

study area and studied to reflect the fragmentation, dominance, heterogeneity, connectivity and aggregation of the study area.

Table 1. Landscape index and meaning.

Landscape Index	Abbreviations	Analytical Scale	Meaning
Largest patch index	LPI	Type/landscape	Describe the percentage of the area of the largest patch of a landscape
Edge density	ED	Type/landscape	Describe the extent to which the landscape is divided by boundaries
Landscape shape index	LSI	Type/landscape	Describe the complexity of the plaque shape
Perimeter area fractal dimension	PAFRAC	Type/landscape	Describe landscape shape features
Patch cohesion index	COHESION	Type/landscape	Describe the degree of connectivity between different landscape types
Patch density	PD	Type/landscape	Describe the degree of fragmentation of the landscape
Aggregation index	AI	Type/landscape	Describe the degree of aggregation of the landscape

(4) Relationship between the landscape pattern index and landscape type transfer matrix

The landscape type transfer matrix can provide an in-depth analysis of the changing characteristics of the landscape type structure and the direction of landscape type transfer, and can describe the landscape types at the beginning and end of the study period as well as the changes and directions of the landscape types within the study period and the relationship between the landscape types and each other [12,29]. The landscape pattern index is a general study and quantitative reflection of the characteristics of different aspects of the landscape, condensing the landscape pattern information and reflecting the landscape structure and spatial configuration, being the spatial characteristics of the landscape and the impact of human or natural including disturbances on ecological processes at different scales, being the comprehensive reflection of the impact of human or natural factors interacting in a certain ecological environment [5,29]. Both the landscape pattern index and the landscape transfer matrix describe changes in landscape types, and they are related in some way. The landscape type transfer matrix expresses the landscape transfer area in the form of a matrix to show the transformation of landscape types during the study period, and the landscape pattern index is a summary of the landscape pattern changes by selecting different indices. Both the landscape pattern index and the landscape type transfer matrix are quantitative descriptions of the landscape type changes and quantitative analysis of landscape characteristics, spatial configuration, and structural characteristics, both of which are reflections of the landscape type transformation laws and quantitative descriptions of the state of landscape types and state changes.

4. Data Analysis

4.1. Spatial Distribution of Landscape Types

Over the study period, the area of all types of landscapes in the Yellow River Delta region has changed with the socio-economic development and environmental changes in its spatial distribution, area and proportion, as shown in Table 2 and Figure 2. In terms of landscape types, the area of cropland was the largest throughout the study period, and cropland was mainly concentrated in the center and southwest of the study area, with a wide spatial distribution, although the change in the area of cropland showed a trend of first increasing and then decreasing. Compared with 2005, the area of cropland decreased in 2018, but it was still the most dominant landscape type in the Yellow River Delta region. The area of three types of landscape types, namely, grassland, construction land, salt fields, and breeding ponds, showed an increasing trend, with the largest increase in the area of salt fields and breeding ponds, which was mainly concentrated in the coastal area, with a zonal distribution and a more concentrated distribution increasing by 536.03 km² during the study period. The second was construction land, which is mainly distributed in the

southeastern part of the study area and is more concentrated, but there is also a more sporadic distribution in the northern part of the study area, and its area has a trend of gradual expansion, with an increase of 294.83 km² during the study period. The landscape type with the smallest increase in area was grassland, which is mainly located in the inlet area, with an increase in area of 13.40 km² during the study period, increasing year by year and with an increasing proportion. The area of the four landscape types, namely, woodland, waters, mudflats, and unused land, showed a decreasing trend during the study period. The area that decreased most was unused land, which was mainly distributed in the northern part of the study area, with the development of unused land gradually being exploited and transformed into cropland, construction land, salt fields, and breeding ponds, where the area decreased by 496.22 km². The second was mudflats, which are mainly distributed in the northern part of the study area, and the inlet area gradually developed into salt fields and breeding ponds, and the area decreased year by year, with a decrease of 261.91 km². The third was waters, the spatial distribution of waters was sporadic, and the area decreased year by year, and the area decreased by 45.44 km². The last was woodland, which is mainly distributed in the northeastern part of the study area, with sporadic distribution and a decreasing area year by year, with an area reduction of 14.86 km². In general, the two landscape types of salt fields and breeding ponds and unused land changed the most, increasing by 536.03 km² and decreasing by 496.22 km², respectively; the area of grassland and woodland changed very little and can be regarded as basically unchanged.

Table 2. Area of various landscape types in the Yellow River Delta(km²) from 2005 to 2018.

Year	Grassland	Cropland	Construction Land	Woodland	Waters	Mudflats	Salt Fields and Breeding Ponds	Unused Land
2005	97.48	3020.30	569.50	109.04	345.83	441.40	549.71	829.38
	1.63%	50.65%	9.55%	1.83%	5.81%	7.40%	9.22%	13.91%
2012	105.42	3179.38	652.45	105.89	316.18	330.18	895.74	377.40
	1.77%	53.32%	10.94%	1.78%	5.30%	5.54%	15.02%	6.33%
2018	110.88	2994.69	864.13	94.18	300.39	179.47	1085.74	333.16
	1.86%	50.22%	14.49%	1.58%	5.04%	3.01%	18.21%	5.59%

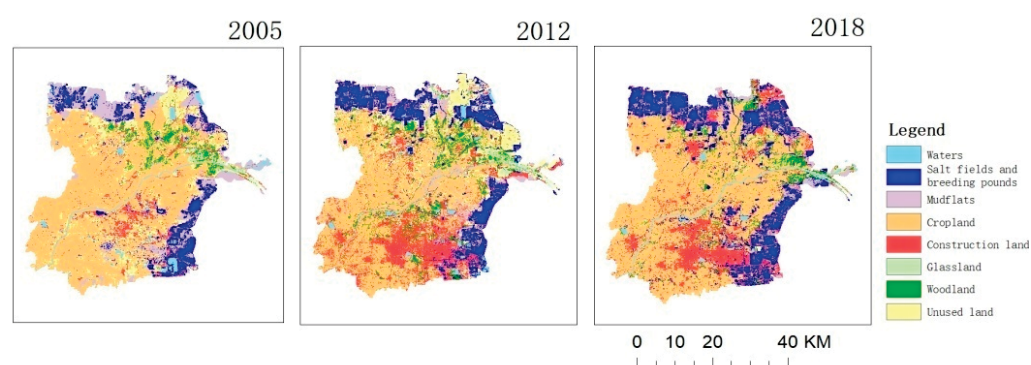


Figure 2. Distribution map of the landscape types.

In terms of year, in 2005, the largest landscape type in the Yellow River Delta region was cropland, and the rest of the landscape types and their proportion were unused land, construction land, salt fields and breeding ponds, mudflats, water, woodland, and grassland; in 2012, the largest landscape type in terms of area and proportion was cropland, and the rest of the landscape types and their proportion were salt fields and breeding ponds, construction land, unused land, mudflats, water, woodland land, and grassland; in 2018, the landscape type with the largest area and proportion was cropland, and the rest of the landscape types and their proportions were, in order, salt fields and breeding ponds, construction land, unused land, water, mudflats, grassland, and woodland. The dynamic degree of each landscape type is shown in Figure 3. During the study period, the proportion of cropland area was above 50%, and its dynamic degree changed less

compared with other landscape types at 0.75% and 0.97%, respectively, which shows that cropland is the most dominant landscape type in the Yellow River Delta region. The area of salt fields and breeding ponds also increased greatly during the study period, and the proportion of area reached 18.21% in 2018, almost twice that at the beginning of the study period, which shows that the development and operation of salt fields and breeding have increased in the Yellow River Delta region in recent years; grassland, woodland, and waters showed a small rate of change during the study period, and the dynamic degree was small; the area of grassland showed a trend of expansion, but the expansion rate was slow and the rate of change was slightly reduced, and the dynamic degree changed less, 1.16% and 0.86%, respectively. During the period of 2005–2012, the area of mudflats and unused land decreased significantly, the rate of change of unused land area was faster, with a dynamic degree of 7.79%, the area of salt fields and breeding ponds, cropland, and construction land increased more significantly, and the rate of increase in salt fields and farming ponds area peaked with a dynamic degree of 8.99%, which shows that the development of unused land during this period was more significant, and the development of undeveloped unused land into usable cropland, construction land, etc. During the period of 2012–2018, the area of cropland and mudflats had a large decrease, and the rate of decrease of the area of mudflats accelerated year by year, and the rate of change was the fastest during the period of 2012–2018, with the dynamic degree reaching 7.61%, and the area of construction land, salt fields, and breeding ponds had a relatively large increase, and the area of construction land continued to expand, and the rate of expansion increased year by year, with the dynamic degree during the period of 2012–2018 reached 5.41%, while the area of unused land had a small decrease, which shows that there is still more space for the development of mudflats, which can be used as salt fields and breeding ponds, etc., while the space for the development of unused land is small, with a decrease of only 44.24 km², and the area of cropland also had a large reduction. It can be seen that during the period of 2012–2018, the Yellow River Delta region adopted certain following projects to increase the area of woodland and grassland or slow down its area reduction; moreover, due to the social and economic development, the area for construction increased, and the area share increased more.

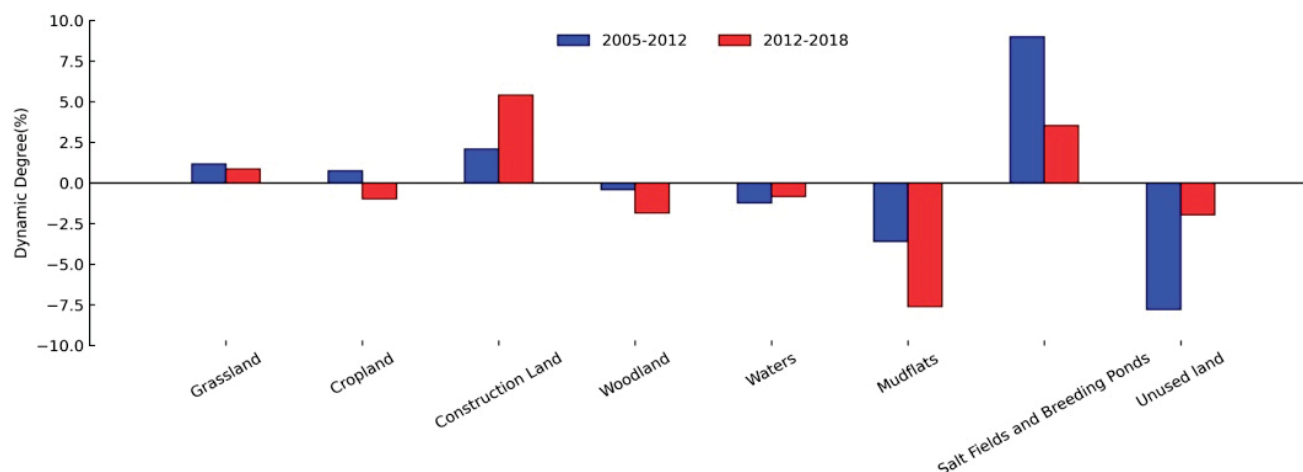


Figure 3. Dynamic degree of landscape type.

4.2. Landscape Type Transfer Matrix

The landscape type transfer between 2005 and 2012 is shown in Table 3. During the period of 2002–2012, the largest increase in the area of salt fields and breeding ponds was 346.03 km², whose transferred-in and transferred-out areas were 257.80 km² and 40.63 km², respectively, and their increase mainly came from mudflats, which reached 152.42 km². The next largest increase in the area of cropland was 159.08 km², whose transferred-in and transferred-out areas were 187.93 km² and 340.95 m², and the increase in cropland area was mainly from unused land and construction land. The area of construction land

increased by 78.92 km², and the area transferred-in and -out was 292.84 km² and 67.53 km², respectively, while the increase in its area mainly came from cropland, whose area was 241.83 km², and unused land was also partly transferred to construction land, but the area was smaller (28.09 km²), which shows that with the development and expansion of cities, the demand for construction land increases. Therefore, it can be seen that with development and urban expansion, the demand for construction land became greater and greater, and part of the cropland was transformed into construction land to meet the expansion of urban development. The area of mudflats decreased, its turn-out area was 186.36 km², and its main turn-out direction was salt fields and breeding ponds, with an area of 152.42 km², so it can be seen that the difficult-to-use mudflats can be utilized through the development of salt fields and breeding industry. The decrease in unused land was the greatest at 451.98 km², and its transferred area was 156.51 km² and its main transfer direction was cropland, construction land, salt fields and breeding ponds, with areas of 83.62 km², 28.09 km², and 33.19 km², respectively, which shows that the main development direction of unused land between 2005 and 2012 was cropland. The turn-out area of the waters was 85.03 km², and the main turn-out direction was salt fields and breeding ponds, whose area was 48.91 km², and the salt fields and breeding ponds were the main development and utilization directions of the waters. The area of grassland slightly increased and the area of woodland slightly decreased, but the area of grassland and woodland changed less, and their transferred-in and transferred-out areas were 39.59 km² and 47.48 km², 40.62 km², and 37.51 km², respectively, and the transferred-in and transferred-out areas basically remained balanced. In general, the area of salt fields and breeding ponds increased more and changed at a faster rate, mainly transformed from waters and mudflats. The current direction of unused land development is mainly cropland, but the construction land needed for development mainly originates from cropland, and the future direction of unused land development can be inclined to construction land.

Table 3. The Yellow River Delta landscape type transfer matrix for 2005–2012.

2005 2012	Grassland	Cropland	Construction Land	Woodland	Waters	Mudflats	Salt Fields and Breeding Ponds	Unused Land
Grassland	0	4.55	0.13	21.25	5.64	7.25	0.13	0.64
Cropland	22.38	0	56.8	12.89	2.96	7	2.27	83.63
Construction land	1.06	241.83	0	0.32	8.12	5.55	7.87	28.09
Woodland	7.92	25.8	0.54	0	0.47	0.26	0.07	5.56
Waters	3.77	40.22	5.49	1.08	0	7.48	13.15	0.81
Mudflats	10.05	3.41	0.21	1.45	12.74	0	14.85	4.59
Salt fields and breeding ponds	1.44	18.56	2.95	0.33	48.91	152.42	0	33.19
Unused land	0.86	6.58	1.41	0.19	6.19	6.4	2.29	0

The landscape type transfer between 2005 and 2012 is shown in Table 4. During the period 2012–2018, the largest increase in the area of land for construction was recorded, with an area increase of 221.68 km², whose transferred-in and transferred-out areas were 341.95 km² and 81.07 km², respectively, and whose increase mainly originated from cropland, whose area was 299.41 km², accounting for 87.56% of the transferred-in area. This was followed by salt fields and breeding ponds, which increased by 190.00 km², with their transferred-in and transferred-out areas of 201.28 km² and 67.78 km², respectively, and the increase in their areas mainly came from mudflats, with an area of 121.66 km², and the area of mudflats converted to salt fields and breeding ponds decreased compared to the period 2005–2018. The area of cropland decreased the most (184.69 km²), and the area of cropland transferred-out was the largest (372.63 km²), with the main transfer direction being construction land. The area of mudflats transferred-out was 197.82 km², mainly in the direction of salt fields and breeding ponds, accounting for 61.50% of the transferred area, and the remaining part was mainly converted into water, with an area of 33.33 km². The

area of unused land transferred-out was 68.17 km², and its main transfer directions were construction land, water, salt fields, and breeding ponds. The area of waters decreased, but the reduction decreased, and the area transferred-in and out of waters was 124.31 km² and 87.7 km², respectively, and the main sources of the transferred area were cropland, mudflats, salt fields, and breeding ponds. The difference between the transferred-in and transferred-out area of grassland was relatively small, and the transferred-in area mainly came from woodland; the transferred-in and transferred-out area of woodland were 23.30 km² and 52.23 km², respectively, and the main transferred-out direction was grassland and cropland.

Table 4. The Yellow River Delta landscape type transfer matrix for 2012–2018.

2012 2018	Grassland	Cropland	Construction Land	Woodland	Waters	Mudflats	Salt Fields and Breeding Ponds	Unused Land
Grassland	0	11.42	0.93	24.84	0.74	13.84	0.46	1.48
Cropland	13.49	0	59.58	21.71	23.13	10.97	1.39	11.57
Construction land	0.74	299.41	0	2.52	9.84	8.81	6.09	14.54
Woodland	7.37	12.34	0.56	0	0.59	0.77	1.26	0.41
Waters	3.17	26.97	8.34	1.15	0	33.33	36.12	15.23
Mudflats	7.06	8.77	1.6	1.62	7.03	0	19.37	10.34
Salt fields and breeding ponds	1.41	12.54	8.61	0.37	42.09	121.66	0	14.6
Unused land	0.77	1.18	1.45	0.02	4.28	8.44	3.09	0

In summary, the transfer in and out of landscape types during the study period is shown in Figure 4, the largest areas of cropland, mudflats, and unused land were transferred-out during the study period, with 713.58 km², 384.18 km², and 224.68 km², respectively. Salt fields and breeding ponds and construction land increased the most, and the increase in the area of salt fields and breeding ponds mainly came from mudflats and waters, which shows that salt fields and breeding ponds can be an important way to develop waters and mudflats. the increase in the area of construction land mainly comes from cropland, so urban development will sacrifice some cropland; the main conversion direction of unused land is cropland and construction land, but the area of unused land transferred out during 2012–2018 is smaller than that during 2005–2012, and the development and utilization of unused land still needs to be improved; grassland and woodland were basically balanced between 2005 and 2012, while during 2012–2018, the area transferred from grassland was higher and the area transferred from woodland was greater, and the main transfer direction of woodland was grassland, and the area of grassland increased year by year and the area of woodland decreased year by year, which shows that the Yellow River Delta region is more suitable for herbaceous plants.

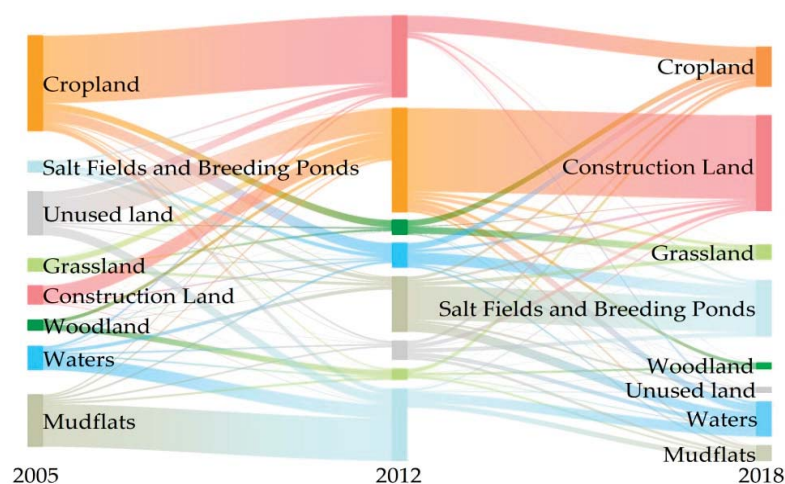


Figure 4. Separate mulberry map of the landscape type transfer matrix.

4.3. Landscape Pattern Index

Landscape pattern index is the change and summary of the landscape pattern, select different landscape pattern index can be summarized on different sides of the landscape characteristics, in order to reflect the landscape pattern change pattern, the selection and analysis of the landscape pattern index as shown in Table 5.

Table 5. Landscape pattern index.

Landscape Type	Year	LPI	ED	LSI	PAFRAC	COHESION	PD	AI
Grassland	2005	0.48	0.43	10.66	1.41	93.6	0.01	78.63
	2012	0.54	0.95	13.65	1.46	92.15	0.02	72.88
	2018	0.39	0.45	10.66	1.41	93.23	0.01	79.7
Cropland	2005	29.98	5.78	27.21	1.48	99.85	0.02	89.49
	2012	53.34	9.91	27.02	1.48	99.86	0.04	89.88
	2018	28.65	5.9	27.83	1.43	99.82	0.03	89.24
Construction Land	2005	1.72	3.07	35.92	1.42	93.67	0.11	63.7
	2012	3.39	6.65	40.16	1.49	92.5	0.22	65.13
	2018	3.35	4.12	36.21	1.44	95.44	0.12	72.76
Woodland	2005	0.42	0.63	13.88	1.48	91.98	0.01	74.43
	2012	0.37	1.07	15.77	1.5	91.37	0.02	66.74
	2018	0.15	0.43	12.99	1.42	88.7	0.01	66.25
Waters	2005	0.62	2.35	31.9	1.45	85.74	0.09	63.8
	2012	0.85	3.29	28.61	1.42	86.53	0.12	65.02
	2018	0.34	2.08	31.21	1.42	86.43	0.12	59.99
Mudflats	2005	1.49	1.31	17.2	1.41	96.04	0.03	83.39
	2012	1.66	1.66	15.89	1.42	95.56	0.05	81.66
	2018	0.65	0.86	18.2	1.45	92.66	0.04	71.57
Salt Fields and Breeding Ponds	2005	2.23	1.07	12.42	1.34	97.57	0.02	89.04
	2012	6.99	1.98	10.89	1.33	98.3	0.03	92.61
	2018	4.95	1.08	9.37	1.32	98.53	0.02	94.36
Unused land	2005	2.31	2.92	25.33	1.45	96.21	0.06	81.43
	2012	1.01	2.6	20.59	1.43	92.98	0.06	77.08
	2018	0.51	1.97	26.16	1.43	89.7	0.07	70.26

LPI(largest patch index) denotes the percentage of the largest patch area in a certain landscape. During the study period, the LPI value of cropland was the largest, which shows that the dominance of cropland was the most obvious among all landscape types in the Yellow River Delta region, but the dominance of cropland showed a trend of increasing and then decreasing between 2005 and 2018, and the magnitude of change was large. The LPI of construction land increased year by year, which shows that the dominance of construction land increased due to economic development; the LPI of the salt fields and breeding ponds increased significantly in 2012 from 2.23 to 6.99, and then decreased in 2018, presumably because salt fields and breeding ponds were the focus of development and utilization from 2005 to 2012. The LPI of woodland and unused land decreased year by year, and with the development of unused land, the proportion of their patch area decreased, and the dominance decreased, while the LPI of grassland, water, and mudflats showed a trend of first increasing and then decreasing. The LPI of grassland, watershed, and mudflats showed a trend of increasing and then decreasing, and the overall dominance was decreased during the study period.

ED (edge density) denotes the extent to which the landscape is fragmented by boundaries [30], and larger ED values indicate more complex patch shapes and a higher degree of fragmentation. During the study period, the ED value of cropland was the largest, and its landscape fragmentation was the largest, and its spatial heterogeneity was also the largest, with the most well-preserved internal features and less influenced by the outside world [21]. The ED of the unused land decreased year by year, which shows that it is disturbed by human activities and its heterogeneity decreases, and it is more disturbed by the

outside world. Except for unused land, the edge density of all landscape types showed a trend of first increasing and then decreasing.

The LSI (landscape shape index) denotes the complexity of the patch shape; the higher the LSI value, the more complex the landscape shape, and the lower the LSI value, the more simplistic the landscape tends to be [31]. The LSI of construction land was the highest and the landscape shape was the most complex. Although the LSI value first increased and then decreased, the LSI of construction land was higher than other landscape types during the study period. The LSI of the salt fields and breeding ponds decreased year by year, which shows that the complexity of their patch shape decreased and tended to be more holistic and large-scale, while the LSI of grassland and woodland first increased and then decreased, and the LSI of water, mudflats, and unused land first decreased and then increased, so the overall complexity tended to be simpler [31]. The LSI of grassland and woodland increased and then decreased, while the LSI of water, beach, and unused land decreased and then increased and the overall complexity changed less. In contrast, the LSI of cropland changed very little, ranging from 27.02 to 27.83, and the complexity of the landscape remained almost unchanged.

The more PAFRAC (perimeter area fractal dimension) converges to 1, the more homogeneous the landscape form and the greater the degree of human interference [21]. The PAFRAC of salt fields and breeding ponds tended to be the closest to 1 among all landscape types and decreased year by year, which shows that they are developing toward homogeneity year by year. The PAFRAC of cropland, water, mudflats, and unused land also decreased year by year, and the greater the degree of human interference, the PAFRAC of grassland, construction land, and woodland showed a trend of first increasing and then decreasing, and the degree of the landscape homogeneity decreased and then increased, and the PAFRAC of woodland was larger, reaching the maximum of 1.50 in 2012, and the landscape morphological patches were also the most complex and the least disturbed by human beings.

COHESION (patch cohesion index) denotes the degree of connectivity between different landscape types and indicates the physical connectivity of landscape patches, where the larger the value, the stronger the landscape connectivity [31]. The highest connectivity index was found for cropland, up to 99.86, which showed the best natural connectivity of cropland; the connectivity index of woodland, mudflats, and unused land decreased year by year, and the connectivity decreased due to the cut of the developed and used landscape [21]. The connectivity index of grassland and construction land showed a trend of increasing and then decreasing, and the connectivity index of water, salt fields and breeding ponds increased year by year, but the change was smaller.

PD (patch density) denotes the degree of fragmentation of the landscape; the higher the patch density, the greater the fragmentation of that landscape type [32]. The PD of construction land was the largest, with a maximum patch density of 0.22 in 2012, and there was a significant decrease in the PD of construction land between 2012 and 2018, indicating that the utilization rate of construction land had climbed [33]. The PD of water and unused land showed an increasing trend and the degree of fragmentation increased; cropland, construction land, forest land, mudflats, salt fields, and breeding ponds all decreased in PD between 2012 and 2018, with less fragmentation, a tendency to complete the landscape, and an increase in utilization.

AI (aggregation index) denotes the degree of aggregation of the landscape and reflects the interconnectedness of each landscape; the higher the AI, the denser the landscape, and vice versa, when it is more dispersed [22]. The AI of cropland was the highest and hardly changed during the study period, which shows that the degree of aggregation of cropland is high and stable. In contrast, the AI of woodland, water, mudflats, and unused land decreased year by year, which shows that the degree of aggregation of the landscape decreased and became more and more scattered, among which the AI of water was the lowest and also decreased continuously. For construction land, salt fields, and breeding ponds, the AI increased year by year, which shows that the plots needed for development

gradually gathered and facilitated centralized development. For grassland, the degree of aggregation first decreased and then increased, and the landscape density of grassland did not change significantly at the beginning and end of the study period.

5. Conclusions and Discussion

- (1) Cropland is the most dominant landscape type in the Yellow River Delta region, with a relatively concentrated distribution, reaching more than 50% of the total area. The landscape types with the largest increase in area during the study period were salt fields and breeding ponds and construction land, with an increase of 536.03 km² and 294.83 km², respectively; the area share of salt fields and breeding ponds was second only to that of cropland since 2012 and widely concentrated in coastal areas, while the area for construction has increased more steadily, with the third largest area share, and its dynamic degree has continued to grow and expand at a higher rate. Furthermore, the area of unused land decreased significantly, reduced to 40.17% of the area at the beginning of the study period, which shows that the unused land had been developed and used for development and construction during 2005–2018, but the dynamic degree of unused land decreased, the rate of less area slowed down, and the rate of development of unused land decreased. The area of mudflats decreased by 291.91 km² during the study period, and the dynamic degree of mudflats continued to increase with a faster rate of change and a higher potential for development and utilization. The dynamic degree of construction land also continued to grow and expand at a higher rate, while the dynamic degree of salt fields and breeding ponds and unused land was the highest from 2005 to 2012, which shows that the development of unused land was more concentrated.
- (2) During the study period, the landscape of cropland, mudflats, and unused land had the largest area of turn-out, with more obvious dynamic changes, and the main transfer-out of cropland was in the direction of construction land, which shows that the expansion of the city has taken up some of the cropland, and the area of cropland converted to grassland increased between 2012 and 2018, which has strengthened ecological restoration measures such as returning cropland to grass to a certain extent. The main direction of the turning out of unused land was from cropland to construction land, and the area turned into grassland and waters increased more. It was presumed that the area of unused land suitable for reclamation into cropland was reduced, and more unused land was used for urban construction and ecological construction. The area of salt fields and breeding ponds increased mainly from mudflats and waters, which were expanded and concentrated, and the development of salt fields and breeding industry can be regarded as the main development direction of waters in the Yellow River Delta region. During the study period, the landscape types constantly changed and there were complex interconversions between the landscapes as urbanization progressed.
- (3) The connectivity index of each landscape type in the Yellow River Delta region was high and the difference between different landscape types was small, which shows that the connectivity between landscapes is good. Cropland in the study time period for each landscape index was stable, with a small change; the LPI of construction land increased year by year, its dominance increased, and during 2012–2018, the construction land tended to be a simple landscape, and the utilization rate improved, the degree of aggregation increased, it can be seen that urban development was greater and more concentrated. The salt fields and breeding ponds also developed in the direction of homogenization and aggregation, and mudflats and unused land after development and utilization, the heterogeneity of mudflats, unused land were reduced after development and utilization,, and the degree of external influence became bigger, and the landscape form developed in the direction of complexity, fragmentation, and dispersion For the area of woodland, this decreased year by year and the maximum patch area also decreased, while the heterogeneity and complexity

of the landscape first increased and then decreased, but the overall trend was one of decrease, and the landscape dispersion of woodland also became higher, which shows that the Yellow River Delta region is not suitable for forestry development, but also to pay attention to the protection of existing woodland.

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Article

Impacts of Returning Straw and Nitrogen Application on the Nitrification and Mineralization of Nitrogen in Saline Soil

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Abstract: In order to discuss the problems of the transformation of soil nitrogen and nitrogen leaching in saline farmland, this study carried out a split-plot experiment with returning straw and various nitrogen application rates. The main treatment of the experiment was returning corn straw, at quantities of 0.64 g (C1) and 0 g (C0), and the secondary treatment was nitrogen fertilizer (urea) at the quantities of 0 g (N0), 0.015 g (N1) and 0.03 g (N2). The results showed that, firstly, with the extension of the incubation time, the nitrogen nitrification rate of saline soil in each treatment decreased gradually until it stabilized without straw. For Days 0–7 of incubation, the nitrogen mineralization rate of saline soil decreased rapidly, and the mineralization rates of C0N0, C0N1 and C0N2 decreased by 86.91%, 89.26% and 83.64%, respectively. The nitrification rate of nitrogen in saline soil was C0N0 > C0N1 > C0N2, which decreased by 68.01%, 67.42% and 60.52%, respectively. Secondly, under the condition of returning straw to the field, the nitrogen mineralization rate of saline soil in each treatment decreased gradually and became stable with the extension of the incubation time. The nitrogen mineralization rate of saline soil in each nitrogen application treatment was C1N2 > C1N1 > C1N0 within 0–3 days of incubation, which decreased by 87.46%, 87.20% and 81.83%, respectively. The nitrification rate of saline soil under different nitrogen treatments was C1N2 > C1N0 > C1N1, and the nitrification rates of C1N0, C1N1 and C1N2 decreased by 66.62%, 62.54% and 47.21%, respectively. Thirdly, during the incubation period, returning straw slowed down nitrogen mineralization and nitrification in saline soil under the reduced nitrogen and no-nitrogen fertilizer treatments, but it enhanced nitrogen mineralization and nitrification in saline soil under the high nitrogen treatment. In conclusion, returning straw and reducing the application of nitrogen fertilizer to saline soil can retain more ammonium nitrogen, thus inhibiting nitrification of the soil nitrogen, reducing the environmental pollution risk of nitrate leaching and reducing nitrogen losses, all of which are of great significance for environmental pollution.

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Keywords: straw return; nitrogen application; fracture zone test; mineralization rate; nitrification

1. Introduction

Soil nitrogen is an important material base for soil fertility, and its transport and transformation in the soil directly affect the utilization and loss of nitrogen [1]. Bioorganic matter such as straw and biochar will affect the nitrogen cycle of soil. Returning straw can improve the soil's physical and chemical properties, reduce the soil's bulk density, increase the soil organic matter content, improve the number of microorganisms and enzyme activity related to the soil nitrogen cycle and accelerate the decomposition of organic matter, thereby improving the mineralization rate of soil organic nitrogen and the level of soil nitrogen [2]. The combined application of nitrogen with straw and biomass carbon can improve the amount of nitrogen mineralized by the surface soil, the nitrogen mineralization rate of the upper soil [3] and the content of microbial biomass carbon [4,5], thereby increasing the assimilation of soil nitrogen. At the same time, the simultaneous use of straw and biomass

carbon will also increase the loss of nitrogen through denitrification, and with an increase in the amount of straw added, the effect will be more obvious [6]. From the perspective of adding straw alone, returning straw to the field not only promotes the transformation and supply of nitrogen for crops, but it also improves the release and absorption of nitrogen [7]. Moreover, returning straw increases the total nitrogen content and nitrogen retention rate of the soil [8], changes the amount and activity of soil microorganisms [9] and, thus, affects soil nitrification. The nitrogen cycle of soil can also be affected by the amount of nitrogen applied. Some studies have shown that the application of nitrogen fertilizer significantly improves the mineralization and nitrification of nitrogen in the chernozem [10], and an increase in nitrogen fertilizer can also improve the mineralization rate of soil nitrogen [11]. Reducing nitrogen can slow down the potential of soil nitrification, prevent and control nitrate nitrogen leaching to deeper soils and reduce nitrogen losses [12].

The mineralization of soil nitrogen is also related to the soil's texture. Applying nitrogen to black soil can significantly inhibit nitrogen mineralization of farmland soil. The mineralization rate of soil net nitrogen decreases significantly with an increase in the application of nitrogen, whereas the net nitrification rate increases significantly with an increase in nitrogen [13], which will eventually encourage the nitrate nitrogen to move downward along the soil profile, increasing nitrogen losses [14]. Salinity in the soil has different effects on nitrogen's mineralization and nitrification. Some studies have shown that the amount of net nitrogen mineralized in coastal saline soil with 184 mg/kg nitrogen fertilizer was significantly lower than that under the 92 mg/kg nitrogen fertilizer treatment ($p < 0.05$). This phenomenon shows that excessive addition of nitrogen does not have a positive effect on the nitrogen supply capacity of the soil [15]. Different nitrogen application rates have different effects on the soil's mineralization and nitrification, whereas different soil types have different responses to nitrogen application rates.

Organic improvement materials have a significant effect on improving soil fertility and productivity. Straw has been used in soil to help minimize pollutants and to enrich the soil, and this approach is being encouraged in many countries. The incorporation of straw into the soil has a significant effect on soil and the atmosphere, for example, by increasing the content of soil organic carbon, improving the soil's structure and adjusting the pH of the soil [16]. Straw is composed of different organic contents, which are not easily transformed into the soil via microbial decomposition compared with other organic matter and humic and fulvic acids [17,18]. The incorporation of straw increases the soil nutrients via carbon cycling through microbial activities [19]. Similarly, the application of enriched compost has also been found to be an attractive option to increase the availability of various nutrients such as nitrogen, phosphorus and potassium [20–23].

To sum up, the transformation of nitrogen in the soil is affected by factors such as soil water, heat, salt environment, organic matter, nitrogen application and microorganisms. At present, the research on the transformation of nitrogen has generally been carried out from the perspective of returning straw and the application of nitrogen alone, and most of these studies have been aimed at non-saline soil. This present study assumed that returning straw to the field can slow down the mineralization and nitrification of nitrogen in saline soil and that excessive nitrogen application can enhance the mineralization and nitrification of nitrogen in saline soil. Through an experiment on the effect of returning straw and applying nitrogen on the mineralization and nitrification of nitrogen in saline soil, this study aimed to verify that returning straw slows down the mineralization and nitrification of nitrogen in saline soil under conditions of reduced nitrogen. The results of this study are of great significance for reducing the risk of environmental pollution caused by nitrate leaching in saline–alkaline farmland and reducing the loss of nitrogen to environmental pollution.

2. Materials and Methods

2.1. Overview of the Research Area

The saline soil samples were collected from Sandaoqiao Town, Hangjinhou Banner, Bayannur City, which belongs to the arid zone in the west of the Hetao Irrigation District,

Inner Mongolia. The study area has a temperate continental monsoon climate, with an average annual temperature of 7.9 °C; annual average precipitation and evaporation of 136.5 mm and 1953.9 mm, respectively; an average wind speed of 2.2 m/s; 3200 h of sunshine and a frost-free period of 152 days.

2.2. Experimental Materials

The test soil was taken from the surface 0–20 cm soil from Chengni Village (40°49′34.463″ N, 106°54′29.463″ E), Sandaoqiao Town, Hangjinhou Banner, with a salt content of 0.4% (moderately saline soil). After collection, the saline–alkaline soil was first dried, then ground and passed through a 2 mm sieve for test using. The test straw was corn straw, in which the total carbon and total nitrogen contents were 444.69 g/kg and 6.19 g/kg, respectively, and the C/N ratio was 71.8. The physical and chemical properties of the saline soil are shown in Table 1.

Table 1. Physical and chemical properties of the saline soil.

Bulk Density/ kg/cm ³	pH	Conductivity/ dS/m	Ammonium Nitrogen/ mg/kg	Nitrate Nitrogen/ mg/kg	Inorganic Nitrogen/ mg/kg
1.45	8.0	2.40	13.79	18.88	32.67

2.3. Experimental Design

In this study, a method of culture with indoor ventilation and a constant temperature was adopted. A split-plot test design with the return of straw and different nitrogen application rates was adopted. The main treatment was returning corn straw, with straw application rates of 0 g (C0) and 0.64 g (C1), and the secondary treatment was nitrogen (urea) application, applying amounts of 0 g (N0), 0.015 g (N1) and 0.03 g (N2) urea, respectively. There were 6 treatments in total, including C0N0, C0N1, C0N2, C1N0, C1N1 and C1N2, as shown in Table 2. Three replicates were set for each treatment, and the average value of the three replicates was used for the experimental results.

Table 2. Design of the nitrogen transformation experiment on returning straw and applying nitrogen.

Treatment	C0N0	C0N1	C0N2	C1N0	C1N1	C1N2
Weight of saline soil/g	200	200	200	200	200	200
Weight of straw/g	0	0	0	0.64	0.64	0.64
Weight of urea/g	0	0.015	0.03	0	0.015	0.03

Each repeated treatment was tested in 250 mL plastic bottles (more than 300 g of soil could be placed into these bottles). The mouth of each bottle was tightly sealed with plastic wrap and a rubber band, and several small holes were made on the surface of the plastic wrap. Then, the bottles were placed in an incubator at 25 °C for culture. The saturated water content of the saline–alkaline soil used in the test was 36.4%, and the field water capacity was 30.0%. In order to simulate the soil water conditions after the irrigation of farmland, the test soil samples were replenished with water every day to keep the soil water content at 30% during the indoor cultivation process. The incubation test lasted for 35 days, and soil samples were collected on Days 1, 3, 7, 15, 25 and 35 of the test. The nitrate and ammonium nitrogen contents of the samples were measured.

2.4. Test Index and Method

The soil EC and pH were determined by the potentiometric method. The content of ammonium nitrogen ($\text{NH}_4^+\text{-N}$) in the soil was determined by 2 mol/L KCl extraction indophenol blue colorimetry. The content of soil nitrate nitrogen ($\text{NO}_3^-\text{-N}$) was determined by dual wavelength ultraviolet spectrophotometry. Soil organic matter was determined by the potassium dichromate volumetric external heating method. The content of total nitrogen

in soil was determined by the semi-micro-Kjeldahl method. The available phosphorus in the soil was determined by the 0.5 mol/L NaHCO₃ method. The formula used for calculating each index in this study was as follows:

$$N_x = \frac{[(NO_3^- - N)_t - (NO_3^- - N)_{t_0}]}{t - t_0} \quad (1)$$

where N_x is the net nitrification rate in mg $NO_3^- - N \cdot kg^{-1} \cdot d^{-1}$; $(NO_3^- - N)_t$ and $(NO_3^- - N)_{t_0}$ are the $NO_3^- - N$ content at t d and 0 d of culturing, respectively, in mg $NO_3^- - N \cdot kg^{-1}$; and t is the day of culture the test, where t_0 indicates 0 d.

The soil net nitrogen mineralization rate N_m was calculated according to Equation (2):

$$N_m = \frac{[(NH_4^+ - N)_t + (NO_3^- - N)_t] - [(NH_4^+ - N)_{t_0} + (NO_3^- - N)_{t_0}]}{t - t_0} \quad (2)$$

where N_m is the soil net nitrogen mineralization rate, in mg $(NH_4^+ - N) + (NO_3^- - N) \cdot kg^{-1} \cdot d^{-1}$; and $[(NH_4^+ - N)_t + (NO_3^- - N)_t]$ and $[(NH_4^+ - N)_{t_0} + (NO_3^- - N)_{t_0}]$ are the content of $NH_4^+ - N + NO_3^- - N$ at t d and 0 d of the culture, respectively, in mg $NH_4^+ - N + NO_3^- - N \cdot kg^{-1}$.

2.5. Data Analysis

Excel 2007 and SigmaPlot V12.5 were used to calculate the test data and plot the chart. SPSS 19.0 software was used for the statistical analysis, and Duncan's method was used for multiple comparisons.

3. Results

3.1. Effects of Different Treatments on the Mineralization Rate of Soil Nitrogen

The dynamic changes in the relationship between the mineralization rate of soil nitrogen and the incubation time were similar under the different treatments in saline soil (Figure 1). Under the conditions of not returning the straw, the nitrogen mineralization rate of the saline soil in each treatment gradually decreased to a stable level with the extension of the incubation time. The mineralization rate of soil nitrogen in each treatment was C0N2 > C0N1 > C0N0. For Days 0–7, the mineralization rate of nitrogen in the saline soil decreased rapidly, and the mineralization rate of C0N1 decreased the fastest. The mineralization rates of C0N0, C0N1 and C0N2 decreased by 86.91%, 89.26% and 83.64%, respectively.

Under the conditions of returning straw to the field, the nitrogen mineralization rate of the saline soil in each treatment decreased gradually and became stable with the extension of the incubation time. The nitrogen mineralization rate of the saline soil in each treatment was C1N2 > C1N1 > C1N0. Within Days 0–7, the mineralization rate decreased rapidly, and the mineralization rates of C1N0, C1N1 and C1N2 decreased by 87.46%, 87.20% and 81.83%, respectively. The reductions in the rates of C1N1 and C1N2 were very similar. In the process of cultivation, returning straw inhibited the mineralization of nitrogen in saline soil under the reduced nitrogen and no-nitrogen fertilizer treatments and promoted nitrogen mineralization in the saline soil under the high-nitrogen treatment.

During the whole incubation time, there were significant differences in the nitrogen mineralization rates of saline soil among the different nitrogen application treatments (Table 3). The nitrogen mineralization rate of saline soil under the different straw treatments was significantly different from 0 to 3 days of incubation, and there was no significant difference throughout the rest of the time. The nitrogen application rate had no significant difference in the effects on the nitrogen mineralization rate of saline soil when the incubation time was 0–1 days and 3–15 days. The interaction of returning straw and nitrogen application (C × N) had a significant effect on the nitrogen mineralization rate of the saline soil when the incubation time was 1–3 days and 15 days.

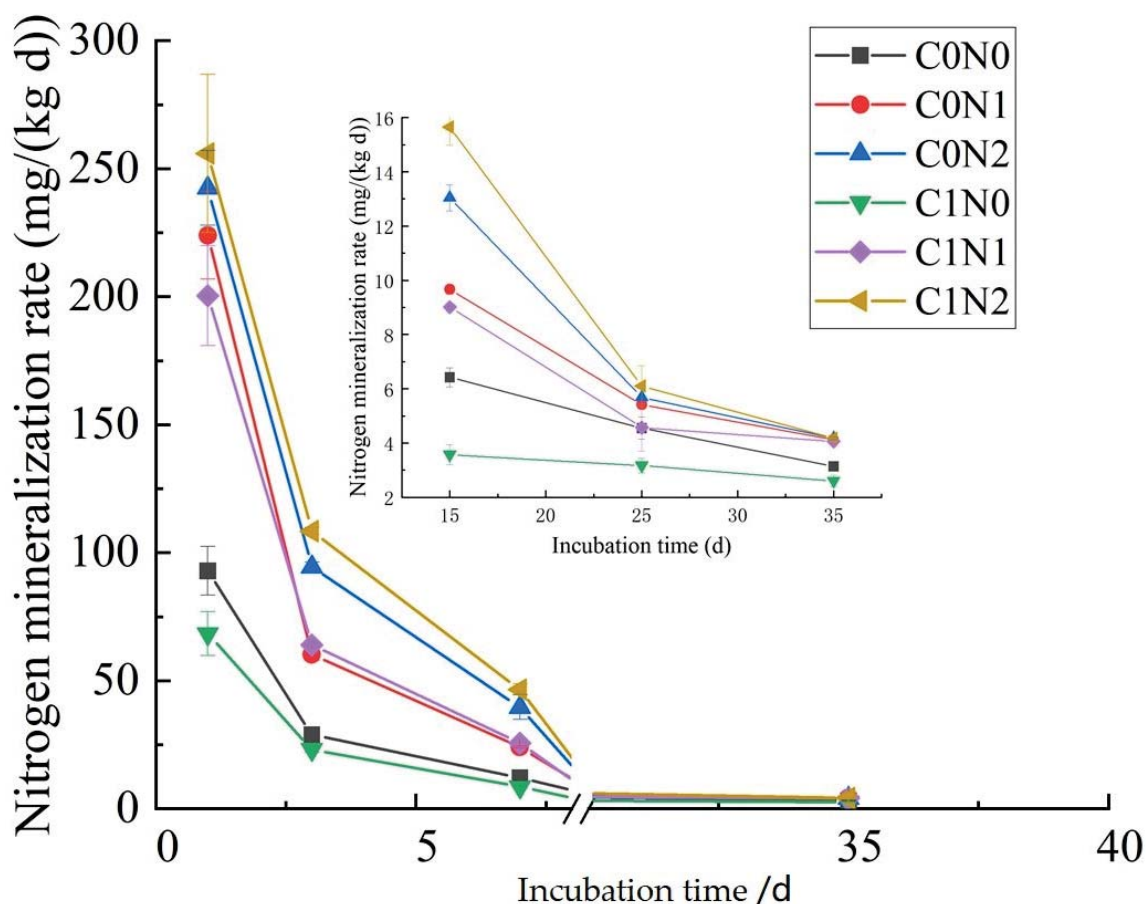


Figure 1. Dynamic changes in the nitrogen mineralization rate in saline soil during cultivation.

Table 3. ANOVA of the nitrogen mineralization rate of saline soil with the return of straw and the application of nitrogen.

Treatment	1 d		3 d		7 d		15 d		25 d		35 d	
	F	p	F	p	F	p	F	p	F	p	F	p
C	0.539	0.477	23.556	<0.001	2.148	0.168	2.391	0.148	6.289	0.028	11.336	0.006
N	41.966	<0.001	2814.437	<0.001	297.619	<0.001	787.073	<0.001	23.614	<0.001	205.053	<0.001
C × N	0.631	0.549	48.142	<0.001	7.539	0.008	67.871	<0.001	4.768	0.03	8.572	0.005

3.2. Effect of Different Treatments on the Nitrification Rate of Soil Nitrogen

The dynamic changes in the relationship between the nitrogen nitrification rate and the incubation time of each treatment in saline soil were similar (Figure 2). When no straw was returned to the field, the nitrogen nitrification rate of each nitrogen treatment in saline–alkaline soil decreased gradually throughout the incubation period until it became stable. At the beginning of incubation, the nitrogen nitrification rate of each treatment in saline soil was $C0N0 > C0N1 > C0N2$. At the early stage of the experiment, the application of nitrogen inhibited nitrification, and the intensity of this inhibition was different among different nitrogen application rates. The nitrification rate decreased rapidly in 0–3 days, and the nitrification rate of $C0N0$ decreased the fastest. The nitrification rates of $C0N0$, $C0N1$ and $C0N2$ decreased by 68.01%, 67.42% and 60.52%, respectively. However, after 3 days of indoor incubation, the nitrogen nitrification rate of the saline soil in each treatment was $C0N0 < C0N1 < C0N2$, which indicated that the nitrogen application rate gradually promoted nitrification.

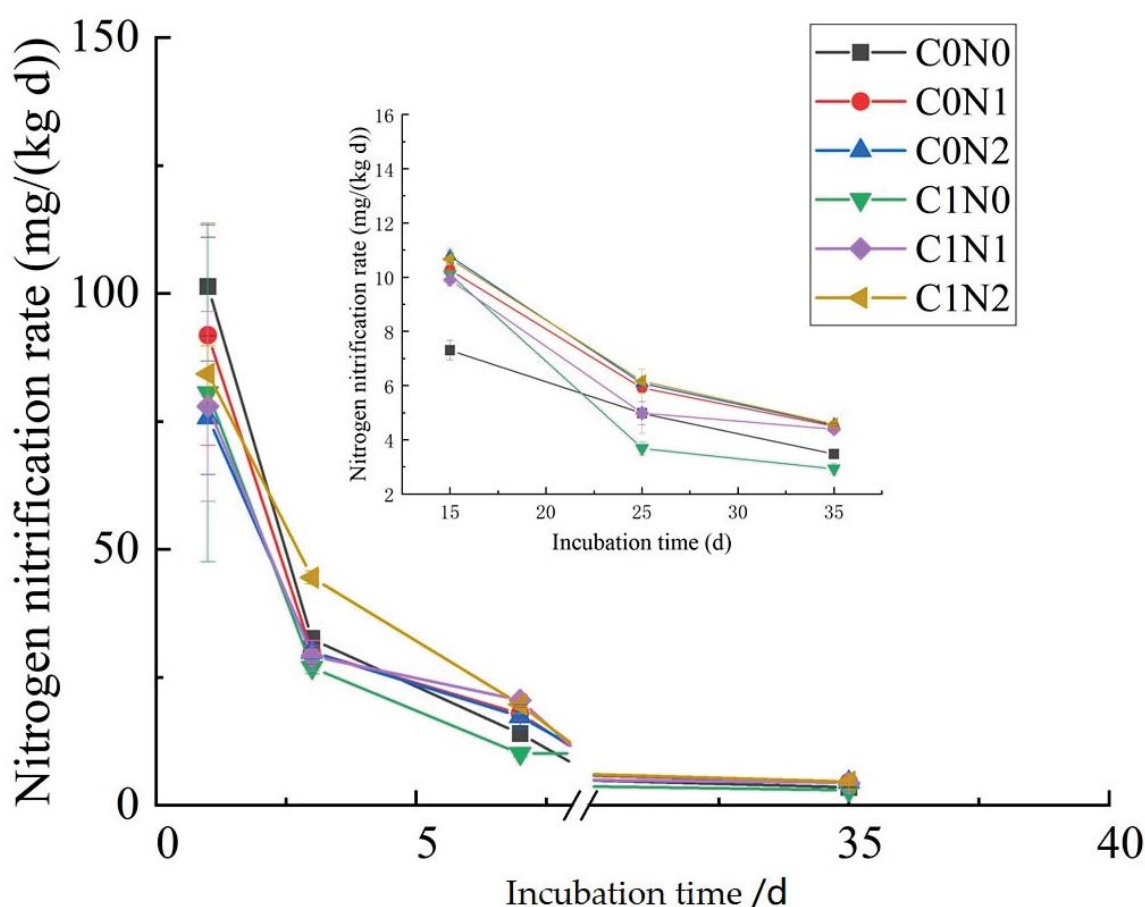


Figure 2. Dynamic changes in the nitrification rate of nitrogen in saline soil during incubation.

Under the conditions of returning straw to the field, the nitrogen mineralization rate of saline soil treated with nitrogen fertilizer decreased gradually until it stabilized during the incubation test. At the initial stage (0–3 d), the nitrification rate decreased rapidly. The nitrification rate of each nitrogen application treatment was $C1N2 > C1N0 > C1N1$. The nitrification rates of C1N0, C1N1 and C1N2 decreased by 66.62%, 62.54% and 47.21%, respectively, and the nitrification rate of C1N2 decreased the slowest. Therefore, compared with no nitrogen, the application of nitrogen (C1N2) will promote nitrification, whereas applying a small amount of nitrogen (C1N1) will inhibit nitrification. After 3 days of incubation, the nitrification rate of nitrogen in the saline soil under each treatment was $C1N0 < C1N1 < C1N2$, and the effect of the nitrogen application on the nitrification rate changed from the initial stage (0–3 d) and then reduced the nitrification rate. Returning straw slowed down the nitrification of nitrogen in saline soil under the reduced nitrogen and no-nitrogen fertilizer treatments, whereas the high-nitrogen treatment promoted the nitrification of nitrogen in saline soil.

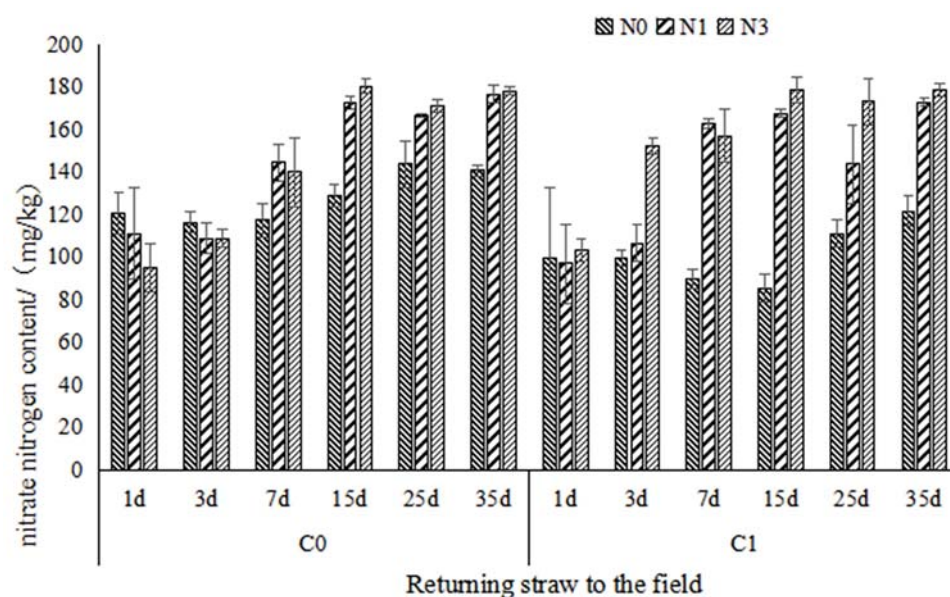
After incubation for 0–7 days, there was no significant difference in the nitrification rate of soil nitrogen under different nitrogen application rates (as shown in Table 4), but after 7 days, there were significant differences in the nitrification rate of soil nitrogen under different nitrogen application rates. There was no significant difference in the nitrification rate between the treatments returning straw and not returning straw for 0–15 days. After 15 days, there was a significant difference in the nitrification rate of soil nitrogen between returning straw and not returning straw. The interaction between returning straw and the nitrogen application rate had a significant effect on the nitrification rate of nitrogen in the saline soil after 3 days of incubation.

Table 4. ANOVA of the effects of returning straw and the nitrogen application rate on the nitrification rate of nitrogen in saline–alkaline soil.

Treatment	1 d		3 d		7 d		15 d		25 d		35 d	
	F	p	F	p	F	p	F	p	F	p	F	p
C	0.515	0.487	9.485	0.01	0.331	0.575	2.391	0.148	13.818	0.003	15.675	0.002
N	0.274	0.764	31.38	<0.001	47.449	<0.001	787.073	<0.001	29.312	<0.001	265.892	<0.001
C × N	0.534	0.600	45.075	<0.001	10.598	0.002	67.871	<0.001	4.576	0.033	10.2	0.003

3.3. Effects of Different Treatments on the Soil Nitrogen Content

It can be seen from Figure 3 that the soil nitrate nitrogen content of each nitrogen application treatment increased slowly with the extension of the incubation time without straw and reached the peak value on Day 15 of incubation. The nitrate nitrogen content of saline soil under the C0N0, C0N1 and C0N2 treatments increased from 18.88 mg/kg on Day 0 to 140.44 mg/kg, 176.50 mg/kg and 178.08 mg/kg on Day 35 of incubation, respectively. The nitrate nitrogen content of the saline soil under each nitrogen application treatment was significantly higher than that under the no-nitrogen application treatment. From 0 to 3 days of incubation, the order of nitrate nitrogen content in the straw-free saline soil with the addition of nitrogen was C0N0 > C0N1 > C0N2. Seven days later, the order of nitrate nitrogen content in the straw-free saline soil with the addition of nitrogen at the same sampling time point was C0N0 < C0N1 < C0N2.

**Figure 3.** Dynamic changes in the nitrate nitrogen content of saline soil during cultivation.

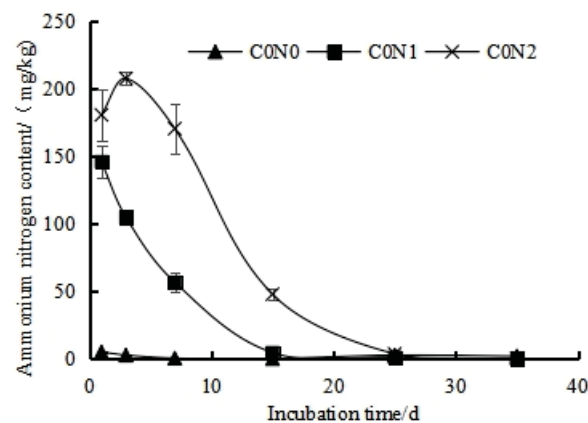
Under the conditions of returning straw to the field, the soil nitrate nitrogen content of each nitrogen application treatment increased slowly with the extension of the incubation time and reached the peak value on Day 15 of incubation. The order of the nitrate nitrogen content of saline soil with the application of nitrogen and returning straw was C1N0 < C1N1 < C1N2 (except on the seventh day of cultivation). For Days 0–3 of the culture experiment, returning straw significantly reduced the nitrate nitrogen content.

According to the analysis of variance in Table 5, after 7 days of incubation, the amount of nitrogen applied had a very significant impact on the content of nitrate nitrogen in the saline soil under the addition of straw. In the incubation period from Days 15–25, returning straw had a significant effect on the nitrate nitrogen content in saline soil. After 3 days of incubation, the interaction of returning straw and the nitrogen application rate had a significant impact on the nitrate nitrogen content in the saline soil.

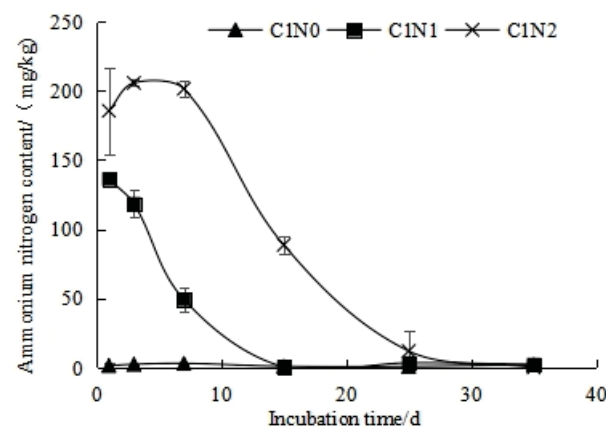
Table 5. ANOVA of the effect of returning straw and the nitrogen application rate on the nitrate nitrogen content in saline soil.

Treatment	1 d		3 d		7 d		15 d		25 d		35 d	
	F	p	F	p	F	p	F	p	F	p	F	p
C	0.515	0.487	1.747	0.211	0.327	0.578	57.910	<0.001	30.06	<0.001	8.368	0.014
N	0.275	0.764	5.771	0.018	47.474	<0.001	430.798	<0.001	64.309	<0.001	141.435	<0.001
C × N	0.533	0.600	8.288	0.005	10.612	0.002	36.764	<0.001	10.041	0.003	5.366	0.022

The dynamic changes in the ammonium nitrogen content of the saline soil are shown in Figure 4. When no straw was returned to the field, the content of ammonium nitrogen in the saline soil under the C0N0 treatment decreased slowly with an increase in the culture time, from 13.79 mg kg^{−1} on Day 0 of the culture to 2.23 mg kg^{−1} on Day 35. The ammonium nitrogen content of each nitrogen application treatment in the saline soil was significantly higher than that of the C0N0 treatment without the application of nitrogen. The content of ammonium nitrogen in the C0N1 soil decreased significantly with the incubation time, whereas the content of ammonium nitrogen under the C0N2 treatment increased first and then decreased. The order of ammonium nitrogen content in the nitrogen application treatments was C0N0 < C0N1 < C0N2. After culture, the content of ammonium nitrogen in the soil of each nitrogen application treatment was 2.23, 0.46 and 1.48 mg kg^{−1}, respectively, and there was no significant difference among the three treatments.



(a)



(b)

Figure 4. Changes in the ammonium nitrogen content in saline soil during cultivation. (a) Without straw returning. (b) Straw returning.

When straw was returned to the field, the content of ammonium nitrogen in the saline soil under the C1N0 treatment without the application of nitrogen was 13.79 mg/kg on Day 0 of the incubation, which continued to decrease with the incubation time until it reached 2.20 mg/kg on Day 35. The content of ammonium nitrogen in the saline soil under each nitrogen application treatment was significantly higher than that under the C1N0 treatment without the application of nitrogen. The content of ammonium nitrogen in the saline soil was significantly higher than that under the no-nitrogen treatment. During the whole incubation period, the content of ammonium nitrogen in the C1N1 soil decreased significantly with an increase in the incubation time, whereas that under the C1N2 treatment increased first and then decreased during the incubation period. Similar to soil without the return of straw, the order of the ammonium nitrogen content under each nitrogen application treatment in saline soil was C1N0 < C1N1 < C1N2. After the culture, the ammonium nitrogen content of each nitrogen application treatment was 2.20, 2.30 and 0.43 mg kg⁻¹, respectively, and there was no significant difference among the three treatments. Similar to the situation with no return of straw, the order of ammonium nitrogen in the saline soil under the different nitrogen application treatments was C1N0 < C1N1 < C1N2. After the culture, the content of ammonium nitrogen in the soil under the different nitrogen application treatments was 2.20, 2.30 and 0.43 mg/kg, respectively. There was no significant difference among the three treatments.

According to the analysis of variance in Table 6, for the incubation period of 0–7 d, the nitrogen application rate had a very significant impact on the ammonium nitrogen content of saline soil. For the incubation period of 7–25 days, returning straw alone, as well as the simultaneous effect of returning straw and the nitrogen application rate, had a significant impact on the content of ammonium nitrogen in the saline soil.

Table 6. ANOVA of the effects of returning straw and the nitrogen application rate on the ammonium nitrogen content in saline soil.

Treatment	1 d		3 d		7 d		15 d		25 d		35 d	
	F	p	F	p	F	p	F	p	F	p	F	p
C	0.884	0.366	0.857	0.373	6.928	0.022	215.712	<0.001	34.863	<0.001	0.0887	0.771
N	1235.051	<0.001	912.212	<0.001	528.741	<0.001	1519.48	<0.001	71.252	<0.001	0.741	0.497
C × N	1.917	0.190	1.566	0.249	10.465	0.002	279.308	<0.001	41.078	<0.001	0.966	0.408

4. Discussion

4.1. Effect of the Nitrogen Application Rate on the Nitrification and Mineralization of Nitrogen in Saline Soil

When inorganic nitrogen fertilizer was applied to the soil, it changed the C/N of the soil and significantly changed the intensity and time of the mineralization/assimilation process of nitrogen in the soil, thus affecting the dynamic changes in the soil inorganic nitrogen [24]. Generally speaking, an increase in the nitrogen application rate improves the mineralization of nitrogen in the soil [25] and also increases the mineralization rate of soil nitrogen, especially in red soil [26]. At the micro-level, the amount of nitrogen applied accelerated the mineralization rate of soil nitrogen in the rhizosphere soil [27]. Although the application of nitrogen has a positive effect on the maintenance of soil fertility, long-term application of high amounts of chemical fertilizer nitrogen significantly reduces the soil's mineralization ability [28].

In this study, the order of the mineralization rate was C0N2 > C0N1 > C0N0. When straw was not returned to the field, the nitrogen mineralization rate in saline soil decreased rapidly over Days 0–7, and the mineralization rates of C0N0, C0N1 and C0N2 decreased by 86.91%, 89.26% and 83.64%, respectively. Moreover, the mineralization rate of C0N1 decreased the fastest. The amount of nitrogen fertilizer promoted the mineralization rate of soil nitrogen within a certain range, but excessive amounts of nitrogen fertilizer inhibited the mineralization of nitrogen in the initial stage of cultivation (0–3 d), which was consistent with previous research results on non-saline soil. Soil nitrification is an important step

in providing nitrogen for plant growth. The application of nitrogen fertilizers to the soil significantly increases the amount and activity of nitrifying bacteria and enhances the nitrification rate of soil [10]. The nitrification rate without nitrogen fertilizer was the highest at the initial stage (0–3 d), but there was no significant difference in the nitrification rate among the different nitrogen application rates. The nitrification rate of C0N1 was the highest when cultured for 1 week, and there was a significant difference between the nitrification rate of C0N1 and that of the no-fertilizer treatment. From Day 15 until the end of the incubation period, the nitrification rate of C0N2 was high, and the nitrification rates of N1 and N2 had no significant difference only on Day 35, whereas the nitrification rates of soil nitrogen at other time points had significant differences. The amount of nitrogen applied at the initial stage of culture (0–3 d) promoted nitrification, but an excessive amount of nitrogen had no significant effect on nitrification.

4.2. Effect of Returning Straw on the Nitrification and Mineralization of Nitrogen in Saline Soil

The mineralization of soil nitrogen is a biological process controlled by microorganisms, and the population size and activity of microorganisms are closely related to the soil nutrient status, temperature, humidity and other environmental factors. Therefore, when the environmental factors were the same, the mineralization of soil nitrogen was affected mainly by the soil nutrient status. When different amounts of external carbon were added to the soil, this increased the soil C/N ratio, affected the population size and activity of soil microorganisms, and changed the mineralization process of soil organic nitrogen. In this research, the mineralization rate of saline soil decreased with an increase in the C/N ratio under the treatments with no nitrogen application and reduced nitrogen under the conditions of returning straw to the field. Especially in the first 3 days of the incubation test, the mineralization rate decreased rapidly. Under the conditions of the high-nitrogen treatment, the C/N ratio of saline soil could be less than 30, and returning straw to the field promoted mineralization. It is generally believed that when the C/N ratio is greater than 30, the microbial fixation of inorganic nitrogen is greater than the mineralization of organic nitrogen, which is manifested as the net assimilation of inorganic nitrogen. When the C/N ratio is less than 30, the mineralization of organic nitrogen is greater than the biological fixation of inorganic nitrogen [10], which is manifested by the increase in the mineralization rate of soil organic chlorine. The input of a large amount of carbon and nitrogen sources improves the aeration of the soil [29]; such an input not only stimulates the activities of microorganisms in the soil, but it also increases the ability of the soil microorganisms to mineralize and decompose organic nitrogen, thus slowing down the rate of consuming ammonia nitrogen [30–32].

Compared with the high nitrogen application rate, the treatment of returning straw to the field combined with the reduced application of nitrogen fertilizer in this study reduced the nitrification rate of saline soil and slowed down the formation rate of nitrate nitrogen. This phenomenon showed that the increase in the NH_4^+ content did not promote soil nitrification, and returning straw to the field slowed down the nitrification of saline soil [33,34]. This was caused mainly by the high C/N ratio of the straw of the crop, so when the straw was returned to the field, a large number of carbon sources entered the soil, significantly increasing the C/N ratio of the soil and promoting the biological fixation of NH_4^+ by soil microorganisms or clay particles. To sum up, previous studies have shown that returning straw to the field can improve the physical and chemical properties of saline soil, increase the amount of soil microorganisms and enhance the ability of the microorganisms to mineralize and decompose organic nitrogen. The research in this article showed that returning straw to the field can not only improve the soil mineralization rate but also slow down nitrification and reduce the risk of NO_3^- -N losses through leaching. Therefore, returning straw to the field is an effective way to reduce the salinization barrier and improve the nutrient utilization efficiency.

5. Conclusions

Under the conditions of not returning the straw, the application of nitrogen slowed down the nitrification rate and accelerated mineralization for Days 0–3 of incubation, whereas the nitrification and mineralization of soil nitrogen were significantly enhanced for Days 3–35 of the culture period.

After 7–35 days of incubation, the treatment of returning straw had a significant impact on the mineralization and nitrification of nitrogen in the saline soil, in which the reduced nitrogen and no-nitrogen fertilizer treatments slowed down the mineralization and nitrification of nitrogen in the saline soil, whereas the high-nitrogen treatment enhanced the mineralization and nitrification of nitrogen in the saline soil.

Returning straw and reducing the nitrogen fertilizer can retain more ammonium nitrogen, thus inhibiting the nitrification of soil nitrogen, reducing the environmental pollution risk of nitrate leaching and reducing soil nitrogen losses in saline soil. From the perspective of the transformation of soil nitrogen, returning straw and reducing the application of nitrogen fertilizer are more effective and environmentally friendly measures for improving saline soils.

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Article

Natural Regeneration of *Morus alba* in *Robinia pseudoacacia* Plantation and the Mechanism of Seed Germination and Early Seedling Growth Restriction in the Yellow River Delta

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Abstract: There is a wide range of naturally regenerated *Morus alba* in the declining *Robinia pseudoacacia* plantation of the Yellow River Delta. It is important to clarify the key mechanism of natural regeneration of *M. alba* for the transformation of declining *R. pseudoacacia* plantation. According to the death density of *R. pseudoacacia*, the plantation of *R. pseudoacacia* was divided into nondeclining, moderately declining, and severely declining forests. The structural characteristics of adult trees and seedlings of *M. alba* in different decline degrees forest were investigated. A pot experiment was conducted to study the seed germination and early seedling growth of *M. alba* in saline alkali soil and nonsaline alkali soil under different soil salt contents and light intensities. The results showed that the natural regeneration of *M. alba* was obviously affected by the decline of *R. pseudoacacia* plantation. With the increase of decline degree, *M. alba* density and seedling density first increased and then decreased, and were the highest in the medium decline plantation. Under full light intensity, the vigor index of *M. alba* seeds and the biomass of seedlings were significantly greater than those of 25% full light intensity. The germination rate and germination index under 1‰ soil salt content were significantly lower than those under 3‰, but the biomass of seedlings was on the contrary. The 1000-seed weight, seed germination, and seedling biomass of moderately declining *R. pseudoacacia* plantations were close to those of nonsaline alkali land, while significantly higher than those of nondeclining plantations, but the germination index of moderately declining *R. pseudoacacia* plantation was higher than that of nonsaline alkali land. Therefore, the germination ability of maternal trees in saline alkali land was higher than that in nonsaline alkali land under salt stress.

Keywords: coastal saline–alkali land; plantation decline; seedling density; maternal tree habitat; seed quality

1. Introduction

Planted forests are an important component of global forest resources. With the rapid increase in the area of global planted forests in recent decades [1], they play increasingly important roles in timber production, environmental improvement, landscape construction, and climate change mitigation [2]. China has the largest area of planted forests in the world. However, the management of planted forests are difficult because of lacking effective and long-term scientific theoretical guidance and sustainable management technology systems suitable for different regions of planted forests. For a long time, plantation forest management has overemphasized and pursued short-term productivity and economic benefits, favoring artificial regeneration and homogeneous pure forest cultivation patterns, ignoring the natural succession and regeneration of planted forests [2], which has led to a

serious decline in many planted forests. Natural regeneration of planted forests is currently attracting attention and is being explored in terms of stand structure [3], litter fall density [4], seedling adaptation [5,6], and seedling establishment [7,8]. However, current studies have shown that the natural regeneration of planted forests and their near-naturalistic succession are difficult to achieve [2,9,10]. Therefore, the elucidation of natural regeneration limitation mechanisms of planted forests is of great importance for their sustainable management.

Seed quality determines the ability of seeds to germinate and the quality of seedlings, and is one of the key factors determining the success of natural regeneration [11,12]. The growing environments of the maternal tree demonstrate significant influences on the quality of the seeds of the offspring, which is known as the maternal effect. The wide variety of environments experienced by maternal trees during seed production directly influences the characteristics (e.g., dormancy, longevity, etc.) of offspring seeds [13–15] and is considered to be an important determinant of natural regeneration [16]. Sionit and Kramer [17] found that exposure to water stress during the pod formation and filling stages of soybean led to a reduction in seed weight. The study of *Quercus brantii* found that the seedlings from drought-stressed maternal trees increased adaptability to drought [18]. The external temperature experienced by the parent plant also affects seed size [19]. Studies on annuals have found that drought stress experienced by grandparents and parents affects the performance of offspring [20]. Herman and Sultan [21] summarized the effects of the various environments experienced by the parent on the fitness of the offspring. For long-lived conifers, the variety of environments they experience provides a guarantee of offspring fitness [22]. Maternal effects can alter the adaptations of offspring in the short term and are more adaptable to changes in the external environment, especially in the context of global climate change, than genetic changes that can only occur over long periods of time in plants [11]. However, the duration and mode of action of the maternal effect is currently unclear.

Light intensity and soil salinity are important environmental factors that affect seed germination and seedling establishment of forests in coastal saline alkali land. During the stage of seed germination, light and salt stress have different effects. Generally, seed germination is not strongly related to light, but soil salinity has a significant effect on seed germination [23]. For non-salt-tolerant plants, seed germination is significantly inhibited as soil salt content increases [24,25], but for salt-tolerant plants, low salt concentrations have less effect on seed germination and even have some promotion [26,27]. During the seedling growth stage, light is the most important determinant of seedling understory growth and survival [6]. In order to intercept more light in the understory, plants increase the leaf biomass ratio and decrease the root biomass ratio [28]. As soil salinity increases, seedling growth is significantly inhibited. The root system is the first sensory organ of salt stress [29], and its biomass allocation increases, but root growth is significantly inhibited beyond the tolerance range [30]. A comparison revealed that plants may have opposing adaptation strategies when subjected to both low light and salt stresses. Therefore, it is important to explore the regeneration mechanisms under planted forests in coastal saline lands for the management of planted forests.

The Yellow River Delta is a typical global coastal saline land with shallow groundwater depth and high mineralization, and there are few tree species suitable for afforestation in this area. Monitoring and mastering of riparian vegetation biomass [31,32] and hydrology [33] is an important part of vegetation management. *Robinia pseudoacacia* forests planted in the 1970s and 1980s are the largest planted forests in the region, but they are now in severe decline and a large number of deaths have occurred. Yao et al. [34] found that *R. pseudoacacia* grew well when the groundwater depth was lower than 1.8 m during the low-water-level period. In winter, the groundwater level in some areas was lower than the sea level, and the incoming water from the Yellow River was relatively small, which caused seawater intrusion and increased the mineralization of groundwater, exacerbating the death of the *R. pseudoacacia* forest [34]. Therefore, the regeneration of *R. pseudoacacia* plantation has become an urgent demand. *Morus alba* is also an important silvicultural species in

the region [35] and is highly adaptable with strong tolerance to salt stress and drought stress [25,36]. Field surveys have revealed the widespread presence of naturally regenerated *M. alba* within *R. pseudoacacia* plantations in the region, but this phenomenon has not attracted enough attention. To reveal the natural regeneration pattern of *M. alba*, identify key limiting factors, and provide theoretical and technical support for the transformation of degraded *R. pseudoacacia* plantations, in this paper, we investigated the distribution characteristics of *M. alba* in *R. pseudoacacia* plantations with different degrees of decline, assessed their natural regeneration capacity, and analyzed the factors affecting the establishment of seedlings. At the same time, *M. alba* seeds in *R. pseudoacacia* forest and nonsaline alkali land were collected to study seed germination and early seedling growth under light intensity and salt stress, and to clarify the key influence mechanism of maternal tree habitat and environmental factors on seed germination and seedling establishment.

2. Materials and Methods

2.1. Study Area

The study was conducted in the Yellow River Delta area in the north of Shandong Province (37°35′~38°12′ N, 118°33′~119°20′ E). The region is a warm, temperate, semihumid continental monsoon climate zone. The average annual temperature is 11.9 °C, the average annual daily range is 10.7 °C, the average annual precipitation is 592.2 mm, the average annual evaporation is 1908.2 mm, and the average annual evaporation ratio is 3.22. The soil is mainly composed of fluvo aquic soil and saline soil. Tidal soil accounts for 44.46% of the total soil area in the region, and saline soil accounts for 50.88% of the total area in the region. The vegetation types in the area are few and simple, mainly herbs and shrubs, with few woody plants, and *Suaeda glauca*, *Phragmites australis*, and *Tamarix chinensis* are the main distribution species [37].

2.2. Experimental Design

2.2.1. Survey of *R. pseudoacacia* Planted Forests

Through fieldwork, the natural regeneration survey of *M. alba* was carried out in the *R. pseudoacacia* plantations in Shandong Yellow River Delta National Nature Reserve (A), Jiufenchang of Gudao Town (B), and Shenxiangou (C) (Figure 1). The planting spacing of *R. pseudoacacia* stands at the above three locations was 3 m × 4 m, and the stand characteristics were shown in Table 1. Based on the mortality density of *R. pseudoacacia*, the *R. pseudoacacia* plantations in the Jiufenchang was defined as an undeclined forest, Shenxiangou was defined as a moderately declining forest, and the reserve was defined as severely declining forest. Three randomly 20 m × 30 m sample squares were set up in each site. In each sample square, *R. pseudoacacia* and *M. alba* ≥ 1.5 m in height were defined as adult trees, and all trees were measured for diameter at breast height (DBH). Trees below 1.5 m in height were defined as seedlings and their height was measured. The number of dead *R. pseudoacacia* in the sample was also measured. Adult trees were classified into DBH sizes, with one diameter class for every 2 cm. Seedlings were divided into five height classes: 50–70 cm, 71–90 cm, 91–110 cm, 111–130 cm, and 131–150 cm. The soil was collected from 0–40 cm within the *R. pseudoacacia* forest and brought back to the laboratory. The soil salt content was measured by conductivity method. The pH value of soil was measured with a pH meter.

2.2.2. Collection of *M. alba* Seeds

In May 2019, mature *M. alba* fruits were collected from the Forestry Practice Base of Shandong Agricultural University in Tai'an (T), the *R. pseudoacacia* plantation in Jiufenchang (DW), and in Shenxiangou (DN). Among them, Tai'an was a typical nonsaline area. A total of 10 maternal trees were collected at each site. The *M. alba* fruits were repeatedly rubbed and rinsed five times, and the full seeds were selected and dried naturally. Using a thousand-seeds method, the 1000-seed weight per maternal tree was counted. The 1000-seed weight of T, DW, and DN was 1.99 ± 0.16 g, 0.98 ± 0.11 g, and 1.35 ± 0.14 g, respectively.

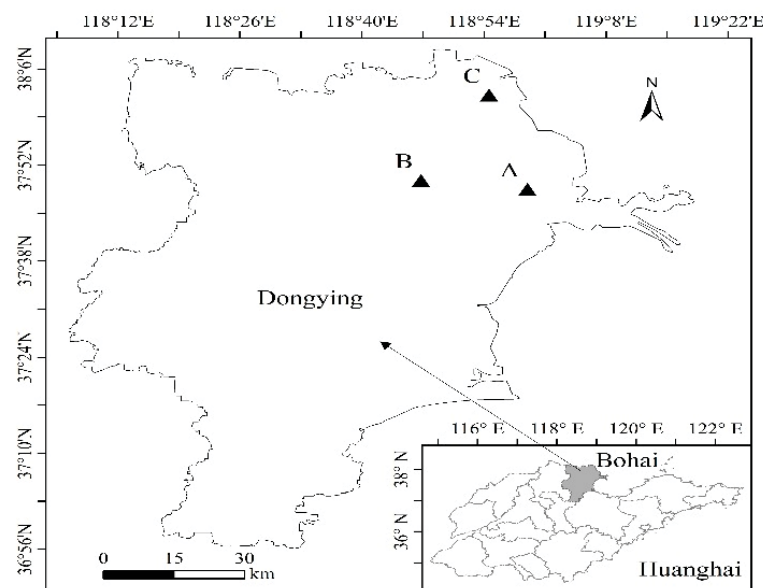


Figure 1. Geographical location of the study sites. A: Shandong Yellow River Delta National Nature Reserve; B: Jiufenchang of Gudao Town; C: Shenxiangou.

Table 1. Characteristics of stand structure of *Robinia pseudoacacia* plantation.

Indicators	Stand Age (Years)	Density of Standing Timber (Trees ha ⁻¹)	Average DBH (cm)	Dead Wood Density (Trees ha ⁻¹)	Soil Salinity (‰)	Soil pH
Jiufenchang	19	1033	8.33 ± 4.32	0	0.19	8.01
Shenxiangou	43	900	19.12 ± 2.88	100	0.21	7.92
Reserve	31	0	0	1200	0.23	7.86

2.2.3. Seed Germination and Seedling Growth Tests with Different Soil Salt Content, Light Intensity, and Maternal Tree Habitat

On 27 May 2019, seeds from different maternal tree habitats (T, DW, and DN) were taken separately and sown according to light intensity gradient (full light and 25% full light) and soil salt content (1‰ and 3‰), and five pots per treatment were sown with 50 seeds per pot. After the seeds were evenly spread on the soil surface, a thin layer of soil was covered to cover the seeds. Regular observations were recorded daily during the experiment to count the number of seeds germinated and watered regularly to keep the soil moist. The experiment ended on 5 November 2019. Three seedlings were selected from each pot, and then the seedlings were removed and divided into roots, stems, and leaves. After bringing it back to the laboratory, the root system was scanned by HP Scanjet 8200 scanner. The scanned images were then analyzed with Delta-T Area Meter Type AMB2 root parameter analysis software to obtain root length (RL, cm), root average diameter (RAD, cm), root surface area (RSA, cm²), and root volume (RV, cm³). The individual tissues were dried in an oven at 85 °C for 48 h. The dry weight was measured with an electronic balance (0.1 mg accuracy) and the seedling biomass (SB, root + stem + leaf mass, g), root biomass ratio (RMR, root mass/seedling biomass, g.g⁻¹), stem biomass ratio (SMR, stem mass/seedling biomass, g.g⁻¹), leaf biomass ratio (LMR, leaf mass/seedling biomass, g.g⁻¹), root shoot ratio (RSR, root mass/(leaf + stem biomass)), specific root length (SRL, total root length/root mass, cm.g⁻¹), and specific root surface area (SRA, total root surface area/root mass, cm².g⁻¹) indices were calculated.

Germination rate (Gr, %), mean germination time (MGT), germination index (Gi), and vigor index (Vi) were calculated as follows:

$$G_r = G_1/N \times 100 \quad (1)$$

$$MGT = \sum (D \times n_i) / \sum n_i \quad (2)$$

$$Gi = \sum (n_i / D) \quad (3)$$

$$Vi = S \times GI \quad (4)$$

where G_1 is the number of germination, N is the total number of tested seeds, n is the number of seeds germinating normally on each day, D is the number of days since seeds were placed in bed, G_t is the net germination number on each day, D_t is the corresponding germination day, and S is the dry weight of seedlings.

2.3. Data Analysis

Soil salt content, light intensity, and maternal tree habitat were used in a three-way ANOVA for the seed germination stage and seedling growth stage tests. The relevant data analyses were performed with SPSS 20.0 (SPSS Inc., Chicago, IL, USA) statistical analysis software, and multiple comparisons were performed. The test level was $p = 0.05$.

3. Results

3.1. Structural Characteristics of *M. alba* in the *R. pseudoacacia* Plantation

As seen in, Figure 2, *M. alba* were naturally distributed within the different declining *R. pseudoacacia* plantations. Within the nondeclining and severely declining *R. pseudoacacia* plantations, the density of adult *M. alba* were close: 633 and 656 trees ha^{-1} , respectively (Table 2). However, the density within moderately declining *R. pseudoacacia* stands was 7667 trees ha^{-1} , which was 12 times higher than both. Within the undeclined *R. pseudoacacia* forest, the DBH class structure was incomplete and the distribution showed a unimodal pattern, with the maximum density of 170 trees ha^{-1} at 8.1–10.0 cm DBH and 367 trees ha^{-1} at DBH greater than 8 cm. Within the severely declining *R. pseudoacacia* plantations, the diameter class structure was inverted-J-shaped, and the density was mainly distributed in the 2.1–12.0 cm DBH range with a density of 450 trees ha^{-1} and 222 trees ha^{-1} for DBH greater than 8 cm. Within moderately declining *R. pseudoacacia* stands, the diameter class structure was also inverted-J-shaped, with the largest number of diameter class 0–2 cm at a density of 4930 trees ha^{-1} , but none with the DBH greater than 8 cm.

Table 2. Characteristics of stand structure of *Morus alba* in the different declining *Robinia pseudoacacia* plantation.

Indicators	Density (Trees ha^{-1})	Chest Height Section Area (Trees ha^{-1})	Average Diameter at Breast Height (cm)	Seedling Density (Trees ha^{-1})
Jiufenchang	633	4.35	8.33 ± 4.32	No seedlings
Shenxiangou	7667	3.04	2.02 ± 0.10	467
Protected Areas	656	1.57	8.56 ± 3.91	26

The different declining *R. pseudoacacia* stands differed significantly in the number of *M. alba* seedlings (). No seedlings were found in the nondeclining *R. pseudoacacia* forests, and very few seedlings were found in the severely declining *R. pseudoacacia* forests, with a density of only 26 trees ha^{-1} . The density of seedlings within medium-declining *R. pseudoacacia* stands was 467 trees ha^{-1} and the distribution of plant height classes was unimodal. The maximum number of plants was 170 trees ha^{-1} at 91–110 cm plant height, after which the density decreased rapidly (Figure 3). Plant height was mainly distributed at 50–110 cm, accounting for 85.71% of the total number of seedlings (Figure 3).

3.2. Effect of Light Intensity and Soil Salinity on Seed Germination and Seedling Growth of *M. alba* Seeds

3.2.1. Seed Germination

The effect of light intensity on Gr, MGT, and Gi was not significant, the effect on Vi was significant (Table 3), and full light was higher than that of 25% full light (Figure 4). Soil

salt content had a significant effect on Gr and Gi, both being higher in 3‰ treatment than in 1‰ treatment, but not on MGT and Vi. Maternal tree habitat had a significant effect on Gr, MGT, Gi, and Vi. The Gr, MGT, and Vi of the DN habitat were not significantly different from those of the T habitat treatment but they were significantly greater than those of the DW habitat, and Gi of the DN habitat was significantly better than those of the T and DW habitat conditions (Figure 4). In terms of interaction, salinity and maternal tree habitat had a significant effect on Vi, and the interaction of light, salinity, and maternal tree habitat significantly affected Gr, MGT, Gi, and Vi. DN had a clear germination advantage in full light at 3‰ salt treatment, but the advantage was more pronounced in low light at 1‰ salt treatment (Figure 4).

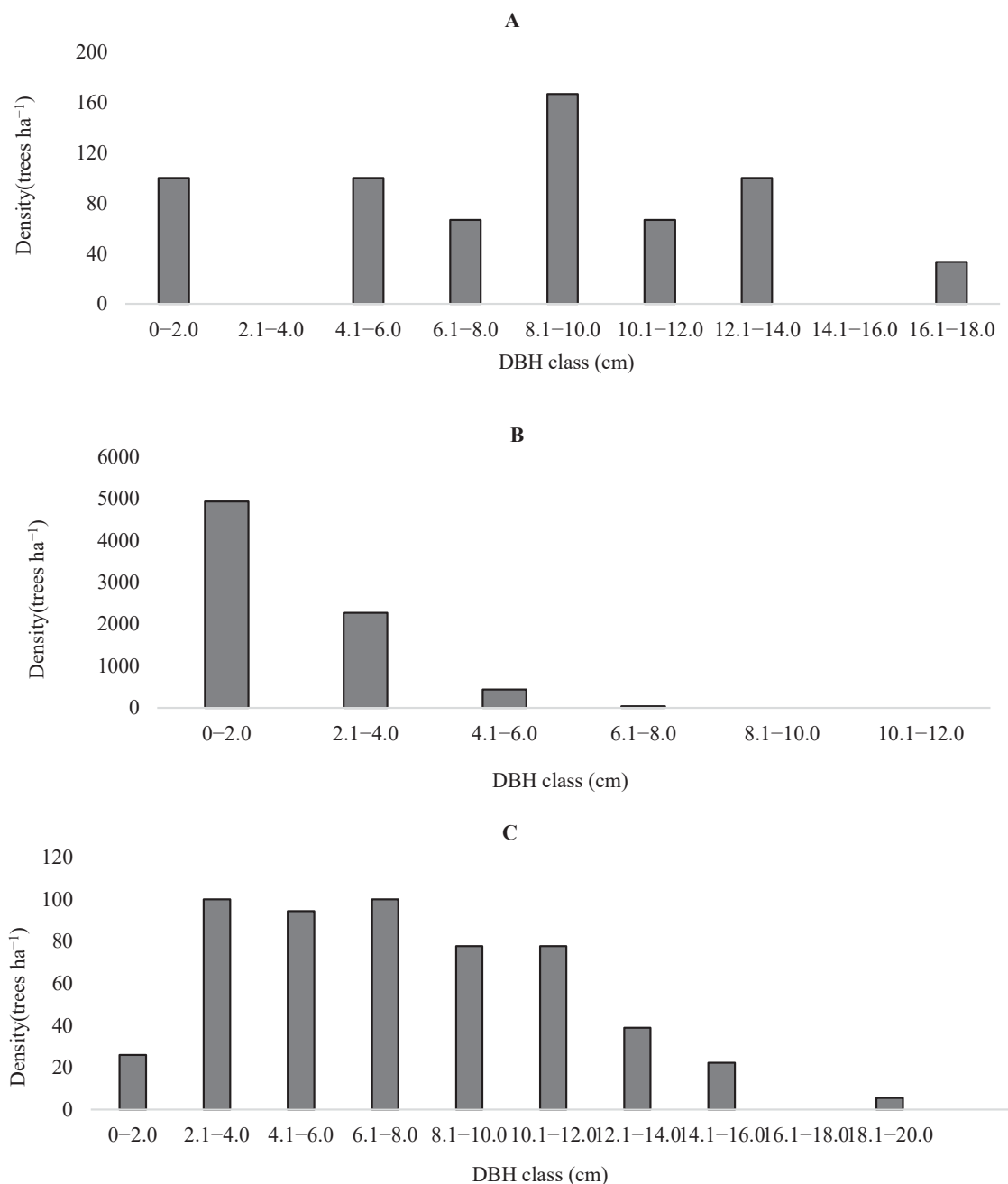


Figure 2. DBH class structure of *Morus alba* distributed in Jiufenchang (A), Shenxiangou (B), and reserve (C) *R. pseudoacacia* plantation.

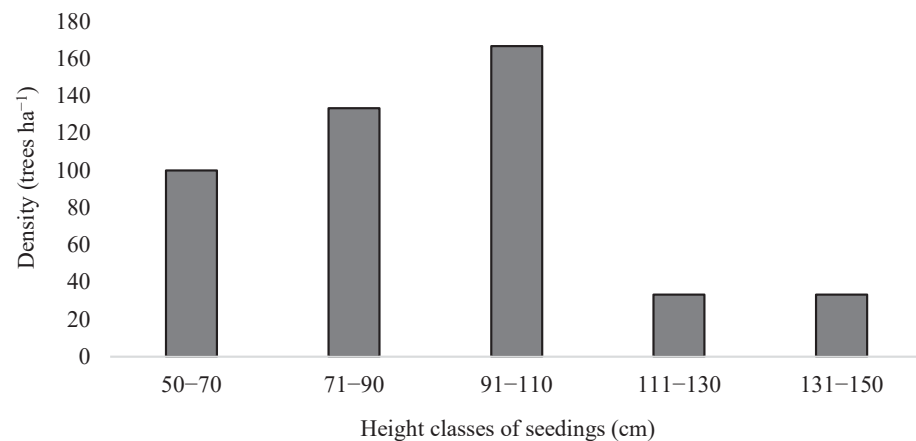


Figure 3. Distribution of height classes of *Morus alba* seedlings within the Shenxiangou *Robinia pseudoacacia* plantation.

Table 3. Three-factor variance analysis table of light intensity, soil salt content, and maternal tree habitat of *Morus alba* on seed germination and seedling growth. Gr: germination rate; MGT: mean germination time; Gi: germination index; Vi: vigor index; RMR: root biomass ratio; SMR: stem biomass ratio; LMR: leaf biomass ratio; RSR: root shoot ratio; SB: seedling biomass; RL: root length; RSA: root surface area; RAD: root average diameter; RV: root volume.

Indicators	Light (A)		Salt (B)		Maternal Tree Habitat (C)		A × B		A × C		B × C		A × B × C	
	F	p	F	p	F	p	F	p	F	p	F	p	F	p
Gr	0.03	>0.05	5.26	<0.05	54.58	<0.01	0.01	>0.05	1.66	>0.05	0.90	>0.05	12.35	<0.01
MGT	0.87	>0.05	0.68	>0.05	14.85	<0.01	0.60	>0.05	0.41	>0.05	1.14	>0.05	5.76	<0.01
Gi	0.64	>0.05	9.86	<0.01	69.90	<0.01	2.09	>0.05	1.34	>0.05	0.84	>0.05	5.29	<0.01
Vi	8.76	<0.01	2.55	>0.05	24.16	<0.01	0.02	>0.05	1.55	>0.05	5.89	<0.01	4.21	<0.05
RMR	0.00	>0.05	1.56	>0.05	2.92	>0.05	5.10	<0.05	3.78	<0.05	0.50	>0.05	4.36	<0.05
SMR	1.95	>0.05	0.60	>0.05	1.19	>0.05	0.79	>0.05	2.93	>0.05	5.83	<0.01	0.40	>0.05
LMR	1.70	>0.05	1.48	>0.05	2.62	>0.05	2.96	>0.05	4.95	<0.05	6.41	<0.01	1.39	>0.05
RSR	0.00	>0.05	1.34	>0.05	2.72	>0.05	5.13	<0.05	3.65	<0.05	0.49	>0.05	4.10	<0.05
SB	46.61	<0.01	24.72	<0.01	34.83	<0.01	4.86	<0.05	10.96	<0.01	2.32	>0.05	2.06	>0.05
RL	1.60	>0.05	2.08	>0.05	9.02	<0.01	0.93	>0.05	2.20	>0.05	0.00	>0.05	0.71	>0.05
RSA	2.60	>0.05	1.22	>0.05	9.99	<0.01	1.48	>0.05	3.01	>0.05	0.07	>0.05	0.98	>0.05
RAD	1.13	>0.05	3.53	>0.05	2.40	>0.05	2.50	>0.05	2.49	>0.05	0.40	>0.05	0.15	>0.05
RV	3.71	>0.05	0.49	>0.05	10.46	<0.01	2.03	>0.05	3.94	<0.05	0.20	>0.05	1.24	>0.05

3.2.2. Seedling Biomass Traits

Light intensity, salinity conditions, and maternal tree habitat had nonsignificant effects on RMR, SMR, LMR, and RSR, and had a highly significant effect on SB (Table 3). For SB, the full light treatment was higher than that of the 25% full light treatment, the 1‰ salt treatment was higher than that of the 3‰ salt treatment, and the T habitat was not significantly different from the DN habitat but was significantly better than that under the DW habitat (Figure 5).

Light intensity × salinity conditions and light intensity × maternal tree habitat had a significant effect on RMR, RSR, and SB, and a nonsignificant effect on SMR and LMR. There was a significant interaction between salinity conditions and maternal tree habitat for SMR, but not for RMR, LMR, RSR, and SB, and the interaction of light intensity × salinity conditions × maternal tree habitat was significant for RMR and RSR, suggesting that seedling biomass allocation was influenced by a combination of factors.

3.2.3. Seedling Root Morphology

The effects of light intensity and salinity conditions on RL, RAD, RSA, RV, SRL, and SRA were all nonsignificant, while the parent tree habitat had no significant effect on RAD

and a highly significant effect on RL, RSA, and RV (Table 3). The light intensity $\times$ maternal tree habitat interaction had a significant effect on RV, while the other types of interaction had no significant effect on RL, RAD, RSA, and RV. The effects of maternal tree habitat on RL, RSA, and RV were all nonsignificantly different but were significantly greater in the T and DN habitat treatments than in the DW habitat treatment (Figure 6).

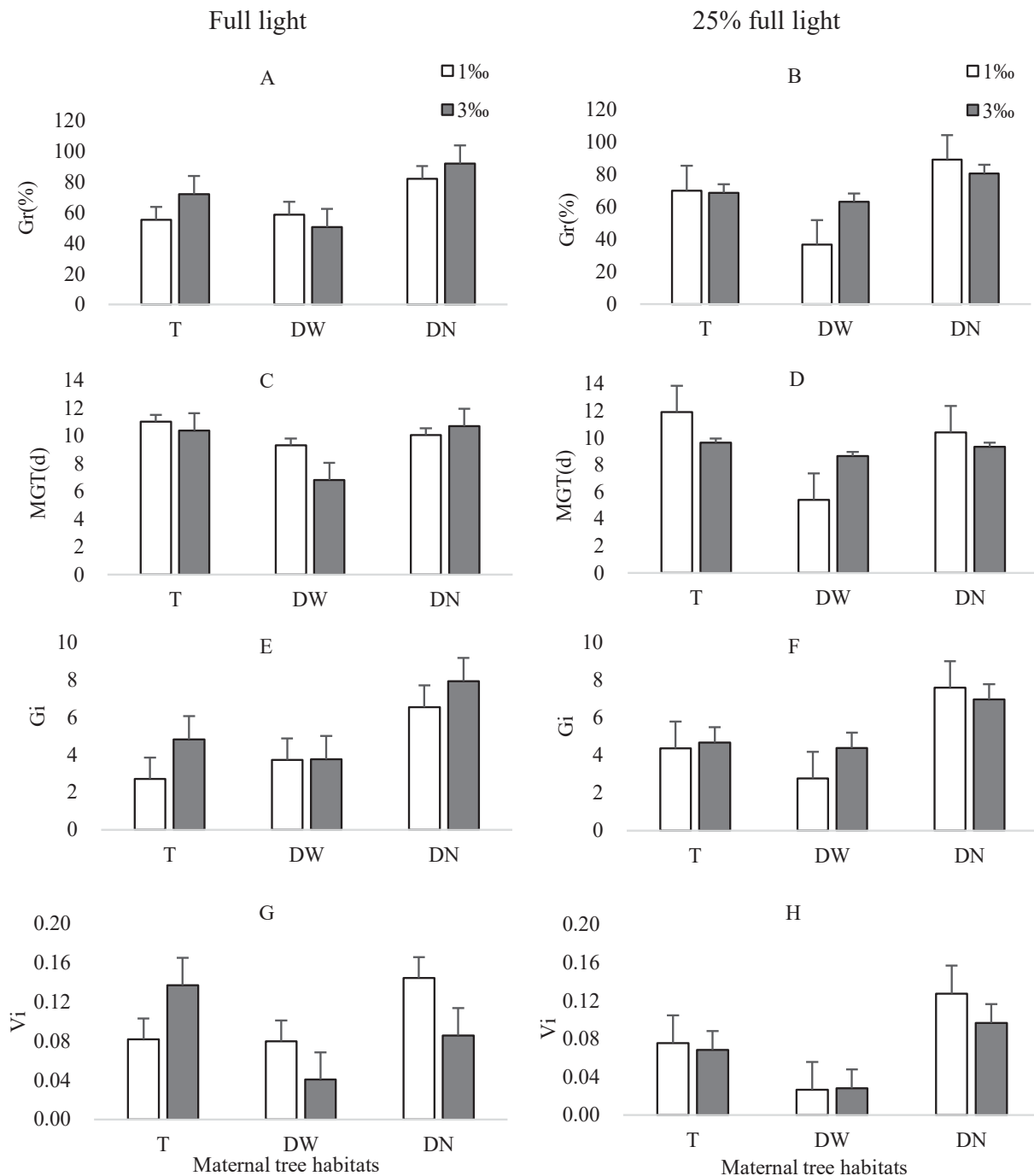


Figure 4. Effects of light intensity and salinity on seed germination of *Morus alba* from different maternal tree habitats. T: seeds from nonsaline soil; DW: seeds from Jiufenchang in saline–alkali land; DN: seeds from Shenxiangou in saline–alkali land. (A): Gr, full light; (B): Gr, 25% full light; (C): MGT, full light; (D): MGT, 25% full light; (E): Gi, full light; (F): Gi, 25% full light; (G): Vi, full light; (H): Vi, 25% full light.

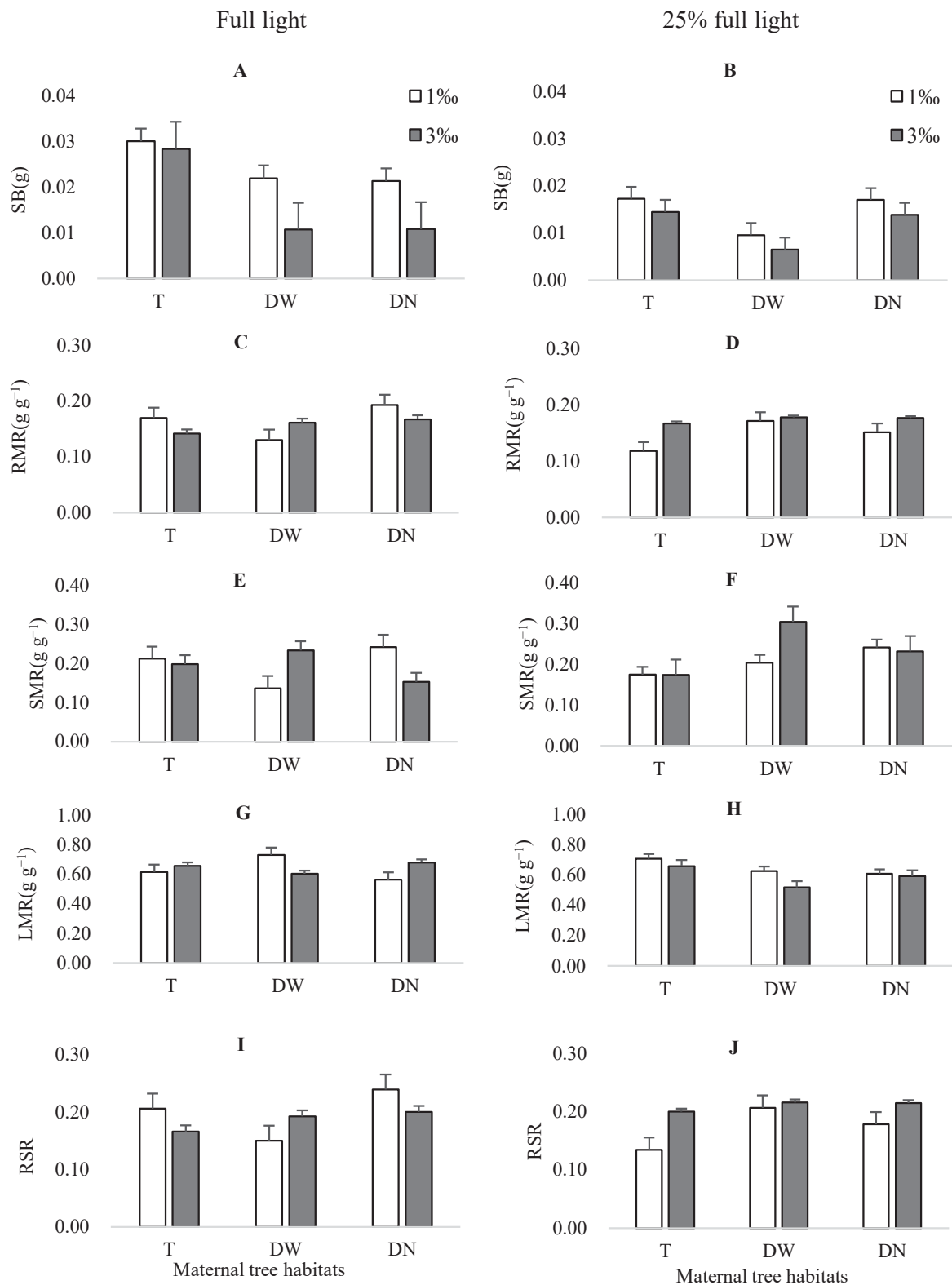


Figure 5. Effects of light intensity and salinity on biomass indices of *Morus alba* seedlings from different maternal tree habitats. T: seeds from nonsaline soil; DW: seeds from Jiufenchang in saline–alkali land; DN: seeds from Shenxiangou in saline–alkali land. (A): SB, full light; (B): SB, 25% full light; (C): RMR, full light; (D): RMR, 25% full light; (E): SMR, full light; (F): SMR, 25% full light; (G): LMR, full light; (H): LMR, 25% full light; (I): RSR, full light; (J): RSR, 25% full light.

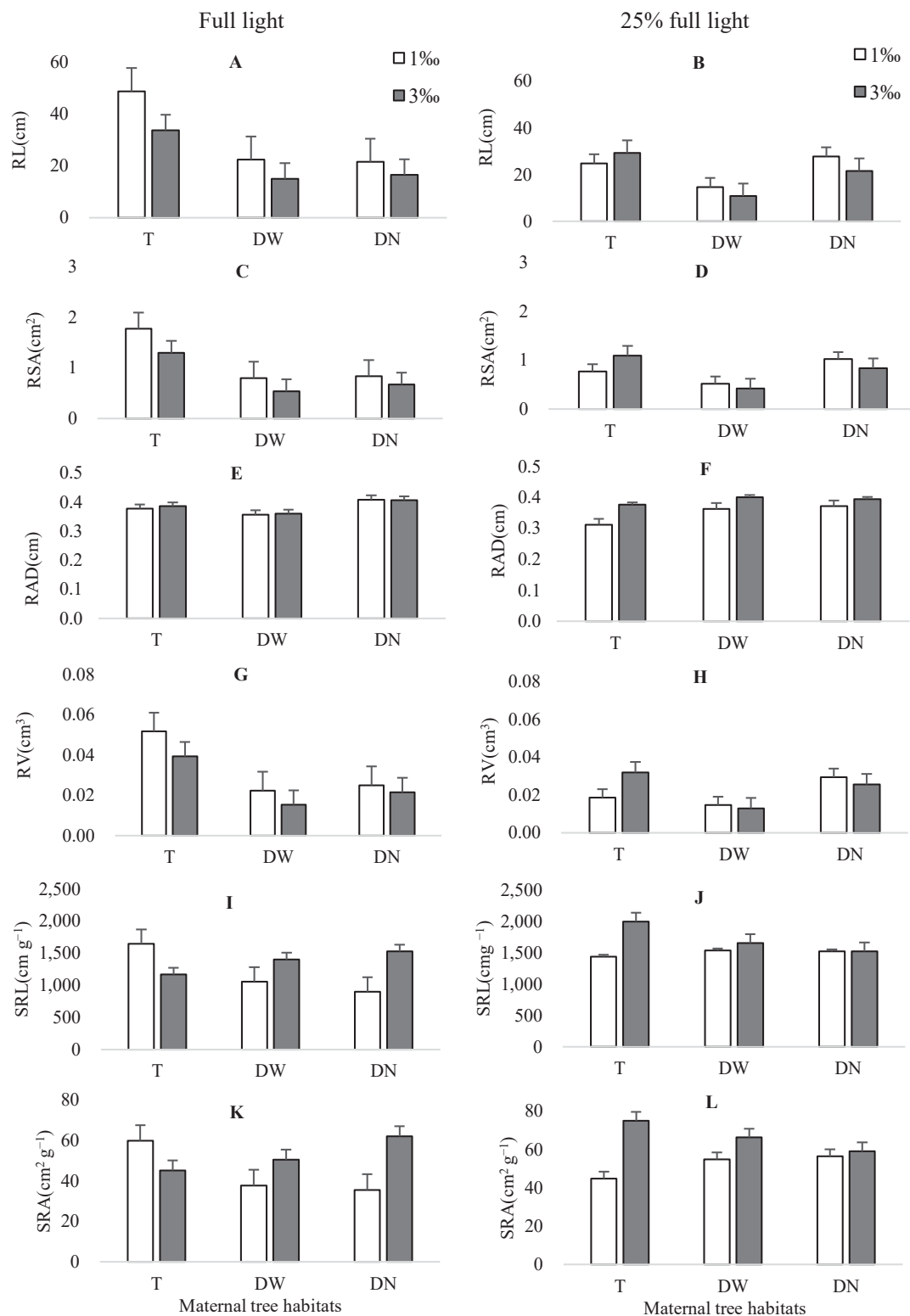


Figure 6. Effects of light intensity and salt content on root of *Morus alba* seedlings morphology from different maternal tree habitats. T: seeds from nonsaline soil; DW: seeds from Jiufenchang in saline-alkali land; DN: seeds from Shenxiangou in saline-alkali land. (A): RL, full light; (B): RL, 25% full light; (C): RSA, full light; (D): RSA, 25% full light; (E): RAD, full light; (F): RAD, 25% full light; (G): RV, full light; (H): RV, 25% full light; (I): SRL, full light; (J): SRL, 25% full light; (K): SRA, full light; (L): SRA, 25% full light.

4. Discussion

4.1. Natural Regeneration of *M. alba* in *R. pseudoacacia* Plantation in the Yellow River Delta

M. Alba is one of the most important afforestation species in the Yellow River Delta, with a certain degree of salt tolerance, drought tolerance, and shade tolerance, and a strong adaptability. The *M. alba* covers a large area of cultivation in the region; the fruit is sweet and sour, birds like to eat it, and it may be carried by birds into the *R. pseudoacacia* plantation, where it sprouts and regenerates successfully under the proper circumstances, which is an important reason for the wide distribution of *M. alba* within the *R. pseudoacacia* plantation. A survey of *R. pseudoacacia* plantations suggested that the natural regeneration of *M. alba* was closely related to the degree of decline of the stand. Within the nondeclining *R. pseudoacacia* plantations in the Jiufenchang, the DBH class structure of *M. alba* was incomplete and there existed no seedling. *M. alba* is a light-demanding plant which requires high light intensity for natural regeneration. Natural regeneration of less shade-tolerant *Quercus* species also requires high light intensities for successful regeneration [3,38]. Therefore, the low light intensity within the forest is a crucial reason for the poor natural regeneration in the Jiufenchang. The *R. pseudoacacia* plantation in Shenxiangou is in moderate decline level, with a continuous *M. alba* DBH class structure, sufficient seedlings, and a population in a steady process of increase. The death of canopy *R. pseudoacacia* in this stand has improved the light environment within the stand and provided for successful regeneration of early *M. alba*. The high number of *M. alba* maternal trees in this stand and the large amount of fruit set provided an adequate source of seeds for natural regeneration. At the same time, *M. alba* densities of up to 7667 trees ha⁻¹ significantly inhibited understory herbaceous growth. Numerous studies show that understory herbaceous vegetation is an important factor preventing natural regeneration [39,40]. The inhibition of herbaceous vegetation therefore increases the chances of seeds reaching the surface, facilitating seed germination and seedling growth, which is an important reason why *M. alba* with small seeds regenerates well in the Shenxiangou. The *R. pseudoacacia* plantations in the reserve are in serious decline, with all *R. pseudoacacia* plantations being dead and the adult *M. alba* with a growing DBH class structure, but with very few seedlings, only 26 trees ha⁻¹. The density of *M. alba* in this stand was only 656 trees ha⁻¹, the stand was not depressed, and herbs were present in large numbers, limiting seed germination and preventing natural regeneration. Therefore, the degree of decline of the *R. pseudoacacia* plantation, the number of *M. alba* maternal trees, and the growth of understory vegetation may be important factors influencing the success of natural regeneration of *M. alba* trees.

4.2. Comparison of *M. alba* Seeds in Saline Alkali Land and Nonsaline Alkali Land during Seed Germination and Early Seedling Growth

The germination rate, mean germination time, and vigor index of the DN habitat were not significantly different from the T habitat treatment and were significantly greater than those in the DW habitat, indicating that the maternal tree habitat had a significant effect on seed quality. The phenomenon has been found in both woody and herbaceous plants in different habitats and is thought to enhance the adaptive capacity of offspring [21]. The 1000-seed weight of *M. alba* was 1.99 ± 0.16 g for T and 1.35 ± 0.14 g for DN, both significantly greater than 0.98 ± 0.11 g for DW. Numerous studies show that seed size determines seed quality and is related to the nutrients contained within the seed [15,41,42]. Seed size is, therefore, a key indicator of seed quality in *M. alba*. González-Rodríguez et al. [11] also found that maternal tree effects significantly altered seed quality. However, Vivas et al. [43] suggested that it is the site condition and tree genotype of maternal tree which play important roles in offspring adaptation, rather than seed quality. The germination index of DN was significantly higher than that of T, indicating that its seed viability was significantly higher in the coastal saline zone. Yin [44] also found that the seed vigor of the introduced tree species *R. pseudoacacia* in the region was higher than that of nonsaline seeds. Thus, long-term salt stress in the Yellow River Delta enhances the salt tolerance of *M. alba* seeds, and seed size is not the only pathway, suggesting a complex mechanism of action for maternal

effects. There was no significant effect of maternal tree habitat on biomass allocation, which suggested similar adaptation patterns in biomass regulation. The differences in seedling biomass, root length, root surface area, and root volume were all not significant in the T and DN habitats compared to those in the DW habitat. Significant advantages of large seeds in seedling biomass and root development were also found in *Pinus thunbergii* [45] and *Quercus acutissima* [38]. In the understory, large seedling individuals improved survival rate [38,46]. Thus, long-term salt stress improves the ability of *M. alba* seeds to adapt to the soil salt stress, and the regulation of seed quality is one of the key regulation modes.

4.3. Effect of Light Intensity and Soil Salinity on Seed Germination and Seedling Growth of *M. alba*

In coastal saline areas, the seed germination and seedling growth within the forest are exposed to the combined effects of light intensity and soil salinity. This pot study showed no significant effect of light intensity on seed germination, germination index, and vigor index, indicating that *M. alba* germination is light-free. However, seedling biomass was significantly higher in full light than in 25% full light, indicating that *M. alba* is a light-demanding species. Under salt stress, 3‰ had a higher germination rate and germination index than 1‰. In May, when the mulberry seeds germinated, the statistical data for many years showed that there was little rainfall in the region [47]. Guo et al. [48] found that the soil water content in *R. pseudoacacia* forest in May was low and the soil salt content was high. The study of soil seed bank in this area found that the increase of soil salt content caused by the rise of groundwater level is an important factor to inhibit the germination of plant seeds [49]. Therefore, the high germination rate under 3‰ of soil salt content increased the possibility of successful seed germination. Salt stress germination tests on *M. alba* seeds in a light incubator exhibited that the difference in germination rate and germination index between 1‰ and 3‰ was not significant [25,50]. This may be related to the inconsistent environment for germination, but may also indicate that *M. alba* has a strong salt tolerance. Numerous studies show that the leaf biomass ratio increases and the root biomass ratio decreases with decreasing light intensity [51,52]; however, the root biomass ratio increases with increasing soil salinity [30]. Thus, the combined effect of multiple stresses may be an important reason for the lack of significant effects of light intensity and salt stress on biomass allocation. Drought also promotes increasing root biomass allocation in plants, but in contrast to light acclimation in the understory. Studies of understory seedling regeneration show that drought is the most important cause of seedling mortality [38,53]. Therefore, light intensity and soil salt content under *R. pseudoacacia* forest in coastal saline alkali land increase the complexity of adaptation of *M. alba* seedlings, which requires further research.

5. Conclusions

This paper shows that natural regeneration of *M. alba* within *R. pseudoacacia* plantation in the Yellow River Delta is widespread. The level of natural regeneration of *M. alba* trees is closely related to the degree of decline of *R. pseudoacacia* plantation. In the moderately declining Shenxiangou, the DBH class structure of both seedlings and large trees is consecutive and is of the growing type. However, in the nondeclining Jiufenchang, the large tree DBH class is inconsecutive and no seedlings were found. Within the severely declining protected forests, *M. alba* trees are consecutive at large diameter levels but have very few young seedlings. Therefore, the extent of *M. alba* regeneration is influenced by the stand structure of *R. pseudoacacia* plantation.

Maternal trees of *M. alba* in saline alkali land significantly influenced seed quality and seedling biomass. The germination index, seedling biomass, and root system characteristics of DN habitat were similar to those of Tai'an and significantly greater than those under DW habitat compared to seeds from nonsaline Tai'an, which was associated with the smallest seed weight per 1000 grains in DW. However, DN had a higher germination index than T,

improving the quality of seeds under salt stress. Therefore, thousand-seed weight can be used as a key indicator to evaluate the seed quality of mulberry in the Yellow River Delta.

In terms of environmental factors, light intensity had no significant effect on seed germination, but seedling biomass was significantly greater in full light than in 25% light penetration. Soil salinity significantly affected seed germination, and the germination capacity at 3‰ was higher than that at 1‰, which improved the adaptability to the change of soil salt content under *R. pseudoacacia* forest. However, the seedling biomass was lower than 1‰ at 3‰. Neither light intensity nor soil salinity had a significant effect on biomass allocation. The effects of light intensity and soil salinity indicate the complexity of the combined effect of multiple factors. Thus, the natural regeneration of *M. alba* trees in coastal saline *R. pseudoacacia* plantations is very complex. In the future, in order to clarify the natural regeneration dynamics of *M. alba*, it is necessary to establish long-term permanent sample plots and strengthen the monitoring of water resources in *R. pseudoacacia* forests.

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Article

Ecosystem Service Value Evaluation of Saline—Alkali Land Development in the Yellow River Delta—The Example of the Huanghe Island

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Abstract: Saline–alkali land is an important land resource with high development potential and an important ecological product with high potential ecosystem service value (ESV). It is of great significance for rational development and protection of saline–alkali land resources to carry out research on the evaluation methods of the ESV of saline–alkali land and to scientifically quantify the ESV of saline–alkali land development. Taking typical saline–alkali land in the Yellow River Delta on the Huanghe Island of China as an example, this research constructed an ESV evaluation index system from the perspective of functional value containing three first-level indicators such as economic value, four second-level indicators such as supply service, and eight lowest-level indicators such as food production. It also considered production and operation costs and evaluated the ESV of the Huanghe Island using the ecological economics method. The results showed that the ESV of the Huanghe Island is CNY 133.586 million, and the unit area value is 50,200 CNY/hm², which is a relatively high value. Among them, the supply service value was the highest, accounting for more than half. In recent years, the development of the Huanghe Island has produced high supply and service value, but due to weak background conditions and low vegetation coverage, regulation and support service values are relatively low, the cultural service value is still to be explored, and there is great potential for ecological and social value. This research can provide references for scientific evaluation of the ESV of saline–alkali land and provide a basis for rational development and utilization of the Huanghe Island.

Keywords: Yellow River Delta; saline–alkali land; ecosystem services; evaluation of value; the Huanghe Island

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1. Introduction

Saline–alkali land is a special natural resource with high salt content in soil. It not only has grassland, wetland, and other types of cover but also is an important wildlife habitat. At present, the contradiction between people and land is increasingly prominent [1]. As an important land resource, saline–alkali land has high development and utilization value. The development and utilization of saline–alkali land in China [2,3] has had a profound impact on ensuring food security and building ecological civilization. Ecosystem services refer to all benefits provided by ecosystems for human survival, including material products and non-material services [4–6]. Ecosystems include wetlands, forests, farmland, etc. Different types of ecosystems can provide different types, quantities, and qualities of services [5,7], and their formed values are also different. The supply and service capacity of ecosystems of the same type are also different due to quality differences and social activities. In recent years, with the rapid advancement of industrialization and urbanization, ecosystem services, as the hub connecting the natural ecosystem and the social and economic system [8,9], have been continuously impacted and destroyed, and their value has been greatly affected.

However, since it is difficult to quantify and manifest all ecosystem services through market transactions, the exact ESV is not completely clear, nor is the impact of human activities on them [10]. As an important kind of land resource, the ESV of rational development and utilization of saline–alkali land is not clear. Therefore, the value of ecosystem services and the evaluation of ecosystem services in saline–alkali land development have become important scientific issues.

With the impact of human activities on ecosystems and the deterioration of ecological environments, the value and evaluation of ecosystem services have become the focus of global research since 1990. In 1997, Costanza formulated the global ecosystem service equivalent factor table, which estimated the monetary amount of the global ecosystem value for the first time [5]. The ecosystem service equivalent factor was also widely used [11]. Xie Gaodi, a Chinese scholar, compiled the value equivalent table of ecosystem services in China and calculated the monetary value of ecosystem services on the Qinghai Tibet Plateau [12]. In recent years, scholars have carried out studies on the ESV of forest [13], grassland [14], farmland [15], wetland [16], marine [17], and other ecosystems. They have also studied value evaluation methods [18], value evaluation index systems [19], value spatio-temporal evolution and tradeoff relationships [20], and driving factors of value change [21]. Evaluation models and methods mainly include the InVest model [22], meta regression [23], etc. In addition, the ESV is always combined with studies of land use change [24,25] and ecological compensation standards [26] to explore the changing rules of ESVs [27], influencing factors [28], and the response relationship between land use change and ecosystem service [29]. The research results have provided good support for territory spatial planning, ecological security pattern construction, and economic decision making [30]. At present, some scholars refer to the equivalent factor of per unit area ESV constructed by Xie Gaodi [31] to evaluate the ESVs in different regions through regional correction [32]. The equivalent factor method is simple but ignores differences in actual service value caused by different quality of similar ecosystems. Farmland, forests, and other ecosystems have high production and tourism value as well as high production and operation costs. Some scholars use the ecological economics method to evaluate ESVs [33–35], but they rarely consider production and operation costs. Therefore, it is also necessary to strengthen the research on evaluation methods of the actual service value of various ecosystems, divide various functional types based on the perspective of functional value, build an evaluation index system of ESVs, study the calculation methods of different value types, deduct the objective production and operation costs, scientifically and accurately quantify the actual ESVs, and provide a reliable basis for the decisions regarding ecosystem development and utilization. There are certain explorations and practices in the field of development and utilization of saline–alkali land around the world, such as the action plan on salinity and water quality in southern Australia [36]. Chinese scholars' studies on the development of saline–alkali land have mostly been concentrated in the Songnen Plain [37], the Yellow River Delta [38], and other typical areas. China's forestry ecological project [39], farmland forest network project [40] to control the increase in soil salt content, and other attempts to develop and utilize saline–alkali land have had a profound impact on food security and ecological civilization construction, but recent studies rarely considered the impact of saline–alkali land development and utilization on the ESV. Saline–alkali land is an important land resource with high ESV and development value. It is of great significance for scientific quantification of the ESV of saline–alkali land and rational development and protection of saline–alkali land resources to strengthen the research on the ESV of saline–alkali land ecosystem services. However, at present, there are few relevant studies on the evaluation of the ESV of saline–alkali land, and a few studies only focus on the evaluation of the ESV under a single utilization mode such as planting a plantation in saline–alkali land [41]. Additionally, there are few studies on the evaluation of the ESV of comprehensive development and utilization of saline–alkali land. The Yellow River Delta is one of the main saline–alkali land distribution areas in China, and it is rich in land resources. However, the ecological environment is fragile, the anti-interference ability

is poor, and it needs to be developed and reasonably utilized. In April 2013, China launched a Bohai Sea granary construction project in the Yellow River Delta to develop and transform saline–alkali land and increase grain production and income. In 2021, China issued “the Outline of the Plan for Ecological Protection and High-quality Development in the Yellow River Basin”, which proposed to protect the Yellow River Delta, prevent soil salinization, and explore the value accounting for ecosystem services. At present, the research objects on the ESV of the Yellow River Delta are concentrated in the wetland of nature reserves [33,42], and there is a lack of relevant research on the index system, evaluation methods, and development value of the ESV of saline–alkali land. Therefore, it is necessary to carry out research on the evaluation of the ESV of Yellow River Delta saline–alkali land exploitation, so as to evaluate and reveal its ESV and development value, which is of great significance for scientific exploitation, protection, and utilization of saline–alkali land.

The Huanghe Island is a typical saline–alkali land in the Yellow River Delta, and the degree of soil salinization is high. Since 2003, in accordance with Yellow River Delta development, National Wetland Park Construction and Bohai Granary Demonstration Area Construction, and other projects, the Huanghe Island has managed saline–alkali land, developed forestry and grassland industries, developed tourism, built wetland parks, and achieved good results. In this research, the Huanghe Island was used as the study area, and according to the current development and operation situation and different functional types, considering its quality and actual output, the market price method, alternative cost method, and other ecological economic methods were used to evaluate the ESV for the development of the Huanghe Island. Additionally, the costs of supply services and cultural services were deducted to obtain more objective and realistic estimation results, which provide a basis for scientific quantification of the value of saline–alkali land and protection of saline–alkali land resources. It also provides references for ecological development and green ecological construction in the area of the Huanghe Island, and it provides references for the evaluation of ESVs of saline–alkali land in other areas.

2. Overview of the Study Area and Data Sources

2.1. Overview of the Study Area

2.1.1. Natural Resource Conditions

The Huanghe Island ($118^{\circ}1'1''$ – $118^{\circ}4'1''$ E, $37^{\circ}54'57''$ – $38^{\circ}0'18''$ N) is located in Binzhou City of Shandong Province, and it has a total area of 26.61 km² (see Figure 1). It was formed by the deposition of the ancient Yellow River, and it is located in the hinterland of the Yellow River Delta at the junction of the coastal plain and the coastal beach. It faces the Bohai Sea. Affected by river siltation and sea tide overflow, the terrain is high in the south and low in the north and is distributed in strips. It has a marine climate, with an average annual temperature of 14.5 °C and an average annual precipitation of 569 mm. The Huanghe Island is a typical saline–alkali land in the Yellow River Delta, and the soil salt content is 0.00–21.02 g/kg. Moreover, there are many types of saline–alkali lands with severe, moderate, and low degrees. The land utilization status of the island is mainly water surface, and there are rich wildlife resources, such as reeds, tamarisk, tamarix, other salt-tolerant plants, hares, foxes, swans, wild ducks, and other wild animals. The Huanghe Island is surrounded by water on all sides, and it borders the Bohai Sea in the northeast and the Yellow River in the south. It is surrounded by the Taoer River and the Qinkou River, and it has a beautiful environment and good ecology. It is also a superposition of the Yellow River Delta Efficient Ecological Economic Zone, the Blue Economic Zone of Shandong Peninsula, the Bohai Rim Economic Circle, and the provincial capital city cluster economic circle.

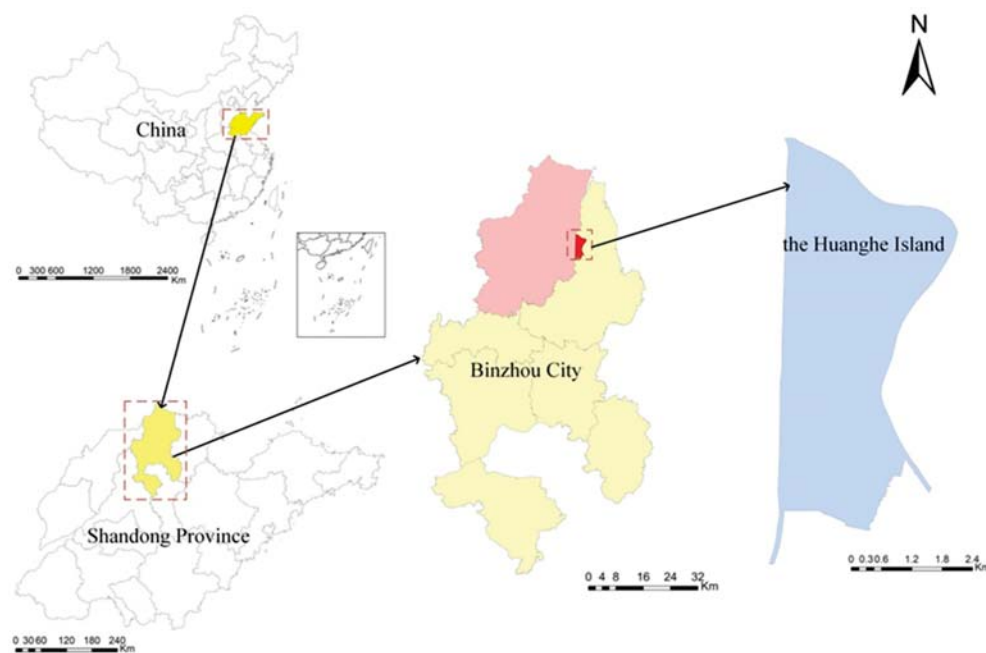


Figure 1. Overview of the study area.

2.1.2. Development and Utilization Status

Since 2003, relying on the advantages of natural geography and resources and seizing the opportunities of the development of the Yellow River delta, the construction of the blue economic zone, and the Bohai granary, the Huanghe Island has made great efforts to develop aquaculture and tourism. It has also carried out an underground pipe salt drainage land renovation project, developed resources of cultivated land, developed ecological agriculture, and built a conservation resource nursery of the native salt-tolerant plant community. It has been developed into an AAAA national tourist attraction, a national wetland park, and a national field scientific observation and research base. At present, the Huanghe Island has completed the construction of water, electricity, roads, networks, and other infrastructure; planted a large number of green trees; and formed five parks, including the “agricultural ecological demonstration park”. Now the Huanghe Island has formed a variety of land use models, such as economic forest grass ecological agriculture and aquaculture, and gradually formed an ecological and efficient sightseeing belt that combines planting, breeding, and tourism. The development and construction of the Huanghe Island has provided good economic and ecological benefits.

The Huanghe Island has vigorously developed forestry and forage industries, and it has vigorously promoted the development of the forest grass intercropping planting mode. The “three in one” of the road forest network, farmland forest network, and river forest network has been preliminarily formed, and salt- and alkali-resistant tree species have been introduced and cultivated. In order to vigorously develop the forage industry, alfalfa greenhouses have been built, equipped with mowers and other agricultural machinery, and the quality of alfalfa products is guaranteed. The Huanghe Island has made great efforts to develop fishery, including standard pond aquaculture and recreational fishery. The varieties of aquaculture include razor clams and prawns, which have significant economic benefits. It has also developed recreational fishery, such as pond fishing and experiential mining, to provide tourists with special services and to effectively promote the comprehensive and modern development of fishery. The Huanghe Island has made great efforts to develop animal husbandry, including seed conservation, breeding, cross improvement, breeding and promotion of improved sheep, supporting the construction of feed warehouses and other infrastructure, and has applied for national invention patents and utility model patents. The Huanghe Island has made great efforts to develop the tourism industry, including agriculture, forestry, animal husbandry, fishing, tourism, and other industries. It

has been rated as a national water conservancy scenic spot, a national wetland park, and a national leisure fishery demonstration base. It has integrated the planning of agriculture, forestry, animal husbandry, fishing, tourism, and other industries. It has also highlighted agricultural characteristics and worked hard to build a national first-class agricultural tourism demonstration base to further develop scenic spots and create a brand. In the future, the Huanghe Island will continue to be characterized by idyllic scenery and organic ecology, integrating wetland culture, agricultural reclamation culture, the culture of the old Yellow River, the culture of Yellow River changes, folk culture, painting, and calligraphy art, which will make it an ecological cultural tourism island in the Yellow River Delta that integrates multiple tourism functions.

2.2. Data Sources

(1) Land use data are from the Shandong Institute of Territorial and Spatial Planning. Through a field survey, land use types were changed and refined based on the development status of the Huanghe Island, and fine-scale land use and vegetation cover information were obtained. The land use status of the Huanghe Island was obtained after a field survey and verification (see Table 1 and Figure 2).

Table 1. Land use status of the Huanghe Island.

Land Use Type	Area (km ²)	Percent (%)	Land Type	Area (km ²)	Percent (%)
Woodland	1.34	5.04	Grassland	3.41	12.81
Mixed forest and grass	4.22	15.86	Water surface	11.37	42.73
Farmland	0.17	0.64	Ditch	4.03	15.14
Garden	0.02	0.08	Construction land	2.05	7.70

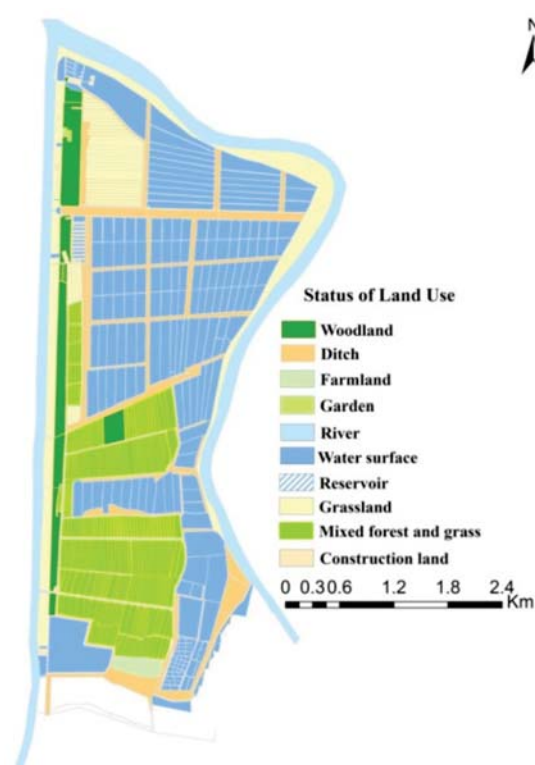


Figure 2. Status of land use.

(2) Soil data, grassland biomass data, plant diversity, and other data were obtained from sampling and measurement. Some parts of the study area have been developed as

aquaculture water surfaces, which was not within the sampling scope; the sampling scope was land. Following the principles of uniform distribution of points and dense distribution of points in key areas, 53 sample points were arranged (see Figure 3). The undisturbed soil was collected with a ring knife, and the soil organic matter, available phosphorus, available potassium, alkali-hydrolyzed nitrogen, and bulk density were determined in the laboratory. Additionally, 1 m × 1 m and 10 m × 10 m squares were laid in the vegetation-covered area to count the number and types of herbs and woody plants, which were dried and weighed in the laboratory.



Figure 3. Distribution of sampling points.

(3) Meteorological data were from the China Meteorological Data Network (<http://data.cma.cn/>) in 1/18 2021, Meteorological Bureau of Wudi County, and Binzhou Statistical Yearbook. These data included rainfall, temperature, solar top atmospheric radiation, and other meteorological data.

(4) The statistical output and price of grain, relevant production and operation costs, wage standards, and other data were obtained from the China Statistical Yearbook, Binzhou Statistical Yearbook, Wudi County Statistical Yearbook, China's agricultural product cost income data collection, relevant news reports of the Huanghe Island, etc., and these were obtained from relevant websites and the Statistical Bureau of Binzhou City and Wudi County.

(5) The data of food, raw materials, and tourism income of the Huanghe Island were obtained from the statistical data of the Huanghe Island Development Company.

(6) Other data were from China's Technical Guide for Delineation of Ecological Protection Red Line, Code for Assessment of Forest Ecosystem Service Functions (GB/T 38582-2020), CNKI database, and the Web of Science database.

3. Research Methodology

3.1. Construction of Value Evaluation Index System

The Millennium Ecosystem Assessment (MA) divided ecosystem services into four categories: supply, regulation, support, and culture [4]. Costanza divided ecosystem service

functions into 17 categories, such as gas regulation, climate regulation, and interference regulation [5]. Although the classification is scattered and not systematic, it is widely used globally. Xie Gaodi divided ecosystem services into four categories: supply, regulation, support, and culture [31]. He also adjusted and optimized the classification of secondary services many times and proposed the value equivalent of ecosystem services per unit area of various land use types, which has been widely used in relevant studies in China. Saline–alkali land is a natural resource with high soil salt content. It not only includes cultivated land, forest land, grassland, marshes, and other land use types but is also an important wildlife habitat. Saline–alkali land can provide corresponding ecosystem services for human beings, but its environment is complex, and the conditions are special, so the service value generated should be further screened. This research refers to MA [4], Costanza [5], Xie Gaodi [31], and other ESV classifications, and it considers the land use type, terrain, vegetation, and saline–alkali land characteristics and data availability of the Huanghe Island. Through field research, three first-level indicators including economic, ecological, and social value; four second-level indicators including supply, adjustment, support, and culture service; and eight lowest-level indicators including food production, raw material production, etc. (see Figure 4) were defined. The connotation of each evaluation index was also defined (see Table 2).

Table 2. Connotation definition of the ESV evaluation index system.

Lowest-Level Indicators		Connotation
V11	Food Production	The function and value of saline–alkali land directly providing edible animal and plant products for human beings
V12	Raw Material Production	The function and value of saline–alkali land providing people with building raw materials, animal feed, and other products
V21	Gas Regulation	The function and value of plants in saline–alkali land fixing CO ₂ and releasing O ₂ through photosynthesis to maintain the dynamic balance of CO ₂ and O ₂ in the atmosphere, so as to realize the function and value of mitigating the greenhouse effect and regulating gas and climate
V22	Conservation of Water Sources	The function and value of saline–alkali land intercepting, absorbing, and storing precipitation through plants, soil layers, and water surfaces, thus playing the valuable role of conserving soil moisture and supplementing surface fresh water and groundwater
V31	Maintenance of Biodiversity	Saline–alkali land is an important genetic source, evolutionary base, and habitat of wild animals and plants, and it has the function and value of maintaining biodiversity
V32	Maintenance of Nutrient Cycling	Saline–alkali land has the function and value of maintaining material exchange and nutrient cycling between organisms and the environment, with soil organic matter, nitrogen, phosphorus, and potassium as the main cycling substances
V41	Leisure and Entertainment	Saline–alkali land can provide functions and values of leisure tourism, cultural activities, and landscape appreciation
V42	Research and Education	Saline–alkali land can provide the function and value of the site for related scientific research, education, and teaching

3.2. Value Evaluation Method Based on Ecological Economics

3.2.1. Selection of Value Evaluation Methods

The ecosystem service value of saline–alkali land is diverse, and a single method cannot accurately evaluate it. Ecological economics is a discipline that studies the structure and movement law of the ecological economic system, which is composed of economic systems and ecosystems approached from the perspective of economics [43].

The equivalent factor method is used to construct value equivalents of various functions of different types of ecosystems based on different types of ecosystem services and quantifiable standards, and it estimates the ESV through the equivalent factor table. One standard unit ecosystem product value equivalent factor is the economic value of the annual grain yield of the farmland with the national average yield of one hectare. The estimation process is relatively simple, and the data demand is not much, but the accounting results do not always reflect the actual situation of the study area [5,12]. Different from the equivalent factor method based on regional differences, the commonly used value research

methods in ecological economics include the market price method, shadow price method, willingness survey method, etc. Additionally, they involve many parameters and complex calculations, but the results are more consistent with the actual situation of the study area. In particular, the accounting results of the supply function are more accurate [33]. Based on the perspective of functional value, this research divided the service value function of saline–alkali land ecosystem; used ecological economics methods; considered the indicator characteristics, method applicability, and data availability of the ESV of saline–alkali land; and comprehensively used the market value method, alternative cost method, opportunity cost method, and other ecological economics methods to evaluate the ESV of the Huanghe Island.

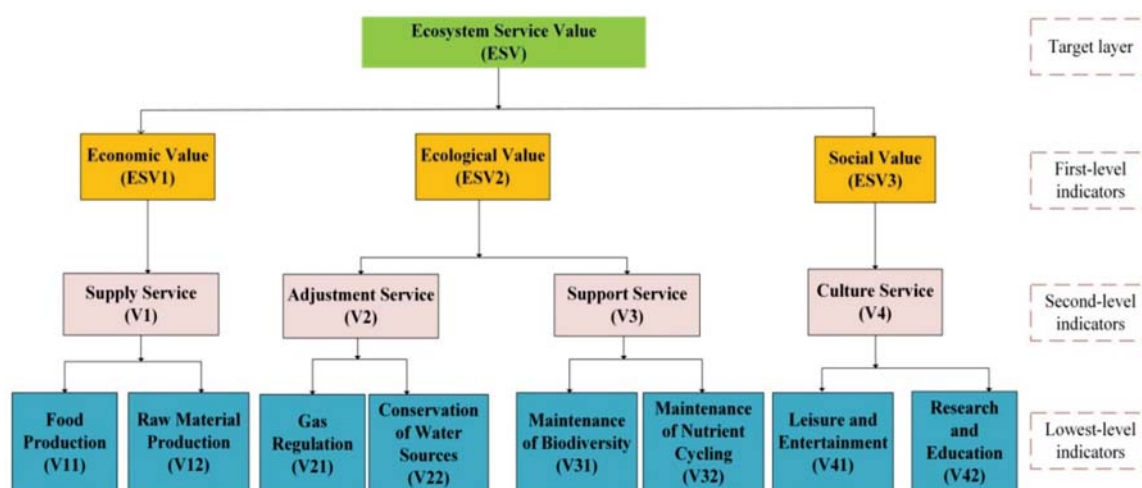


Figure 4. Construction of evaluation index system.

3.2.2. Evaluation of Supply Service Value

Evaluation of Food Production Value

The development and utilization of the Huanghe Island for many years has realized the organic combination of agriculture, forestry, animal husbandry, and fishery production. The fruits, vegetables, seafood, grains, meat products, and other animal and plant food products produced by the Huanghe Island can be directly traded in the market, although they have high production costs. In this research, the market value method was used to evaluate the total income of food production, and the cost input was deducted to obtain the food production value. The calculation is shown in Formula (1)

$$V_F = \sum_{i=1}^n (A_i \times B_i - S_i \times B_i) \times T \quad (1)$$

where V_F represents the average annual food production value (ten thousand CNY/year), n is the total number of food categories, A_i is the average annual unit price of the i th food (ten thousand CNY/t), S_i is the average annual cost of the category i th food (ten thousand CNY/t), B_i is the average annual production of the category i th food (t), and T is the time (a), which was one year in this study. According to statistical data from the Huanghe Island Development Company, the annual fruit output of the Huanghe Island includes apples, pears, grapes, dates, etc., with an average annual output of 41.00 t and an average price of 5540 CNY/t. Vegetables include eggplants, peppers, carrots, etc., with an average annual yield of 45.21 t and an average annual price of 2330 CNY/t. Animal husbandry is mainly the raising of green goats, with an average annual yield of 16.59 t and an average annual price of 21,000 CNY/t. Aquaculture mainly includes shrimp and razor clam. The average annual output of shrimp is 490.33 t, with an average annual price of 29,330 CNY/t, and the average annual output of razor clam is 5957.50 t, with an average annual price of 19,730 CNY/t. Referring to the grain production data of Wudi County in recent years, Wudi County has three major grain products: wheat, corn, and sorghum.

Their annual output value is 13594.34 CNY/hm², and the farmland area of the Huanghe Island is 0.17 km². Based on the data compiled from China's agricultural product data, Wudi County's grain production data, and local data collection, including production costs, labor costs, land costs, etc., it was estimated that the production costs of aquaculture, fruits, vegetables, and green goats are 8.58, 2.99, 0.86, and 21.98 CNY/kg, respectively, and the production cost of grain is 840 CNY/mu. The annual average food production value was calculated after deducting the production costs.

Evaluation of Raw Material Production Value

The Huanghe Island is a typical saline-alkaline area. It can improve the vegetation cover and soil conditions of saline-alkaline land by planting saline-tolerant plants such as alfalfa and white wax. It can also be used as a raw material to obtain certain economic benefits through market sales. Raw material production mainly includes pastures and adult trees (excluding seedling trees). In this paper, the market value method was adopted to evaluate the total production revenue of raw materials, and the production value of raw materials was obtained by deducting the production cost. The calculation is shown in Formula (2)

$$V_M = \sum_{j=1}^n (A_j \times B_j - S_j \times B_j) \times T \quad (2)$$

where V_M is the production value of raw materials (ten thousand CNY/year), n is the total number of raw materials, A_j is the unit yield of the category j -th raw materials (t), B_j is the market price of the category j -th raw materials (ten thousand CNY/t), S_j is the average annual cost of the category j -th raw materials, and T is the time (a), which was one year in this study. According to the statistical data and relevant data collected by the Huanghe Island Development Company, the average annual forage grass output is 2973.33 t, the average unit price is 1800 CNY/t, and the average cost is 800 CNY/t. On average, 600 adult trees are sold every year, with an average unit price of 690 CNY/tree and an average cost of 49.59 CNY/tree. Based on this, the annual average production value of raw materials was calculated.

3.2.3. Evaluation of Adjustment Service Value

Evaluation of Gas Regulation Value

The Huanghe Island has grassland, forest land, mixed forest and grass, and other vegetation types, which produce high gas regulation value through photosynthesis. In this study, alternative cost methods such as carbon fixation cost, afforestation cost, and oxygen production cost of plants were used to evaluate their value, as shown in Formula (3)

$$V_G = 0.44 \times Q \times P_C + 1.2 \times Q \times P_O \quad (3)$$

where V_G is the value of gas regulation (ten thousand CNY/year), Q is the biomass (kg), and P_C is the cost of carbon fixation (CNY/kg). In this research, afforestation cost was used, and P_O is the cost of oxygen production (CNY/kg). Additionally, industrial oxygen production price was used in this study. For every 1.00 g of dry matter produced by plants, 1.63 g of CO₂ is fixed, which means 0.44 g of C [44] and 1.20 g of O₂ are released [45]. Biomass data were obtained through field investigation and references to the relevant literature. Grassland biomass was obtained by field investigation, and the area biomass was 381.47 g/m² as assessed by a spatial interpolation tool in ArcGIS 10.2. Parameters of afforestation cost, oxygen production price, and forest biomass (stand net productivity) were determined and calculated by referring to the relevant literature [41,46]. The cost P_C of carbon fixation and the price P_O of oxygen production were based on public data, and their values were 1200 CNY/t [41] and 1000 CNY/t [41], respectively. Based on the forest stand net productivity determined by the forest stock expansion method [46], the forest land of the Huanghe Island is mainly planted with ash, and the biomass of ash is 8.73 t/(hm² • a) [41].

Evaluation of Water Sources Conservation Value

The Huanghe Island can store water through water conservancy facilities, intercept rainfall through vegetation and soil, and produce a certain water conservation value. The market value method and water balance method were used to calculate the value of water storage of water conservancy facilities and rainfall interception by soil and vegetation, as shown in Formulas (4)–(8)

$$V_W = V_C + V_R \quad (4)$$

where V_W is the total value of water conservation (CNY/year) and V_C is the water storage value of water conservancy facilities (CNY/year), as shown in Formula (5). V_R is the value of soil and vegetation interception of rainfall (CNY/year), as shown in Formula (6).

$$V_C = S_w \times P_W \quad (5)$$

S_w is the water storage capacity of water conservancy facilities (m^3). There is an irrigation water storage reservoir on the Huanghe Island, and the basic data collected show that its water storage capacity S_w is $1.219 \times 10^7 \text{ m}^3$.

$$V_R = (R - E) \times A \times P_W \quad (6)$$

R is the average annual rainfall (mm/a), and E is the annual average evapotranspiration (mm/a), which is calculated by rainfall, solar top radiation, temperature, etc. according to the China's Technical Guide for Delineation of Ecological Protection Red Line issued by the Ministry of Ecology and Environment of China, as shown in Formula (7). A is the area of various land use types (hm^2), and the land use mode of the Huanghe Island is shown in Table 3. P_W refers to the unit storage cost (CNY/ m^3). In earlier studies, P_W was usually taken as the constant price of the cost of building 1 m^3 of storage capacity in China in 1990, meaning the cost of unit storage capacity was 0.67 CNY/m^3 [47–50]. Later, scholars modified this parameter [51], and this research determined that P_W is 0.92 CNY/m^3 [51].

$$E = \frac{P \times \left(1 + \omega \frac{PET}{P}\right)}{1 + \omega \frac{PET}{P} + \frac{P}{PET}} \quad (7)$$

PET is the multi-year average potential evaporation (mm), and the calculation is shown in Formula (8). The highly generalized ω coefficient of land cover factor in China's Technical Guide for Delineation of Ecological Protection Red Line issued by the Ministry of Ecology and Environment of China was adopted (see Table 3). P is the annual average rainfall for many years (mm).

$$PET = C \times Ra \times (T_a + 17.8) \times TD^{\frac{1}{2}} \quad (8)$$

Table 3. The referencing values of parameter ω for evaluating the importance of water conservation.

Land Use Type	Arable Land	High Coverage Forest Land	Low Coverage Forest Land	Bush Wood	Grassland	Artificial Land Use	Other Land Use
Values of ω	0.5	2.0	1.0	1.0	0.5	0.1	0.1

In Formula (8), C is the temperature coefficient, which has a value of 0.0023 [52] according to the cited study. Ra is the atmospheric radiation at the top of the sun ($\text{MJ}/(\text{m}^2 \cdot \text{d})$). T_a is the average temperature ($^{\circ}\text{C}$), and TD is the temperature difference ($^{\circ}\text{C}$). According to the basic data of the Meteorological Bureau of Wudi County, the Ra of the Huanghe Island is $234285.23 \text{ MJ}/(\text{m}^2 \cdot \text{d})$, the T_a is 14.5°C , the TD is 30.45°C , and the calculated PET is 96043.71 mm .

3.2.4. Evaluation of Support Service Value

Evaluation of Maintenance of Biodiversity

Saline–alkali land can provide a habitat for many animals and is an important source of the animal and plant gene pool. The Huanghe Island is rich in animal and plant species, including animals such as swans, hares, ducks, and plants such as reeds, alkali buns, and tamarisk, which have a value in maintaining biodiversity. As animals often move, the number is difficult to determine, so only the diversity value of plants was calculated in this research. According to the connotation of plant diversity index, the opportunity cost method was used to estimate plant diversity by combining the plant quantity and relevant parameters determined by the investigation, as shown in Formula (9)

$$V_B = \sum_{k=1}^n Y_k \times S_k \quad (9)$$

where V_B refers to the value of biodiversity (CNY/a), n refers to the number of biodiversity levels, Y_k refers to the land area (hm^2) of the category k -th biodiversity location, and S_k refers to the annual opportunity cost of species loss per unit area of the category k -th biodiversity ($\text{CNY}/(\text{hm}^2 \cdot \text{a})$). The calculation of plant diversity value in this study did not include water surfaces or ditch land.

We calculated the Shannon–Wiener index H of plant diversity at the sampling point, as shown in the Formula (10), and then determined the value of S_k . The distribution of the Shannon–Wiener index H in the study area was obtained through spatial interpolation, and, with reference to the Code for Assessment of Forest Ecosystem Service Functions (GB/T 38582-2020), the biodiversity level was determined to be seven, the area of each level Y_k was calculated, and the unit value (i.e., opportunity cost) S_k was determined (see Table 4).

$$H = - \sum_{m=1}^n P_m \log_2 P_m \quad (10)$$

Table 4. Value division of the grades of Shannon–Wiener Index H grades.

The Number	Shannon–Wiener Index H	Class of Biodiversity	Unit Value S_k (CNY/ $\text{hm}^2 \cdot \text{a}$)
1	<1	7	3000
2	[1,2)	6	5000
3	[2,3)	5	10,000
4	[3,4)	4	20,000
5	[4,5)	3	30,000
6	[5,6)	2	40,000
7	≥ 6	1	50,000

H is the Shannon–Wiener index of plant diversity, P_m is the proportion of the individual number of species m to the total individual number, and n is the number of species.

Evaluation of the Maintenance of Nutrient Cycling

Soil nutrients are an important indicator of soil quality, which not only affects plant growth and development but also plays an important role in nutrient cycling. The Huanghe Island is a typical saline–alkali land distribution area, and the high salt content and low nutrient level of the soil are important factors limiting plant growth. After land development, construction, and remediation in recent years, soil salinization has improved, the contents of soil organic matter, nitrogen, phosphorus, potassium, and other nutrients has increased, and the value of maintenance of nutrient cycling has gradually increased. Based on the relevant data of organic fertilizers and nitrogen, phosphorus, and potassium fertilizers, this research used the shadow price method to estimate the maintenance of nutrient cycling of

soil [53], as shown in Formula (11). The types of land use involved included garden plots, farmland, forest land, forest grassland, and wasteland.

$$V_N = \sum_{p=1}^n Y_p \times d \times \rho \times M_p \times P_F \quad (11)$$

V_N refers to the maintenance of nutrient cycling (CNY), n refers to the number of land use types involved, Y_p refers to the area of type p land (m^2), and d refers to the soil depth (m). In this research, the soil depth was set as 0.4 m according to crop growth. ρ is the soil bulk density (kg/m^3), M_p is the organic matter and N, P, K contents (mg/kg) in the soil of type p land, and P_F is the price of fertilizer (CNY/mg for compound fertilizer and CNY/g for organic fertilizer).

The soil organic matter, soil bulk density, and nitrogen, phosphorus, and potassium contents of various land uses were obtained by spatial interpolation after sampling and measurement and by land classification statistics (see Table 5). Among them, the conversion coefficient of organic matter and organic carbon is 1.724 [54], and this research adopted the organic carbon price determined by Hou Yuanzhao [55] according to the afforestation cost method, meaning the fixed carbon afforestation cost constant price in northern China is 273.3 CNY/t. This result was also adopted by other relevant studies [56,57], and the price of nitrogen, phosphorus, and potassium fertilizers was determined according to the price of nitrogen, phosphorus, and potassium compound fertilizers and data of nitrogen, phosphorus, and potassium elements provided by the Statistics Bureau of Wudi County.

Table 5. The soil physical and chemical properties of different land types.

Land Type	Organic Matter (g/kg)	Nitrogen (mg/kg)	Phosphorus (mg/kg)	Potassium (mg/kg)	Soil Bulk Density (g/cm ³)
Grassland	9.01	16.53	7.81	83.97	1.51
Forest land	9.31	14.69	6.10	107.80	1.50
Mixed planting of forest and grass	14.37	44.14	6.14	180.62	1.49
Farmland	8.54	22.74	4.83	339.85	1.53
Garden	6.91	15.33	5.00	90.97	1.55

3.2.5. Evaluation of Culture Service Value

Evaluation of Leisure and Entertainment Value

Saline–alkali land is a natural tourism resource. The Huanghe Island has been developed into an AAAA national tourist attraction, which has a high value of tourism, health care, vacation, leisure, and entertainment. It is popular with an increasing number of tourists, and it can obtain high tourism income. In recent years, the number of tourists to the Huanghe Island has increased year by year, and the economic income has gradually increased. According to the number of tourists and consumption data provided by its development company, the alternative market method and market price method were used to estimate its leisure and entertainment value, as shown in Formulas (12) and (13).

$$V_L = (C_A \times N - C_p \times P - C_d) \times T \quad (12)$$

In Formula (12), V_L is the total annual income of the tourism industry (CNY/year), C_A is the per capita tourism consumption (CNY/person), N is the average annual number of tourists (person), C_p is the labor cost, that is, the salaries of scenic spot staff (CNY/year), P is the number of staff, C_d is the daily maintenance cost of park facilities and equipment, T is the calculation time (a), and the value is one year. The wage standard was calculated according to the average per capita disposable income of urban residents in Wudi County. According to the statistics of the Huanghe Island Development Company, the Huanghe

Island has received 226,900 tourists annually in the past three years, and the per capita consumption is about CNY 63.20. The Huanghe Island scenic spot has an annual staff of 40.

$$C_d = C \times S \quad (13)$$

This research referred to relevant studies [58] to calculate the daily maintenance cost of facilities and equipment in parks. In formula (13), C is the maintenance cost of park infrastructure and S is the construction land area of the park. Referring to studies on the standard of park maintenance and management expenses [58], the standard of expenses in 2017 was 0.50 CNY/m². This research modified it according to the residents' consumption level index, and the maintenance cost of park infrastructure was 0.555 CNY/ m².

Evaluation of Research and Education Value

Saline–alkali land is of high scientific research value. More and more scientific research projects and topics are carried out in saline–alkali land, which aim to improve saline–alkali land and make rational use of saline–alkali land resources [59–61]. According to the LetPub Science Fund query system, during 2011–2020, a total of 186 fund applications for saline–alkali land were supported by the National Natural Science Foundation of China. The funded projects mainly belonged to the ministry of earth sciences and the ministry of life sciences. The projects of the ministry of life sciences were aimed at promoting soil improvement of saline–alkali land through relevant studies and playing the role of reserving land resources of saline–alkali land. The projects of the ministry of earth sciences aimed at monitoring and evaluating soil salinity in saline–alkali land through remote sensing and other technical means. In addition, saline–alkali land was also used to carry out teaching and research activities, such as research and learning practice for middle school students. The scientific research value of saline–alkali land mainly consists of scientific research activities and teaching activities. In this research, the scientific research value was quantified by the number of papers published, and the scientific research value was evaluated by considering the input and research cycle of each paper. According to the statistical data of the Huanghe Island Development Company, the teaching activities were evaluated through the number of teaching activities and amount of income. The calculation method is shown in Formula (14)

$$V_S = V_R + V_E \quad (14)$$

where V_S is the total value of scientific research and education (ten thousand CNY), V_R is the value of scientific research (ten thousand CNY), and V_E is the value of education (ten thousand CNY). The Huanghe Island is a typical saline–alkali land, with high, medium, and low salinization types distributed throughout. It has more wetlands, rich biological varieties, and diverse animals and plants, which is of high scientific research and education value. The scientific research value refers to the value of the Huanghe Island as an experimental scientific research base, which is evaluated by the alternative cost method. As the Huanghe Island as an experimental base has a short period of scientific research, while the large-scale Yellow River Delta has a longer period of research, this study took the Yellow River Delta as a reference and quantified results according to the publication of relevant papers in 2021. The results of relevant journal papers with the research theme of the Yellow River Delta were retrieved on CNKI, and 269 journal papers were published in one year. This study searched the Web of Science database for 319 English papers with the theme of “Yellow River Delta” published by China’s scholars in one year. According to the references [62,63], the investment in each scientific research paper was about CNY 357,600, and the scientific research cycle of China-funded projects was generally three years. Therefore, the average annual investment in each paper was 1/3, which is CNY 119,200, and the value of the Yellow River Delta per unit area was converted to the Huanghe Island [64]. The educational value refers to the value of the Huanghe Island as a place for teaching and research training. Based on the number of participants and charging standards, the market value method was used to evaluate its value.

4. Results and Analysis

4.1. Comprehensive Analysis of the Total ESV of the Huanghe Island

Based on the constructed saline–alkali land ESV index system and the functional value evaluation methods of ecological economics, the total annual ESV of the Huanghe Island was CNY 133.586 million (see Table 6), and the unit value was 50,200 CNY/hm².

Table 6. The results of the ecological economic method to evaluate the ESV of the Huanghe Island.

First-Level Indicators	Value (×10 ⁴ CNY)	Percent (%)	Second-Level Indicators	Value (×10 ⁴ CNY)	Percent (%)	Lowest-Level Indicators	Value (×10 ⁴ CNY)	Percent (%)
Economic Value	8015.05	60.00	Supply Service	8015.05	60.00	Food Production	7679.29	57.49
Ecological Value	3807.00	28.50	Adjustment Service	1917.50	14.35	Raw Material Production	335.76	2.51
						Gas Regulation	795.98	5.96
			Support Service	1889.50	14.15	Conservation of Water Sources	1121.52	8.40
						Maintenance of Biodiversity	341.18	2.55
						Maintenance of Nutrient Cycling	1548.32	11.59
Social Value	1536.56	11.50	Culture Service	1536.56	11.50	Leisure and Entertainment	1166.89	8.73
						Research and Education	369.67	2.77
Sum Value	13,358.60	100.00	Sum	13,358.60	100.00	Sum	13,358.60	100.00

The values of the first-level indicators are ranked as economic value > ecological value > social value; the values of secondary indicators are ranked as supply service > adjustment service > support service > culture service (the value of adjustment and support services were relatively close); and the values of the lowest-level indicators are ranked as food production > maintenance of nutrient cycling > leisure and entertainment > conservation of water sources > gas regulation > research and education > maintenance of biodiversity > raw material production. The food production value was the main ESV component of saline–alkali land development, as it accounted for more than half the value. Except for food production value, the value of other value types was relatively average. The values of raw material production, the maintenance of biodiversity, and research and education accounted for a small proportion, which has great potential.

4.2. Classification Analysis of ESV of the Huanghe Island

4.2.1. Supply Service Value Analysis

The value of supply services of the Huanghe Island was CNY 80.1505 million, accounting for 60.00% of the total value. The value of food production was the main value component, which reached up to CNY 76.7929 million. This accounted for 57.49% of the total value. The value of raw material production was CNY 3.3576 million, accounting for 2.51% of the total value. The Huanghe Island used to be a saline–alkali wasteland, and after years of development and construction, it has formed a new pattern of coordinated development of agriculture, forestry, animal husbandry, and fishing industries. With its advantages of being close to the river and the sea, water is diverted into the island to develop aquaculture water surfaces in a large area. Shrimp, razor clam, and other seafood products have high output, good quality, high price, and high sales volume, and they have produced significant economic benefits. The cost of aquaculture is relatively high, and this research deducted the cost of aquaculture on the basis of the ecological economics method to estimate the net income. The Huanghe Island also obtained certain agricultural economic benefits by planting fruits and vegetables. Ash, alfalfa, and others can be used as raw materials for pastures and economic trees and have contributed obvious economic

benefits. Ash and alfalfa can be used as raw materials for foraging and economic trees, and they have contributed obvious economic benefits. It can be seen that through reasonable development and utilization, saline–alkali land resources can provide high economic benefits, high supply service value, and high economic value.

4.2.2. Adjustment Service Value Analysis

The adjustment service value of the Huanghe Island was CNY 19.175 million, accounting for 14.35% of the total value. The values of gas regulation and conservation of water sources were CNY 7.9598 and 11.2152 million, respectively, accounting for a respective 5.96% and 8.40% of the total value. There was a certain value gap between the two. In recent years, although the large-scale economic development of the Huanghe Island has brought good economic benefits, it has exerted certain pressures on the stability of the ecosystem and the magnitude of ecological value. As a large area of land has been developed as aquaculture water surfaces, the vegetation coverage is low, and the vegetation types are mainly shrubs and grass. Compared with mature forest land, the biomass in these areas is small, and the gas regulation capacity is limited. In addition, the interpolation data of biomass had possible errors, which also makes the calculated gas regulation value limited. The Huanghe Island is saline–alkali land with relatively poor soil nutrition, insufficient freshwater resources, a weaker vegetation growth and development level than non-saline–alkali land. It also has low vegetation coverage, strong evaporation, and inability to intercept rainfall, which leads to weak water conservation capacity. Therefore, when developing saline–alkali land to obtain economic benefits, attention should also be paid to the size of vegetation coverage and economic and ecological benefits should be taken into account.

4.2.3. Support Service Value Analysis

The support service value of the Huanghe Island was CNY 18.895 million, accounting for 14.15% of the total value. Maintenance of nutrient cycling was the main component of its value, which was CNY 15.4832 million. This accounted for 11.59% of the total value. The natural environmental advantages of the Huanghe Island have provided a good growth environment for animals and plants, and there are abundant wild animals and plants. Even if the soil conditions are poor, there are still many plant species, which are also natural habitats for animals. Considering the availability of data, it is difficult to determine the number of animals, and this study only accounted for the diversity value of plants. In addition, the field survey was uncertain, and the spatial interpolation of the Shannon–Wiener index H may have some errors, so the calculated value of maintenance of biodiversity is not relatively high. The Huanghe Island is saline–alkali land with poor nutrient conditions. In recent years, with the implementation of projects such as underground pipe salt drainage, water-saving sprinkler irrigation, and planting salt-tolerant plants, soil conditions of the Huanghe Island have improved, and the soil nutrient content has also increased significantly. However, it still needs to be further improved. It can be seen that scientific development and regulation of saline–alkali land can reduce soil salinity, improve soil physical and chemical properties, improve the ability to maintain nutrient circulation, and thus improve support service value.

4.2.4. Culture Service Value Analysis

The culture service value of the Huanghe Island was CNY 15.3656 million, accounting for 11.50% of the total value. Leisure and entertainment value was the main value component, which was CNY 11.6689 million, accounting for 8.73% of the total value. This research considered the daily maintenance of service facilities and equipment and the remuneration cost of management service staff, which makes the results more reliable. As an AAAA level national ecotourism resort, the Huanghe Island has gradually formed an ecological sightseeing tourism model that combines planting, breeding, tourism, and entertainment. Five parks, including the “Yellow River Cultural Creative Industrial Park”, have been established, attracting a large number of tourists for sightseeing, health preservation,

vacation, and leisure. The annual economic income has gradually increased, reflecting a high value of leisure tourism. The value of research and education was relatively low at CNY 3.6967 million, only accounting for 2.77% of the total value. As a typical saline–alkali land, the Huanghe Island has become a base for teaching, scientific research, and training in recent years. It has attracted national, provincial, and ministerial scientific research teams to perform scientific research, and it has attracted a large number of young people to participate in research, education, and training. However, due to the short development time and few achievements in scientific research projects, this research only estimated and converted the data of the Yellow River Delta papers that could be found, and the average annual scientific research value was CNY 345,400, which is relatively low. The average annual income of youth research training and summer camp activities reached CNY 3.3513 million. It can be seen that saline–alkali land has a certain culture service value, is an important eco-tourism resource, and has considerable economic benefits. However, the value of research and education needs to be further explored. In particular, the investment in related scientific research needs to be further improved.

5. Discussion and Conclusions

5.1. Discussion

In this research, the ESV of Huanghe Island development was calculated as 50,200 CNY/hm² using the ecological economic evaluation method. Li Yongtao [42] and Xu Yumei [65] also used this theory and method to estimate the ESV of the Yellow River Delta, with unit values of 59,300 and 24,600 CNY/hm², respectively. The calculated value of this study differed somewhat from the results of these two studies and was in the middle to upper range. There are three possible reasons for this. The first reason is differences in research scope and development and utilization level. The study area was relatively small, and the development and utilization levels were relatively high. The first two research areas were the core area of the Yellow River Delta and the modern Yellow River Delta, respectively, which are large in scope, early in time, and average in development and utilization level. Differences in regional conditions and development levels may have caused the differences in value. The second reason is that there were differences in value evaluation methods. In Xu Yumei's research, the calculation of several indicators was based on the research of Costanza [5], which is not necessarily consistent with the actual situation of the Yellow River Delta. The data used in this research were reflective of the actual situation of the Huanghe Island. Based on the value function perspective, the value function of ecosystem services was divided, the ecological economics method was used for evaluation, and the equivalent factor method was not adopted simply and directly. The third reason is that there were differences in the selection of evaluation indicators. Li Yongtao calculated the value of silting and land production in the Yellow River Delta, i.e., the value of increasing land area, and Xu Yumei calculated the value of salt production, while the Huanghe Island does not have such value. To compare the differences in the results of the equivalence factor method and the ecological economics method, this study also applied the equivalence factor method [31] to estimate the ESV in the study area. To improve the accuracy of the evaluation, the unit value equivalent factor of the hydrological regulation (conservation of water sources) function was adjusted by applying the spatial and temporal regulation factor of precipitation [31], and the ESV was calculated to be CNY 366.5986 million, and the per unit area the ESV was 137,800 CNY/hm². The hydrological regulation (conservation of water sources) value accounted for 91.24%, while the food production value accounted for only 0.91%, which was quite different from the results of the evaluation methods based on ecological economics. This difference is mainly because of differences in the principles, data sources, indicator meanings, operability, appropriate evaluation scales, and evaluation processes of the two methods. The supply service value of the Huanghe Island calculated in this research was high, and the food production value was more than 50%, which was mainly related to the long-term underground pipe salt drainage control of the Huanghe Island and the development and construction of aquaculture projects. Existing studies

on the ESV of saline–alkali land generally did not consider production, operation, and development costs [33,42,65]. In fact, the reason why the economic value of the ESV of developed saline–alkali land accounts for a large proportion is not that the saline–alkali land itself has a high production value but that the saline–alkali land has been developed and utilized for a long time and has been invested with a certain amount of development, production, and operation costs. In this research, higher production and management costs such as food production and tourism operation were taken into account and deducted from the ESV to obtain more objective evaluation results. Due to the long development time of the Huanghe Island, it is difficult to obtain comprehensive development input data, so this research did not fully estimate the development cost. In the future, research on the development input and output of the Huanghe Island will be continued to investigate the impact of development costs on the ESV of saline–alkali land.

Based on existing research conditions, this study considered the characteristics and data availability of the study area and then selected some indicators. Saline–alkali land does not only have the ecosystem service functions described in this research, and the evaluation methods of each function also refer to other types of ESV evaluation studies. The evaluation results were closely related to the selected indicators and the applied methods. The suitability of the evaluation methods and the reliability of the results need to be further verified. In other saline–alkali regions, the evaluation indicators of the ESV should be adjusted according to the actual situation, and the evaluation method should also be further improved.

Current studies on the evaluation of ESV have not formed a unified index system, and there are many types of ecosystem services, great differences in attribute characteristics, inconsistent understanding of the estimation range, double-calculation and inflated phenomenon of some indicators, and huge differences in conditions in different places of the same type. These factors may reduce the accuracy of estimation results, resulting in low repeatability and strong subjectivity. Therefore, the actual economic significance of the estimated results remains to be explored. In 2023, we should strengthen studies on the standardization of ESVs, construct a unified index system, and develop a standardized evaluation process. Reasonable assessment parameters should also be determined, and the comparability of the evaluation should be improved.

5.2. Conclusions

Considering the attributes of saline–alkali land and the characteristics of the Huanghe Island, this study constructed a saline–alkali land ecosystem service value evaluation index system, which includes three first-level indicators of economic, ecological, and social value; four second-level indicators of supply, adjustment, support, and culture; and eight lowest-level indicators of food production and raw material production. Using the value evaluation method based on ecological economics, the daily production and operation costs were considered, and it was estimated that the ESV of the Huanghe Island development is CNY 133.586 million and the unit value is 50,200 CNY/hm², indicating that the Huanghe Island has relatively high ESV and development value. The research verifies that saline–alkali land is an important land resource with high ESV and development value. Reasonable exploitation and utilization of saline–alkali land resources can provide higher economic benefits.

From the first-level indicators, economic value accounted for the largest proportion, followed by ecological value and then social value. From the perspective of second-level indicators, the supply service value was the highest, and the food production value was the main component. This was directly related to the comprehensive development of agriculture, forestry, husbandry, and fishery in the Huanghe Island in recent years. The second was the adjustment service value. Due to the low vegetation coverage of the Huanghe Island, although it has certain gas regulation and water conservation capacities, it was still relatively weak. The third was the support service value. Measures such as engineering improvement and vegetation planting of the Huanghe Island have had a certain

impact on its nutrient cycle and gas regulation, which have improved its ability to maintain nutrient cycles. However, the maintenance of biodiversity value needs to be improved. The lowest was the culture service value, among which the leisure and entertainment value was the main component. As a typical saline–alkali land, the Huanghe Island has great scientific research value. However, due to the short period of scientific research that could be searched, the estimated value of research and education was relatively low.

The research did not directly use equivalent factor tables and regional correction coefficients to estimate the ESV but instead comprehensively used the market value method and other ecological economic methods to evaluate the ESV of the Huanghe Island. In the value evaluation, higher production and management costs such as food production and tourism operation were considered, and they were deducted in the calculation of the ESV, making the evaluating results more objective and more consistent with the actual situation of the study area.

The evaluation method based on ecological economics is different from the equivalent factor method in terms of method principle, data source, indicator connotation, and price basis. It accounts for the value at a specific time point. The data collection has certain difficulties and workloads but does not require coefficient correction. Moreover, the data collected by the ecological economics method is actual production data, which have strong timeliness, can be more intuitive, and can accurately display the current ESV.

Through the research results, management suggestions that are conducive to the ESV of saline–alkali land and the measures to promote the sustainable utilization of saline–alkali land resources were obtained. Saline–alkali land can be exploited and utilized to obtain economic value. While obtaining economic benefits, the ecological benefits should not be ignored. Through water-saving sprinkler irrigation and other projects, soil conditions of saline–alkali land can be improved, and its ecological value can be increased. Managers of saline–alkali land can develop tourism industries according to local conditions, create scenic spots with unique characteristics, and explore various tourism functions. At the same time, they can attract scientific research projects to carry out scientific research activities on the improvement of saline–alkali land, so as to increase its social value. The purposes of this research were to provide references for the rational development and utilization of saline–alkali land resources in the Yellow River Delta and to further promote ecological protection and high-quality development of the Yellow River Basin. Although saline–alkali land can be developed into forest land and cultivated land, compared with general forest land and cultivated land, its background conditions are poor. In the process of development, the vulnerability of its ecosystem should be fully considered, and scientific and reasonable development and utilization should be given attention.

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Article

Bio-Organic Fertilizer Combined with Different Amendments Improves Nutrient Enhancement and Salt Leaching in Saline Soil: A Soil Column Experiment

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Abstract: Salt-affected soils frequently experience leaching and desalination issues, which severely restrict plant growth and water uptake. Hence, in this experiment, four treatments including CG (no amendments addition); OF (organic fertilizer addition); OH (organic fertilizer and Hekang amendment addition); and OB (organic fertilizer and fulvic acid addition) were designed to examine the effect of organic amendment on soil chemical properties, water and salt transport, and soil desalination laws of coastal saline soil. The results showed that the addition of organic amendments significantly reduced soil pH (8.47–8.52) and salt content (2.06–2.34 g kg⁻¹), while increasing soil organic matter content, available phosphorus, and available potassium. OH treatment has a higher available phosphorus content than other treatments. OH and OB treatments elevated the soil desalination ratio (32.95% and 32.12%, respectively) by raising the leaching volume and leaching rate. Organic amendments significantly promoted Na⁺ (4.5–32%) and SO₄²⁻ (12–27%) leaching compared to CG. Organic treatments, particularly OB treatment, not only increased the content of soil organic matter and available nutrients but also promoted salt ion leaching, improved soil permeability and increased soil desalination and water leaching rates. Our results may provide a theoretical basis for revealing the desalination law of coastal saline soil.

Keywords: coastal saline soil; organic fertilizer; organic amendment; soil nutrient content; water and salt migration; desalinization rate

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1. Introduction

Global agricultural production and food security face enormous threats due to soil salinization, which is a widespread phenomenon of soil degradation [1,2]. It is normally caused by the accumulation of water-soluble salts in the soil resulting from the interaction between prevailing landscape and weather conditions as well as improper irrigation management [3,4]. Excessive soil salinity facilitates the absorption of Na⁺ and Cl⁻ in plants and impacts photosynthesis by reducing carbon (C) assimilation and water use efficiency, which results in water loss, atrophy, and necrosis of plants, leading to crop failure and desertification of land [4,5]. Currently, over 900,000 km² of the world's total land is salt-affected, and affected land is growing at a rate of 10% per year [6,7]. Consequently, it has become very pertinent to ameliorate and re-utilize salt-affected soils to curb this development.

Salt-affected soils usually exhibit lower availability of soil nutrients due to poor soil structure and low organic matter content [8]. The exogenous amendments application is a common and effective method for salt-affected soils to improve soil nutrient availability

and soil fertility [7,9]. Many researchers have reported that soil productivity and fertility can be improved by adding organic materials such as compost, green manures, food processing waste, and farmyard and poultry manures [10]. Bio-organic fertilizer is produced by fermentation with the above materials and a small amount of functional microbial strains [11,12] and has always been considered as a remediation material for improving soil nutrient content and soil fertility, promoting nutrient uptake by vegetation and reducing the toxicity of salt to plants [2,3,7,13]. In addition, considerable studies have suggested that organic fertilizer plays a crucial role in stimulating Na^+ leaching and electrical conductivity (EC) reduction [7,14]. However, some researchers have also pointed out that long-term use of organic fertilizers may reduce the effectiveness of bio-organic fertilizers leading to salt accumulation [1]. Meanwhile, some organic materials have been used for soil remediation and vegetation restoration due to their efficiency. HeKang (HK) is an acid conditioner that contains an amount of hydrolyzed maleic anhydride, and it has been shown to reduce soil salt content but also improve soil physical and chemical properties [15,16]. Fulvic acid (HA) is a type of organic aromatic substance soluble in acidic and alkaline water solutions, and it has a significant influence on alleviating salt stress, promoting nutrient absorption, and regulating soil microorganisms [17,18]. Some studies have reported that the combined application of organic acid amendment and organic fertilizer efficiently improves nutrient availability and promotes soil desalination [9]. Liu et al. [18] reported that the combined application of FA and inorganic fertilizer reduced soil EC and pH of coastal saline soil, and increased nitrogen uptake of wheat. However, few studies are available on the synergistic effect of the combined application of bio-organic fertilizer and acid amendment in saline soils, especially in reducing salt and enhancing nutrients.

Water leaching is another measure of soil reclamation; it reduces soil water salinity by discharging salts from the upper horizons to the lower soil layers [3,5]. In general, salt always migrates with the movement of water, and the amount of leaching water to a large extent affects the redistribution of soil salt [19]. Excessive water leaching could lead to the loss of soil nutrients resulting in low nutrient utilization [20]. Improper leaching and irrigation practices could adversely affect some environmental pollution problems, such as unavoidable waste and pollution of water resources [21]. Therefore, it is crucial to determine the amount of leaching water and the migration of salt ions during leaching. For saline-sodic and sodic soils, it is important to increase soil permeability by altering the quantity and structure of soil aggregates to promote the passage of water required to remove salts [22]. Previous studies have reported that adding soil amendments can improve soil physical structure by increasing soil permeability and promoting water leaching and utilization efficiency [7,8]. However, the effects of organic amendments combined with organic fertilizers on water and salt migration and desalination efficiency of saline soils under leaching conditions are still unclear.

Overall, to reveal the synergistic effect of various amendment materials and organic fertilizers on coastal saline soil and the regularity of salt migration under leaching conditions. In this study, a soil column leaching experiment of organic amendments combined with organic fertilizer was designed. The chemical properties after organic amendments addition were measured, the migration and transformation of salt ions in the leaching state were studied, and the desalination rate and water volume requirement of the soil column under different treatments were monitored. The aim of this study was (1) to determine the improvement effect of the organic fertilizer and amendments on chemical properties of coastal saline soil; (2) to clarify the influence of organic amendments on the dynamics of water and salt distribution of coastal saline soils; and (3) to reveal the effect of organic amendments on desalting efficiency and law of soil column under leaching conditions. We hypothesized that the addition of organic fertilizer combined with acid amendments would reduce soil salt content, improve soil nutrient content, and promote the removal of salt ions.

2. Materials and Methods

2.1. Site Description and Soil Properties

The sampling site is located on a farm in Ninghe District (117°30′4″ N, 39°25′54″ E), Tianjin City, China. The study area belongs to fluvial alluvial and surface alluvial sedimentary soils, which are mostly salinized tidal soils. The study area has the typical characteristics of a semi-arid and semi-humid monsoon climate in a warm continental temperate zone, with four distinct seasons, high temperatures, rainy summers, drought, and little rain in winter. The annual average temperature is 11.4–12.9 °C, the annual average precipitation is 520–660 mm, and the average number of precipitation days per year is 63.8 days. The annual potential evapotranspiration is 1500–2000 mm, and the annual sunshine duration is 2470–2900 h. The annual solar radiation is 4935 MJ m⁻². Average relative humidity is the highest in July and August at about 80%. Nine representative soil profiles were selected to collect soil samples at 0–20 cm and 20–40 cm soil layers. All soil samples were taken back to the laboratory for soil column experiments. The soil sample of the same layer was thoroughly mixed and air dried and passed through a 4 mm sieve to fill the soil column. The sample soil has a pH (8.4–8.8) and bulk density (1.40–1.45 g cm⁻³). The soil has 14.77–15.19% sand, 31.60–33.78% silt, and 51.03–53.63% clay, which is classified as clay by United States soil texture classification standards (United States Department of Agriculture). Other soil properties are shown in Table 1.

Table 1. Basic soil properties of the study area.

Soil Depths (cm)	pH	EC (μs cm ⁻¹)	Salt Content (g kg ⁻¹)	SOM (g kg ⁻¹)	Bulk Density (g cm ⁻³)	Soil Texture			AN (mg kg ⁻¹)	AK (mg kg ⁻¹)	AP (mg kg ⁻¹)
						Sand (0.02–2 mm)	Silt (0.002–0.02 mm)	Clay (<0.002 mm)			
0–20	8.80	634.00	2.26	7.29	1.45	15.19	33.78	51.03	26.20	110.67	6.05
20–40	8.40	598.00	2.03	6.85	1.40	14.77	31.60	53.63	30.70	93.00	6.19

Note: SOM represents soil organic matter; AN represents soil available nitrogen; AP represents soil available phosphorus; AK represents soil available potassium; EC represents soil conductivity.

2.2. Experimental Material and Design

Bio-organic fertilizer was jointly developed by Nanjing Ningliang Bio-fertilizer Co., Ltd. and Jiangsu Academy of Agricultural Sciences of Nanjing Agricultural University. It contains high-quality chicken manure, Chinese medicine drugs, and other materials; high-efficiency compound strains are added after full fermentation. Fulvic acid is a macromolecular organic compound with a small molecular weight [20]. Fulvic acid contains hydroxyl and carboxyl groups, which can combine with alkaline substances to form fulvic acid to regulate soil pH and effectively improve saline-alkali soil [18]. Fulvic acid, produced by Shandong Yupin High-tech Biotechnology Co., Ltd. Hekang (Hk), is a type of liquid fertilizer specifically used for saline-alkali land improvement. The main component of HK is Hydrolytic Polymaleic Anhydride (HPMA) which was hydrolyzed by maleic anhydride and is non-toxic to the environment and algae [23]. HK is produced by Beijing Feiying Greenland Science and Technology Co., Ltd. The above amendments materials can be purchased as commercial fertilizers. The organic fertilizer and amendments are shown in Table 2.

Table 2. Basic composition and content of amendment material.

Amendment	pH	EC (ms cm ⁻¹)	SOM (g kg ⁻¹)	N (g kg ⁻¹)	P ₂ O ₃ (g kg ⁻¹)	K ₂ O (g kg ⁻¹)	Basic Component	Carboxyl (mg kg ⁻¹)	Density (g cm ⁻³)
Organic fertilizer	8.2	23.2	515	25.6	22.4	18.6	-	-	-
Fulvic acid	7.5	15.6	600	12.5	10.8	120	-	-	-
Hekang	2.1	0.77	-	-	-	-	polymaleic anhydride	180	1.15

We set up 4 groups in the soil column experiment: (1) CG, without amendment addition; (2) OF, soil with organic fertilizer of 60 g m^{-2} ; (3) OH, soil with organic fertilizer of 60 g m^{-2} and Hekang amendment of 4.5 g m^{-2} ; and (4) OB, soil with organic fertilizer of 60 g m^{-2} and fulvic acid of 7.5 g m^{-2} . Each of the above treatments was repeated three times, and soil water and salt monitoring sensors and data collectors were installed to monitor and record water and salt data.

2.3. Soil Column Experiment

Soil column experiments were conducted using plexiglass columns of 20 cm in internal diameter and 50 cm in height in December 2020. First, a 5 cm layer of quartz sand was placed as a filter layer to prevent the column outlet from becoming blocked by soil in the bottom of the column. Then, a layer of nylon mesh was evenly spread over the quartz sand in each column. According to the original bulk density (1.4 g cm^{-3}), the required soil of 0–20 cm was weighed, and the organic fertilizer and amendments were sprayed or applied to the original soil according to the experimental design. After mixing evenly, it was evenly divided into 4 equal parts and filled in the soil column. The soil of the 20–40 cm layer was weighed according to the original bulk density (1.45 g cm^{-3}) and no material was added (Table 1). Each layer of soil was filled 4 times, with 5 cm each time, and a 5 cm layer of irrigation water was set aside above the soil column. The materials were evenly mixed in the topsoil (0–20 cm). To collect the leachate, a 1 cm diameter hole was drilled in the bottom of each column (Figure 1).

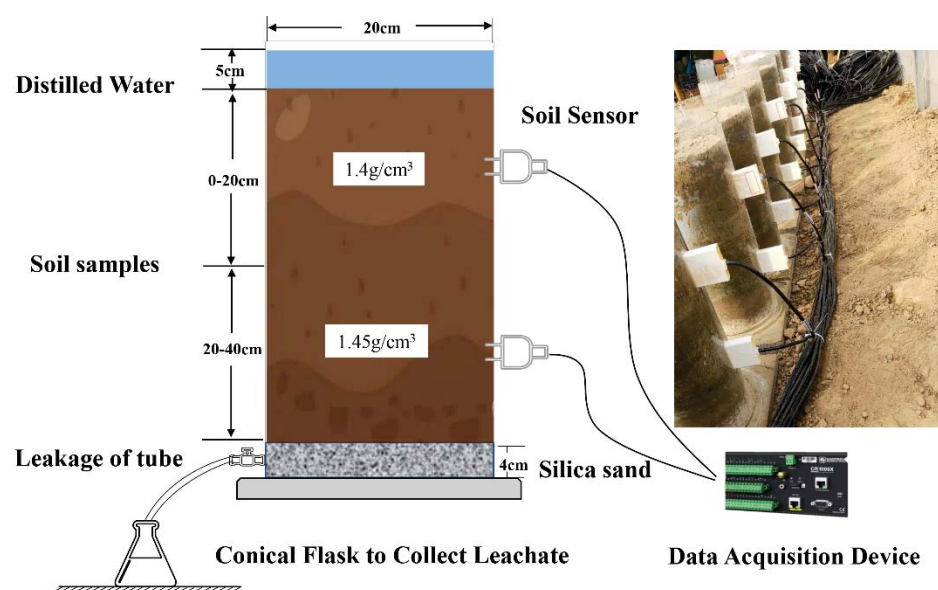


Figure 1. Design diagram of soil column experiment.

A rectangular hole about 6.2 cm long and 1.5 cm wide was drilled at 10 cm and 30 cm of each soil column. To monitor soil moisture and salinity dynamics at 0–20 cm and 20–40 cm, the soil sensor (CS655) was inserted vertically, and glass glue was evenly applied to the connection between the sensor and the soil column to prevent water leakage. The data collector (CR3000), which can record and store data for 3 months, was connected to the end of the soil sensor. Data reading began one week after stable installation. The volumetric water content and electrical conductivity were monitored by salt sensors (CS655) and a data processor (CR3000). In addition, soil sensors were installed in 0–20 cm and 20–40 cm layers of soil columns, and a set of data was collected at 15 min intervals, and the sensors were calibrated before installation. Soil sensors and data collectors were purchased from Nanjing Ubaida Technology Co., Ltd., and calibrated one week before installation (Figure 1).

The soil column was filled with water equivalent to 80% of the saturated water capacity in the field and sealed with plastic film so that the water could fully penetrate the saturated

state, then left to stand for 24 h. Intermittent leaching was used, and the leaching process was initiated every 12 h. In addition, 500 mL of leaching water was added each time, and the number of leaching times was based on the leakage rate of each soil column. Leachate from each soil column was recorded and collected each time it exceeded 100 mL to measure the conductivity. At the same time, the 5 d, 10 d, 15 d, and 20 d leakages were collected, and the leaching solution was configured according to the soil-water ratio of 1:5 to determine the content of soil salt ions in each soil column. Water and salt data were recorded by the water and salt sensor every 7 days. The desalination ratio (V_R) and desalination efficiency (E_M) were used as indices to measure the desalination performance of the organic amendments; the following formulas were used for calculation.

$$V_R = \frac{m_1 - m_2}{m_1} \quad (1)$$

$$E_M = \frac{m_2 - m_1}{w} \quad (2)$$

where m_1 represents the salt content of the initial soil column, g kg^{-1} ; m_2 represents the salt content of the soil column after leaching, g kg^{-1} ; and w represents the amount of leaching water.

2.4. Soil and Water Sampling and Analysis

Before (February 2021) and after (March 2021) the leaching experiment, soil samples were collected at 0–20 cm and 20–40 cm layers using a small borehole soil auger (diameter 38 mm, length 100 cm). A total of 30 soil samples were collected from 12 soil columns for laboratory analysis at each sampling time. To evaluate the improvement of organic amendments on salt-affected soils, soil pH, salt content, electronic conductivity, and soil organic matter, available phosphorus, and available potassium of 0–20 cm layer were analyzed in the Lab. Leachate from each soil column was recorded and collected each time it exceeded 100 mL and brought back to the laboratory to measure electrical conductivity and salt ions content. During the leaching experiment, soil volumetric water content and electrical conductivity in 0–20 cm and 20–40 cm layers were measured by salt sensors in situ.

The pH value and salt content of soil samples were determined. Leaching filtrate was prepared with a 1:5 soil-water mass ratio extract to determine salt ions. The soil pH value was measured by the pH meter method. The salt content of the soil was measured by mass method. The organic matter (SOM) was oxidized by potassium dichromate and heated by an external heating method. The available phosphorus (AP) was measured by the $0.5 \text{ mol L}^{-1} \text{ NaHCO}_3$ extraction molybdenum antimony colorimetric method. The available potassium (AK) was determined by NH_4Ac^- extraction-flame photometry. Soil urease activity, soil catalase activity, and soil alkaline phosphatase activity were determined using the method described by Liu et al. [18]. Soluble CO_3^{2-} and HCO_3^- were analyzed using neutral titration. Soluble Cl^- was analyzed by the silver nitrate titration method, and soluble SO_4^{2-} was measured by barium sulfate turbidimetric method. The concentrations of soluble K^+ , Na^+ , Ca^{2+} , and Mg^{2+} were measured as described by Liu et al. [18].

2.5. Statistical Analysis

Soil physical and chemical indexes were processed with Microsoft Excel 2007 (version 8.0.1 for Windows). Significant differences between different treatments were compared by using a one-way ANOVA with Duncan's new multiple-comparison test ($p \leq 0.05$) using SPSS (version 20.0, IBM, Armonk, New York, NY, USA). The significant difference between the initial and final salt content of the soil column under different treatments was analyzed by the one-way ANOVA and Tukey test ($p < 0.01$). All figures were drawn by Origin 2022b (version 9.65.169, Origin Lab Corporation, Northampton, MA, USA)

3. Results

3.1. Effect of Soil Properties after Adding Modified Materials

Significant differences in soil pH and salt content were observed in the different treatments (Table 3). Treatments with organic amendments addition had a lower pH value (8.47–8.52) than control in topsoil (0–20 cm). Except OF, the salt content of other organic treatments was lower than the control, ranging from 2.06 g kg⁻¹ to 2.13 g kg⁻¹. There were significant differences between the various treatments in SOM, AP, and AK ($p < 0.05$). The organic matter content of OF, OH, and OB was 8.3 g kg⁻¹, 7.58 g kg⁻¹ and 7.47 g kg⁻¹, respectively, which increased by 13.8, 5.7, and 2.5% compared to CG, respectively. The contents of AK and AP in organic treatment increased by 51–71 and 14–37% to control, respectively, and ranked OF > OH > OB > CG. There was a significant difference in AKP between organic treatments and control ($p < 0.05$). The AKP activity in the treatments followed the order OF > OH > OB > CG.

Table 3. Variation of chemical properties between different treatments in 0–20 cm layer.

Treatments	pH	Salt Content (g kg ⁻¹)	SOM (g kg ⁻¹)	AK (mg kg ⁻¹)	AP (mg kg ⁻¹)
OF	8.49 ± 0.07 ^b	2.34 ± 0.26 ^a	8.30 ± 0.06 ^{ab}	188 ± 6.97 ^a	8.35 ± 0.66 ^a
OH	8.52 ± 0.12 ^b	2.06 ± 0.32 ^{ab}	7.58 ± 0.32 ^{bc}	182 ± 5.71 ^a	7.15 ± 0.15 ^b
OB	8.47 ± 0.12 ^b	2.13 ± 0.08 ^a	7.47 ± 0.18 ^{bc}	166 ± 2.86 ^a	6.98 ± 0.42 ^b
CG	8.87 ± 0.11 ^a	2.27 ± 0.22 ^a	7.29 ± 0.41 ^c	110 ± 17.91 ^b	6.10 ± 0.06 ^c

Note: different lowercase letters in the same column indicated significant differences ($p < 0.05$, $n = 3$). AK: available potassium; AP: available phosphorus; SOM: soil organic matter; OF: organic fertilizer alone; OH: organic fertilizer and HK addition; OB: organic fertilizer and FA addition; CG: control group. All the data are expressed as mean value ± standard deviation.

3.2. Dynamics and Difference of the Soil Volumetric Water Content and EC during Leaching

The dynamics of soil volumetric water content (SVWC) and EC with leaching time in different treatments are shown in Figure 2. The SVWC of different treatments was 0.2–0.3 m³ m⁻³ in 0–20 cm layer at 2 d and gradually increased by 0.40–0.48 m³ m⁻³ with leaching time. The SVWC of these treatments in the 20–40 cm layer had a similar trend to the 0–20 cm layer. Except for CG, leakage was observed in different treatments at 3 d, and SVWC was ranked CG > OH > OB > OF. With increasing leaching time, soil EC of 0–20 cm soil layer increased between 2–4 d. OH and OF treatments increased rapidly over time, at 2.5 dS m⁻¹ and 1.75 dS m⁻¹, respectively. Subsequently, soil EC gradually decreased due to increasing leakage volume, and ranked CG > OH > OF > OB. The soil EC in the 20–40 cm layer was higher than that in the 0–20 cm layer. OB treatment increased the fastest with leaching time increased, and it had the highest conductivity of 2.8 dS m⁻¹, while it decreased gradually with increasing leachate volume.

Change in SVWC (soil volumetric water content) and EC between different treatments under cumulative infiltration water (2, 4, 6 L) are presented in Table 4. SVWC increased with the increase in infiltration water volume. The SVWC in the 0–20 cm soil layer was lower than in the 20–40 cm soil layer when leaching water was 4 L and 6 L. After adding 6 L of water, SVWC ranged from 0.40 to 0.45 m³ m⁻³ and significantly differed between treatments, ranking CG > OH > OB > OF in the 0–20 cm and CG > OH > OB > OF in the 20–40 cm. The variation of soil EC increased with the increase in soil depth and decreased with the increasing infiltration of water, which is the opposite of SVWC. There were significant differences in EC between different treatments ($p < 0.05$). Soil EC ranged from 0.63 to 0.97 dS m⁻¹ in the 0–20 cm and from 1.03 to 1.37 dS m⁻¹ in the 20–40 cm soil layer when infiltration water volume was 6 L.

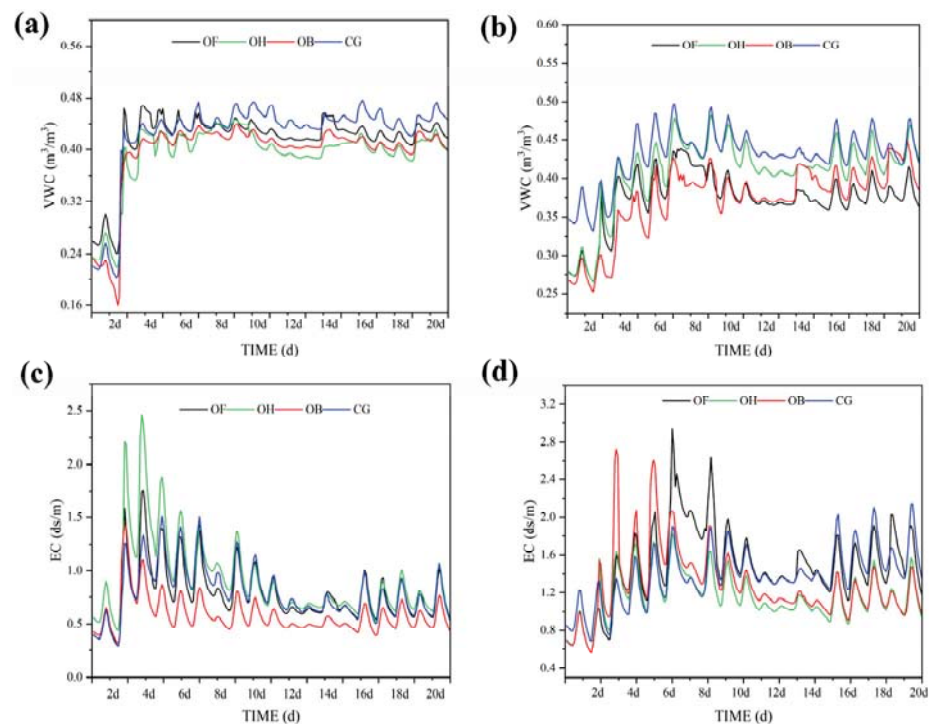


Figure 2. Variations of soil volumetric water content ((a): 0–20 cm; (b): 20–40 cm) and electrical conductivity ((c): 0–20 cm; (d): 20–40 cm) over time in different treatments.

Table 4. Variation of SWC and EC under different cumulative infiltration water amounts.

Treatments	Soil Layer (cm)	Cumulative Infiltration Volume (2 L)		Cumulative Infiltration Volume (4 L)		Cumulative Infiltration Volume (6 L)	
		SVWC (m³ m ⁻³)	EC (dS m ⁻¹)	SVWC (m³ m ⁻³)	EC (dS m ⁻¹)	SVWC (m³ m ⁻³)	EC (dS m ⁻¹)
OF	0–20	0.45 ± 0.01 ^a	1.24 ± 0.27 ^a	0.46 ± 0.00 ^a	1.22 ± 0.11 ^a	0.45 ± 0.01 ^a	0.78 ± 0.02 ^{ab}
	20–40	0.38 ± 0.03 ^A	1.45 ± 0.24 ^{BC}	0.41 ± 0.00 ^B	1.64 ± 0.02 ^B	0.40 ± 0.00 ^B	1.29 ± 0.04 ^A
OH	0–20	0.45 ± 0.00 ^a	1.47 ± 0.22 ^a	0.42 ± 0.00 ^{bc}	1.23 ± 0.03 ^a	0.43 ± 0.00 ^{bc}	0.89 ± 0.11 ^a
	20–40	0.43 ± 0.03 ^A	1.87 ± 0.02 ^A	0.43 ± 0.01 ^B	1.50 ± 0.01 ^C	0.44 ± 0.00 ^A	1.15 ± 0.03 ^A
OB	0–20	0.35 ± 0.00 ^b	1.20 ± 0.08 ^a	0.42 ± 0.00 ^c	0.88 ± 0.01 ^b	0.42 ± 0.00 ^c	0.63 ± 0.12 ^b
	20–40	0.30 ± 0.00 ^B	1.29 ± 0.07 ^C	0.42 ± 0.01 ^B	1.17 ± 0.05 ^D	0.44 ± 0.01 ^A	1.03 ± 0.00 ^B
CG	0–20	0.35 ± 0.04 ^b	1.37 ± 0.06 ^a	0.43 ± 0.00 ^b	1.21 ± 0.07 ^a	0.44 ± 0.00 ^{ab}	0.97 ± 0.12 ^a
	20–40	0.39 ± 0.04 ^A	1.69 ± 0.06 ^{AB}	0.48 ± 0.01 ^A	1.97 ± 0.03 ^A	0.45 ± 0.01 ^A	1.37 ± 0.13 ^A

Note: SVWC represents soil volumetric water content and EC represents soil electrical conductivity. Different low-ercase letters represent significant differences between treatments under the same cumulative water volume in the 0–20 cm layer, and different capital letters represent significant differences between different treatments under the same cumulative water volume in the 20–40 cm layer ($p < 0.05$). All data are expressed as mean ± standard deviation.

3.3. Desalination Ratio and Efficiency of Different Treatments

At the end of the leaching experiment, the final soil salt content was significantly reduced ($p < 0.01$), ranging from 1.42 g to 1.87 g kg⁻¹. There was a significant difference in final soil salt content between control and organic treatments ($p < 0.05$), showing CG > OF > OH > OB (Figure 3). The soil salt content of different soil columns decreased with leaching volume (Table 5). Leaching water from different treatments ranged from 5.8 L to 7 L, and the highest water consumption was OF and OH treatments. Leaching rates ranged from 0.06 mL h⁻¹ to 22.4 mL h⁻¹ and showed OB > OH > OF > CG. The desalination ration V_R and desalination efficiency E_M showed the effect of organic amendments on soil permeability. The desalination rates of OF, OH, and, OB treatments were 32.61%, 32.95%, and 32.12%, respectively, which were higher than control. There was

no significant difference in E_M between different treatments. The desalination efficiency of OH was the highest, and the CG was the lowest.

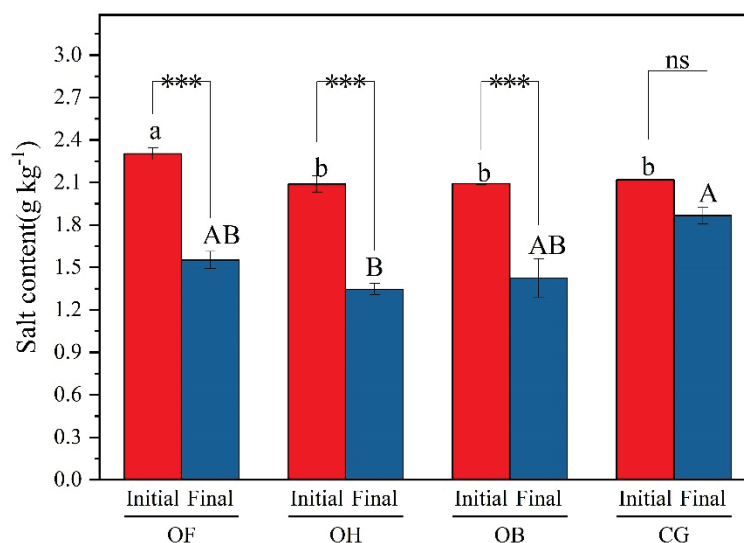


Figure 3. Variation of salt content between different treatments before and after leaching. Different lowercase letters represent significant differences between treatments under the same cumulative water volume in the 0–20 cm layer, and different capital letters represent significant differences between different treatments under the same cumulative water volume in the 20–40 cm layer ($p < 0.05$). *** means a significant difference between initial salt content and final salt content under the same treatment ($p < 0.01$); ns means no significant difference.

Table 5. Desalination efficiency in different columns.

Treatment	Leachate Volume (L)	Leaching Rate (mL h ^{−1})	V_R (%)	E_M (g kg ^{−1} mL ^{−1})
OF	7.00 ± 0.70 ^a	18.3 ± 3.8 ^a	32.61 ± 2.32 ^a	0.108 ± 0.01 ^a
OH	7.00 ± 0.40 ^a	21.2 ± 7.80 ^a	32.95 ± 4.16 ^a	0.101 ± 0.01 ^a
OB	6.80 ± 0.47 ^a	22.4 ± 9.68 ^a	32.12 ± 6.70 ^a	0.098 ± 0.02 ^a
CG	5.80 ± 0.23 ^a	0.06 ± 0.00 ^b	18.44 ± 1.23 ^b	0.060 ± 0.00 ^a

Note: Different lowercase letters in the same column indicated significant differences between different treatments ($p < 0.05$, $n = 3$); V_R represents desalination ratio; E_M represents desalination efficiency. All data are expressed as mean ± standard deviation.

3.4. Leakage Volume and Salt Ion Accumulation of Different Treatments

The conductivity of soil leachate can represent the soluble salt content in the soil column. Figure 4 shows the change of leachate EC with leaching water volume. With the increase in leaching water, the soil conductivity of the different treatments decreased significantly. The soil leachate EC ranged from 0.06 to 0.21 dS m^{−1}. At the end of leaching, the leachate EC in OH and OB were 0.07 dS m^{−1} and 0.11 dS m^{−1}, respectively, which were significantly lower than control and OF. The accumulated leachate collected from OH and OB treatments was 1913 mL and 1533 mL, respectively, which was significantly higher than that of the control.

As shown in Figure 5, the salt ion content of leachate collected from different columns decreased with leaching time. The main soil salt ions under the different treatments were Na⁺, Mg²⁺, Ca²⁺, SO₄^{2−}, Cl[−], and a small amount of HCO₃[−] ions. SO₄^{2−}, Na⁺, and Mg²⁺ were the most affected by leaching water volume. There was a significant difference in Na⁺, SO₄^{2−}, Mg²⁺, and Cl[−] between different treatments ($p > 0.05$). Total ions between the different treatments were ranked as OF > CG > OB > OH at 5 d, and changed to CG > OF > OB > OH at 10 d. At the end of leaching, Na⁺ in the OF, OB, and OH treatments were 4.5, 12.6, and 32% lower than that of CG, respectively. The SO₄^{2−} content in OF, OB, and OH treatments were 12, 13.3, and 27% lower than in the control, respectively.

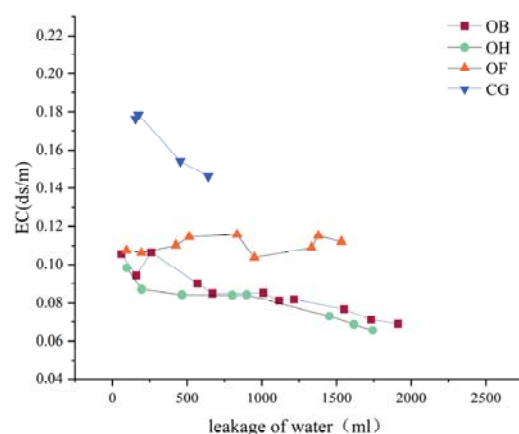


Figure 4. Variation of leachate EC with the amount of leaching water.

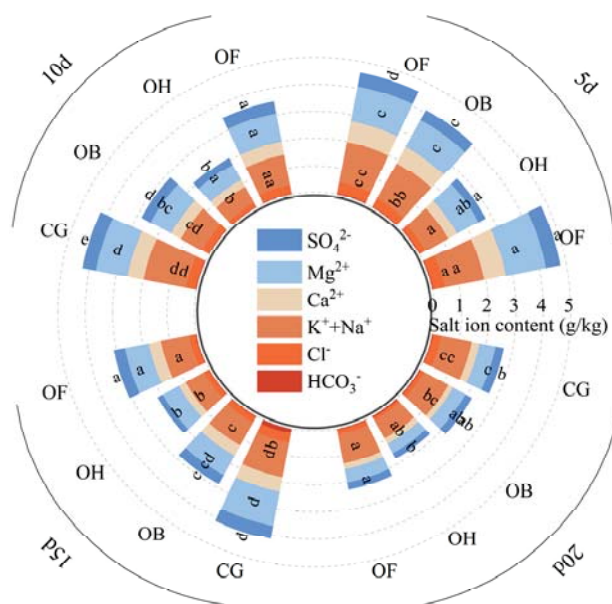


Figure 5. Variation of salt ion content in leachate with leaching time. Different lowercase letters at the same time indicated significant differences among different treatments ($p < 0.05$).

4. Discussion

Numerous studies have demonstrated that the use of organic fertilizers or chemical amendments not only reduces soil salinity but also improves soil fertility in salt-affected soils [4,8,9]. Similar results were found in our study, with the addition of organic fertilizer and amendments significantly reducing soil pH and salt content (Table 3). This could explain by the following reasons: (1) the release of carbon dioxide, hydrogen ions (H^+) and organic acids from organic manure under the decomposition of microorganisms neutralized the alkaline ions in the soil [24] and (2) the H^+ released from the decomposition of organic fertilizer reacts with salt and carbonate, making them more soluble and flowing out with water [4,25]. Our study showed that organic amendments also significantly increased soil organic matter, and AP (Table 3). After compound fermentation of straw, chicken manure, and microbes, bio-organic fertilizer contains a significant amount of organic matter, including free humic acid, and various biopolymer residues [26]. It continuously provides plants with vital nutrients including N, P and K through decomposition and mineralization [27]. It should be noted that organic amendments had a higher nutrient content than control (CG), particularly available phosphorus, which is consistent with Liu et al. [18] suggested that the addition of fulvic acid enhanced the availability of phosphorus by promoting the conversion of inorganic phosphorus in salt-affected soils. The possible mechanism of this result is that a large number of anions contained in organic

amendments compete with phosphates to chelate Al^{3+} , Ca^{2+} , Fe^{3+} , etc. in the soil, which reduces the number of adsorption sites and leads to phosphorus release and improved fertility [18,28].

It was found that the soil water content of the organic treatments increased with leaching time and was lower than that of the control (Figure 2a,b; Table 4). This result appears to differ from Sun et al. [29], which found that biochar addition increased soil water content at different soil depths in coastal saline soils. This difference is not only related to the types of amendment materials, but also has a significant relationship with soil texture [30]. Larney et al. [11] noted that the addition of organic amendments may not increase the moisture content of clay compared to degraded sandy soil due to its greater inherent water-holding capacity. The addition of organic amendment may reduce soil volumetric water holding capacity on a silt loam due to higher bulk density than sandy soil [31]. Zhou et al. [30] indicated that the effects of organic amendments mainly affected the retention of capillary water but not hygroscopic water. In this study, experimental soil was classified as clay soil that contains high capillaries and micro-pores, and few air pores, resulting in poor water and air permeability. Capillary pores contain capillary water that can be effectively absorbed by roots, representing soil water retention capacity, while micro-pores and air pores contain mostly hygroscopic water and gravity water [32]. Organic materials, particularly organic fertilizer, have been demonstrated to increase connectivity by altering intra- and inter- aggregate pore structure [33]. Therefore, we speculate that the addition of organic amendments may have resulted in lower soil water content than the control by promoting soil leaching ineffective water from non-capillary porosity. Another result of our study verified this phenomenon, in which the leaching rate and leachate of the treatment with acid amendments addition (OH, OB) were significantly higher than those of the control. This result indicated that the addition of organic amendments improved soil permeability, which is similar to Shi et al. [34] who observed that the addition of organic fertilizer improves the permeability between aggregates by better balancing macro-pores. In addition, the hydrophobic nature of other organic modifications may have facilitated this process [11]. However, the mechanisms need further exploration.

In this study, we observed that soil columns with different treatments formed significant salt peaks of 10 and 30 cm (Figure 2c,d). The soil EC in the 0–20 cm layer was lower than the soil EC in the 20–40 cm layer, and both decreased with the increase of infiltration water (Table 4). This result indicated salt accumulation and desalting with leaching time. The final salt content and salt accumulation of OH treatment was lower than other treatments, but the desalting rate was higher than other treatments (Figure 3; Table 5). This may be due to the addition of amendments, which improved soil permeability and promoted the replacement of Na^+ and SO_4^{2-} in soil, resulting in the dissolution of salt and its removal with water [15,35]. Our results showed that the desalination rate of different treatments ranged from 18.3 to 33%, slightly higher than the study of Heng et al. [36] (15–32% drip irrigation). These differences may be due to the types of amendment materials and leaching methods. In addition, the original soil bulk density and salinity may be crucial factors for leaching results [37]. Moreover, we found that the organic amendment addition increased the desalination efficiency and leaching rate (Table 5). Improving desalination efficiency and flow rate is an important way to save water [38]. Through an ion exchange reaction, the organic acids, humic acid, and so on produced from the breakdown of the organic amendment swap out the insoluble ions, such as Na^+ in the salt, causing the water to flow out faster and increasing the soil column's desalination efficiency [37,39].

Previous studies have introduced many effective methods and alternative materials for improving saline-sodic soils [29,34,40]. However, research is still being conducted to determine the types and quantities of salt ions that will leave the water after the amendment material has been added. Our study showed that the major leaching salt ions were Na^+ , Mg^{2+} , and SO_4^{2-} , and SO_4^{2-} leaching in soil profiles was strong (Figure 5). In addition, leachate EC and Na^+ and SO_4^{2-} content in leachate gradually decreased over leaching time (Figure 4), and the salt ions concentration in organic treatments was lower than in the

control. This is consistent with Du et al. [37], which indicated that water leaching removes a large number of harmful salt ions, such as Na^+ and SO_4^{2-} , and organic amendments increased soil permeability and promoted salt ion leaching. It is worth mentioning that at the early stage of leaching, the application of organic fertilizer alone increased the content of soluble salt in the soil (Figure 4), which may be due to the generation of salts in the composting process of bio-organic fertilizer [13].

5. Conclusions

Organic fertilizer combined with acid amendments improved soil chemical properties by reducing soil pH and EC, and increasing SOM, AP, and AK content. Organic fertilizer combined with organic amendments promoted soil permeability properties by improving cumulative infiltration volume and leaching rate. OH, and OB treatments reduced soil salt content by promoting the removal of Na^+ , SO_4^{2-} , and Mg^{2+} from salt-affected soil. OB and OH had a higher desalination efficiency and rate than CK. This study preliminarily explained the migration characteristics of water and salt—and the desalination law under the synergistic effect of organic amendments addition and water leaching—and may provide effective measures and techniques for coastal saline soil improvement. Future studies should concentrate on the principles and mechanisms of salt and water transport in the context of organic soil amendments applied in natural fields.

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Article

Water Efficiency of Coriander under Flows of Application of Nutritive Solutions Prepared in Brackish Waters

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Abstract: The impact of the salinity of the nutrient solution on water efficiency can be changed by the application flow. The aim of this work was to analyze the water efficiency and production components of coriander plants, cultivar Verdão, exposed to nutrient solutions (1.7, 3.0, 4.5, and 6.0 dS m⁻¹) applied with different flow rates (1.0, 2.0, 3.0, and 4.0 L min⁻¹) in an NFT hydroponic system. Two experiments were carried out in a greenhouse with two sources of salts to prepare the electrical conductivity. In the first experiment, NaCl was used, and CaCl₂·2H₂O was used in the second. Variables were analyzed related to the production components and the consumption of water use efficiency. It was found that the water efficiency and production components of coriander plants were more affected by increases in electrical conductivity in the nutrient solution. CaCl₂·2H₂O better promotes the lower production of dry mass, plant height, water consumption, and the instantaneous and intrinsic efficiency of water use than NaCl. The coriander's water relations were inhibited by increases in the concentration of salts in nutrient solution, while increases in the flow rate of the nutrient solution negatively affected the productive parameters of the coriander plants.

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Keywords: *Coriandrum sativum* L.; salinity; soilless cultivation

1. Introduction

Coriander (*Coriandrum sativum* L.) is an annual herbaceous vegetable belonging to the Apiaceae family and is widely cultivated worldwide [1]. In several regions of Brazil, it is also widely cultivated and consumed, including in the Brazilian semi-arid region. However, rustic production techniques are still used, with a low technological level and a disorderly application of inputs [2].

This is especially the case in the Brazilian semiarid region with regard to the hydroponic systems; these use brackish water to prepare and replace the nutrient solution. This has been the subject of several studies which analyze the viable technical results that are verified for crops such as cauliflower [3], lettuce [4], parsley [5], chives [6], and coriander [7].

There is unavoidable salt accumulation in the root zone, especially in closed-loop hydroponic systems in which the nutrient solution recirculates more than once in the crop rows [8]. The increases in ion concentration at the cellular level in the plants also induce nutritional and osmotic imbalances, as well as the accumulation of reactive oxygen species, which negatively affect the metabolism and cellular function of the plants [9]. So, they compromise crop growth and productivity.

The water quality and the salt concentration vary according to the place of extraction and the time of collection. An average range of 0.1 to 3.0 dS m⁻¹ is estimated, with a cationic prevalence of Na⁺ and Ca²⁺, in the water in the Brazilian semi-arid region [10].

Another aspect to be related to this study was an adjustment in the flow of the application of nutrient solution, whose relevance is verified by a great mass flow into the rhizosphere region, allowing greater availability of nutrients and oxygen to plants [11].

The importance of this adjustment is mentioned in the study of cauliflower culture, especially when brackish water is used to prepare the nutrient solution; an ideal flow rate of 1.5 L min^{-1} is indicated [3]. However, increases in the flux solution flow also reduce the nutrient absorption capacity. It occurs because of the short exposure time of the root system to the ions, which makes it impossible for these nutrients to bind to all the available adsorption sites in the roots [12]. Otherwise, high flow rates may favor a reduction in the temperature of the nutrient solution. It occurs due to the great volume and the short exposure time in the pathway into the cellular channel, with less effect of the heat exchange on the plants [11].

In addition, regions with water limitation need to use brackish water as an alternative source to optimize water efficiency. They also use the parameters by adapting the nutrient solution management, which is essential to success in the hydroponics businesses [3,13].

Although some parameters have already been studied in some cultures, such as the production of dry mass and the height of the aerial part of plant bunches, with reference to the performance of the productivity and the water use efficiency [14–16], there is little information about the potential gain provided by flow adjustment or consideration of the varying cation prevalence in brackish water.

The aim of this work was to analyze the water efficiency and production components of coriander plants, cultivar Verdão, exposed to nutrient solutions prepared with brackish water and applied at different electrical conductivities and flow rates. Our hypothesis was that the increase in the circulation flow of the solution could attenuate the deleterious effects caused by salinity on the water relations and productive aspects of coriander. Thus, the importance of this study is its presentation of a new perspective to determine the ideal flow of the nutrient solution in hydroponic coriander crops, especially in regions with scarce water resources, where the agricultural use of brackish water is fundamental for their economic and social development.

2. Materials and Methods

2.1. Experimental Conditions

Two experiments were carried out in a greenhouse at the Agricultural Engineering Department—DEAGRI, Federal Rural University of Pernambuco—UFRPE, Recife, PE ($8^{\circ}01'05''$ south latitude and $34^{\circ}56'48''$ west longitude and average altitude of 6.5 m) between November 2019 and February 2020.

The greenhouse is $7 \times 21 \text{ m}$, with a ceiling height of 3 m and a maximum arch height of 4.5 m, with nylon side screens and 150-micron film on the roof. Inside the greenhouse, the temperature ($^{\circ}\text{C}$), relative humidity (%), and global solar radiation (MJ m^{-2}) were monitored daily in each experimental stage through an automatic weather station—model CR1000 (Campbell Scientific, Ltd., Logan, UT, USA).

During the experimental period, the relative humidity of the air varied between 41.8 and 98.2% (Experiment I) and 45.4 and 98.7% (Experiment II); the air temperature showed a range between 21.3 and 38°C (Experiment I) and 22.3 and 38.4°C (Experiment II). In addition, the average global solar radiation was 4.90 MJ m^{-2} (Experiment I) and 4.41 MJ m^{-2} (Experiment II) (Figure 1).

2.2. Hydroponic System

The organization of the hydroponic structure (Nutrient Film Technique) inside the greenhouse consisted of an installation of thirty-two experimental plots on each side, with a central street of one meter in width. Each experimental plot consisted of a hydroponic profile with a trapezoidal shape—75 mm, 3 m long, and 0.20 m distance between plants (Figure 2).

The benches, installed to provide physical support to the profiles, were built in a 50 mm PVC tube and were designed to provide three points of support for the gutters, which gave the profiles an inclination of 3.33%. On each bench were placed four hydroponic profiles, spaced 0.60 m apart (Figure 3).

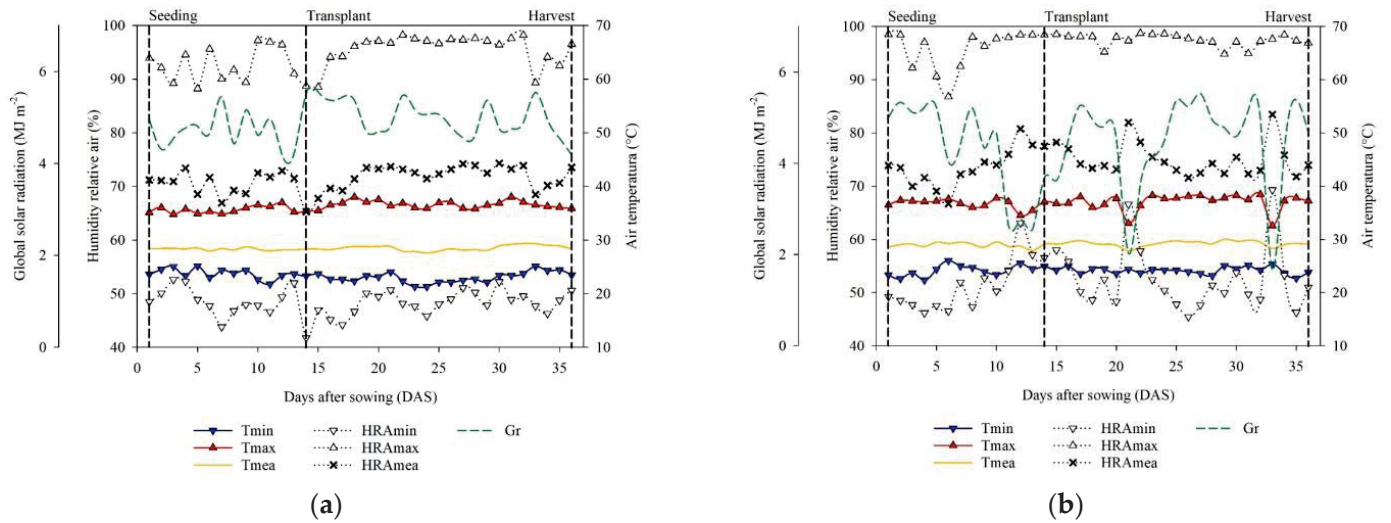


Figure 1. Values of relative humidity (%) and temperature (°C) of air and global solar radiation (MJ m^{-2}) within protected environment between November 2019 and March 2020. First result with NaCl (a) and second cycle— $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ (b).



Figure 2. Arrangement of the plants in the hydroponic system.

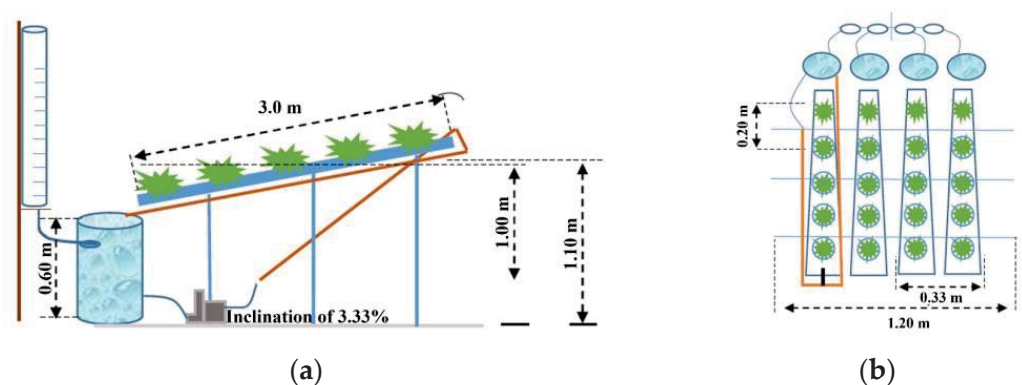


Figure 3. Side view (a) and top view (b) of the experimental plot.

Each hydroponic profile was individually and independently worked. It was also associated with (i) 220 V, 34 W electric circulation pumps for each one; (ii) a 50 L storage

tank for nutrient solution; and (iii) a second storage tank, which contained the respective brackish water used to prepare 15 L of nutrient solution. The brackish water storage tank was interconnected with a nutrient solution storage tank. In addition, with the aid of an automatic device and gravity, it automatically replenished the level of the nutrient solution stock reservoir, which decreased as a result of the plants' water consumption.

2.3. Experimental Treatments

One after the other, two trials were carried out with the same experimental design, in randomized blocks, and analyzed in a 4×4 factorial scheme with four blocks, totaling sixty-four experimental plots. The treatments entailed the use of four nutrient solutions (1.7, 3.0, 4.5, and 6.0 dS m⁻¹), applied with different NaCl amounts for the preparation of the brackish water and a second experiment with CaCl₂·2H₂O.

The nutrient solution was prepared only once for the entire experiment in a 1000 L reservoir filled with a local water supply (EC $\approx$ 0.12 dS m⁻¹). An amount of fertilizer adapted for leafy vegetables [17] was solubilized, with the following added: 750.0 g of calcium nitrate, 500.0 g of potassium nitrate, 400.0 g of magnesium sulfate + micronutrients, and 150.0 g of monoammonium phosphate. This fertilizer input corresponded to the following nutrient concentrations in mmol L⁻¹: 13.59 N, 2.37 Ca, 5.50 K, 2.61 P, 1.37 S, and 1.48 Mg, and in μ mol L⁻¹: 180.0 B, 30.0 Cu, 180.0 Fe, 140.0 Mn, 8.0 Mo, and 90.0 Zn, corresponding to an electrical conductivity of 1.58 dS m⁻¹.

According to each treatment, after the preparation and subsequent distribution of the nutrient solution in the reservoirs, the amount of salts was estimated [18]. The first cycle was with NaCl, and the second cycle was with CaCl₂·2H₂O. Thus, the same initial electrical conductivities of nutrient solution (ECns) were obtained: 1.7, 3.0, 4.5, and 6.0 dS m⁻¹ in both assays (Table 1).

Table 1. Details of electrical conductivity values and concentrations of salts used to prepare different saline waters.

Treatment (Initial ECns)	ECns ¹ (dS m ⁻¹)	ECw ²	Saline Water	
			NaCl	CaCl ₂ ·2H ₂ O
			(mmol L ⁻¹)	
1.7	1.58	0.12	0	0
3.0	1.58	1.42	13.00	9.81
4.5	1.58	3.12	28.06	21.13
6.0	1.58	4.62	43.12	32.46

Notes: ¹ Electrical conductivity of nutrient solution; ² electrical conductivity of water.

The nutrient solution management with the aid of a hydraulic register and the desired nutrient solution application rates (1.0, 2.0, 3.0, and 4.0 L min⁻¹) were calibrated and periodically reviewed. As for the nutrient solution application events, with aid of an electric timer they took place between 6:00 am and 6:00 pm, with intervals of 15 min of operation and 15 min of rest. At nighttime, an electric timer was programmed to inject solution every 2 h for 15 min.

Automatically, the reposition of the nutrient solution stock reservoir was carried out with the respective brackish water used to prepare the nutrient solution. The electrical conductivity (ECns), pH (pHns), dissolved oxygen (DONs), and the temperature (Tns) of the nutrient solution were monitored on alternate days for possible adjustments.

The coriander cultivar used was Verdão; the sowing was carried out in 100 mL disposable white cups, duly perforated from the middle part to the base of the cup, simulating a mesh cup for hydroponics. Coconut fiber was properly washed and used as a substrate; twenty seeds per cup were sowed.

After sowing (DAS), up to the sixth day, the seedlings were irrigated twice a day, in the morning and in the afternoon, with 50 mL of the local water supply (EC $\approx$ 0.12 dS m⁻¹)

per cup. Between the 6th and the 13th DAS, with the same frequency of application and volume, the irrigation was carried out with nutrient solution [17] diluted by 50%.

Thinning was performed on the 13th DAS, leaving ten plants per cup. Transplant to the hydroponic system was carried out on the 14th DAS, and the application to each treatment was started. In each experimental plot, ten cups were distributed: eight central ones, which were considered to be in a useful area, and two in the ends of the gutter, which were considered borders. So, in total 640 cups were used and put in the greenhouse; each cup had ten plants.

In the first trial (using NaCl as the source of salt), the control of aphids (*Toxoptera* spp) and whitefly (*Bemisia tabaci* G.) was carried out using the active ingredient Deltamethrin, at a dosage of 30 mL 100 L⁻¹ water, in a single application, without causing damage to the crop. In the second trial, no intervention was necessary with regard to the phytosanitary issue.

2.4. Variables Analyzed

At the end of each harvest, 21 days after transplanting (DAT), the fresh mass of the aerial part (FMAP) was determined using a precision scale. Immediately after weighing, this material was placed in paper bags and dried in an oven with a forced circulation at 65 °C until constant weight for quantification of the dry mass of the aerial part (DMAP). Then, the water content in the aerial part (WCAP) was calculated [19]. Plant height (PH) was measured using a tape measure, from the base of the substrate to the apex of the highest leaf.

Water consumption (WC) was determined at 30 DAS, according to Equation (1):

$$V_{ETC} = [(R_f - R_i) \times \pi \times D^2] / (4 \times n \times \Delta t) \times 10^5, \quad (1)$$

Thus, V_{ET} —evapotranspiration volume, mL plant⁻¹ day⁻¹; R_f —final reading of water level in automatic filling tank, cm; R_i —initial reading of water level in automatic filling tank, cm; D —internal diameter of automatic filling tank, m; Δt —time interval between readings, days; n —number of plants in profile of time interval, Δt .

The water productivity was estimated considering the relationship of the fresh mass of the aerial part (FMAP)/DMAP with the evapotranspired volume (L⁻¹). The instantaneous (A/E) and intrinsic (A/g_s) efficiency of the water use were also measured using the Portable Infrared Gas Analyzer—IRGA, model LCpro-SD (ADC Bioscientific, Hoddesdon, England).

All the data underwent normality and homosticity tests and were submitted to analysis of variance using an F test with a probability level of 0.05. Thus, the data meet the assumptions of the ANOVA and the normality test. In the case of significant effect, it was verified with regression analysis. For all the analyses, the statistical software SISVAR version 5.2 was used [20].

3. Results

3.1. Subsection

The first cycle with NaCl in the water was prepared and replaced with a nutrient solution. There was an increase in EC_{ns} in all the concentrations and flow rates compared to the initial values. Apart from the EC_{ns} level of 1.7 dS m⁻¹, the final value was lower than the initial value (Figure 4a–d). When the initial and final values of the EC_{ns} were compared, there were reductions of 6.67, 9.23, 8.20, and 15.63% within the EC_{ns} of 1.7 dS m⁻¹. Moreover, there were increases of 33.04, 37.61, 38.86, and 38.22% within the EC_{ns} of 6.0 dS m⁻¹ for the flows of 1.0, 2.0, 3.0, and 4.0 L min⁻¹, respectively.

Likewise, in the second cycle, in water prepared with CaCl₂·2H₂O and the replacement of the nutrient solution, there was also a reduction of 21.25, 28.78, 18.36, and 15.74% within the EC_{ns} of 1.7 dS m⁻¹. In addition, there were increases of 35.13, 29.70, 14.73, and 38.97% within the EC_{ns} of 6.0 dS m⁻¹ for the flows of 1.0, 2.0, 3.0, and 4.0 L min⁻¹, respectively. This occurred when the initial and final EC_{ns} values were compared (Figure 5a–d).

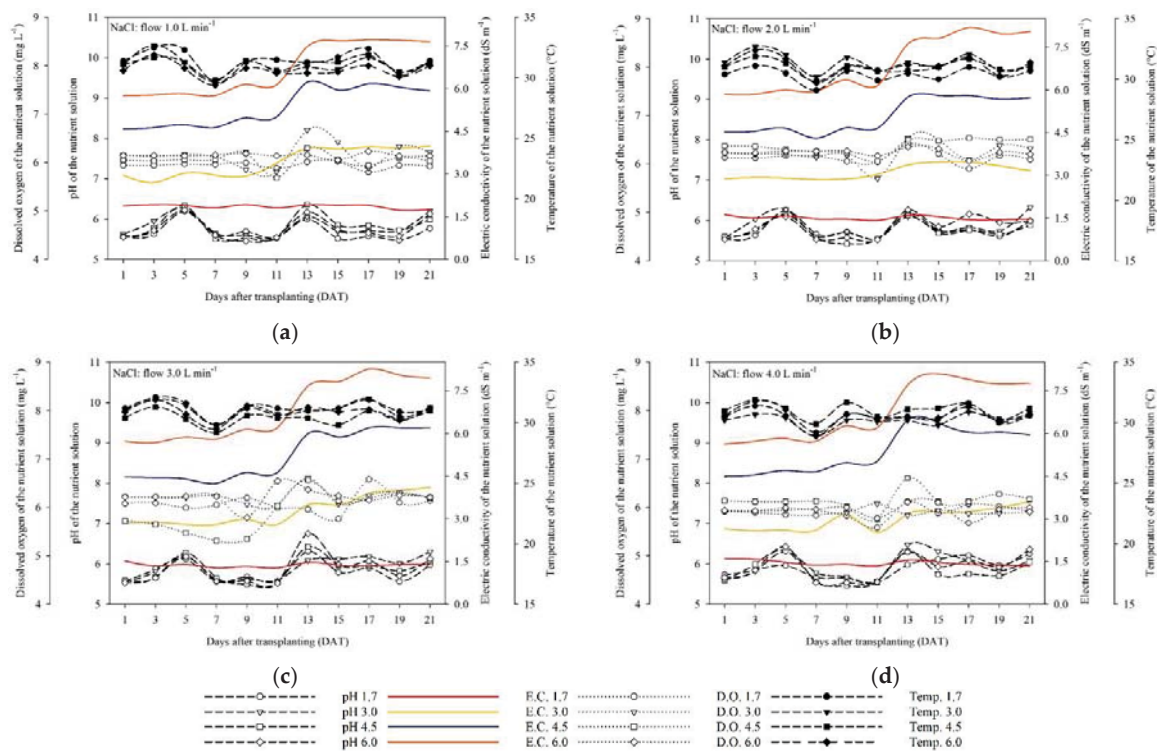


Figure 4. Values of electrical conductivity, pH, dissolved oxygen, and temperature of nutrient solutions that were prepared in brackish water with prevalence of NaCl and used in cultivation of coriander plants, cv. Verdão, applied in different flows (1.0 (a), 2.0 (b), 3.0 (c) and 4.0 (d) L min⁻¹).

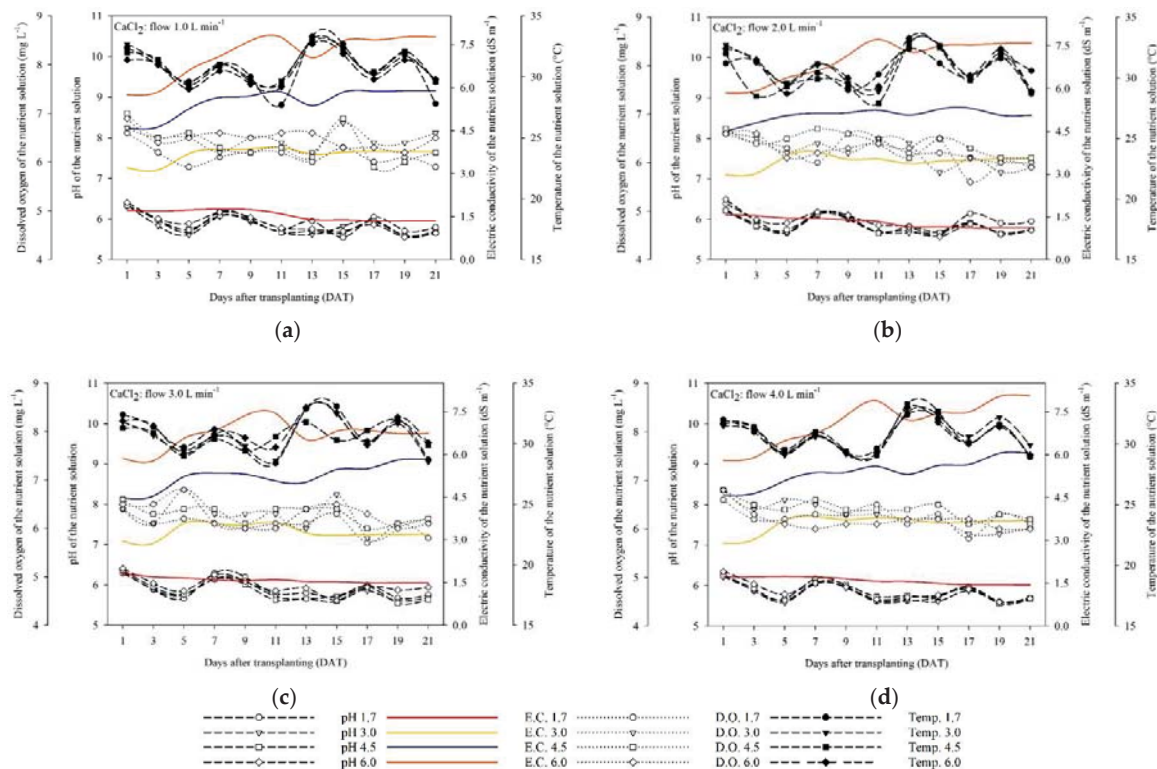


Figure 5. Values of electrical conductivity, pH, dissolved oxygen and temperature of nutrient solutions that were prepared in brackish water with a prevalence of CaCl₂·2H₂O and used in cultivation of coriander plants, cv. Verdão, applied in different flows (1.0 (a), 2.0 (b), 3.0 (c) and 4.0 (d) L min⁻¹).

In general, it was verified in both cultivation cycles that the pH of the nutrient solution (pHns) fluctuated in initial value within the range between 5.42 and 6.75 with the prevalence of NaCl in water (Figure 4a–d). Moreover, it was between 5.54 and 6.50 with $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, which was used to prepare the brackish water (Figure 5a–d).

The dissolved oxygen concentration in the nutrient solution (DOns) ranged from 5.3 to 7.0 mg L^{-1} for all the treatments, whose mean values were 6.10 and 6.26 mg L^{-1} in the cultures with the cationic predominance of NaCl and $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, respectively (Figures 4a–d and 5a–d).

It was possible to observe in the final crop cycle that those coriander crops were cultivated with brackish waters and a prevalence of calcium. So, there were reductions in the DOns levels of up to 12.45%. Thus, the dissolved oxygen was compared to the first cycle in all treatments. This was different to the sodium chloride that was also used in the experiment. So, small positive and negative variations up to 2.11% were verified. The exception was the treatment by the ECns of 4.5 dS m^{-1} and the flow of 3.0 L min^{-1} , in which there was an increase of 8.51% in the dissolved oxygen of the nutrient solution.

In general, the temperatures of the nutrient solutions were similar in those two experiments, independently of the cationic predominance, the electrical conductivity, or the application rate of the nutrient solution. In the first cycle of nutrient solutions, which were prepared in salinized water with NaCl, it was found that the temperatures of those liquids varied between 28.8 and 32.7 °C, with an average of 30.8 °C, while in the second cycle with the salinization of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, the average temperature was 30.7 °C and ranged between 27.7 and 33.3 °C (Figures 4a–d and 5a–d).

3.2. Dry Mass, Plant Height, Water Content, and Water Consumption

The interaction between the treatments (ECns $\times$ flow) influenced ($p \leq 0.01$) the plant height (PH) in both cycles, and there was also a significant effect ($p \leq 0.05$) on water consumption (WC) when $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ was used. The isolated, electrical conductivity of the nutrient solution (ECns) affected ($p \leq 0.01$) the dry mass of the aerial part (DMAP), the PH, and the WC in both experiments, and it also caused a significant effect ($p \leq 0.05$) on the water content in the aerial part (WCAP) under the prevalence of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$. The nutrient solution flow rate affected ($p \leq 0.01$) WC and ($p \leq 0.05$) DMAP (Experiment I), and it also influenced ($p \leq 0.01$) DMAP, WCAP, and ($p \leq 0.05$) PH (Experiment II) (Table 2).

Table 2. Mean squares (MS) analysis of variance (ANOVA) for dry mass of aerial part (DMAP), water content in aerial part (WCAP), plant height (PH), and water consumption (WC) of coriander plants, cv. Verdão, exposed to different levels of electrical conductivity and nutrient solution flow rate under cationic prevalence of NaCl and $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$.

SV	DF	Mean Squares							
		DMAP		WCAP		PH		WC	
		NaCl	CaCl_2	NaCl	CaCl_2	NaCl	CaCl_2	NaCl	CaCl_2
ECns	3	18.22 **	17.33 **	4.04 ns	2.88 *	188.07 **	190.45 **	0.34 **	0.41 **
LR	1	52.95 **	51.15 **	5.74 ns	2.66 ns	517.40 **	564.21 **	0.71 **	1.15 **
QR	1	1.69 **	0.20 ns	6.37 *	3.78 *	39.22 **	1.17 ns	0.31 **	0.05 *
Flow	3	0.78 *	0.54 **	0.28 ns	5.19 **	6.75 ns	6.09 *	0.15 **	0.01 ns
LR	1	2.01 **	0.84 **	0.62 ns	4.60 *	16.24 *	17.37 **	0.15 **	0.01 ns
QR	1	0.02 ns	0.00 ns	0.22 ns	10.98 **	2.60 ns	0.64 ns	0.28 **	0.04 *
ECns $\times$ Flow	9	0.49 ns	0.15 ns	1.89 ns	0.94 ns	6.34 **	4.51 **	0.01 ns	0.02 *
Residue	48	0.22	0.07	1.36	0.87	2.79	1.52	0.01	0.01
CV%		11.90	8.06	1.29	1.04	6.54	5.27	10.82	15.31

Notes: SV = source of variation; DF = degrees of freedom; CV% = coefficient of variation; ECns = electrical conductivity of nutrient solution; LR = linear regression; QR = quadratic regression; *, ** significant at $p \leq 0.05$ and $p \leq 0.01$ levels of probability, respectively; ns = not significant.

When there was a prevalence of NaCl (Figure 6a), the estimated losses in DMAP of 0.565 g per bunch were estimated for each dS m^{-1} increment and 0.157 g per bunch per unit of flow added. Under the $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ prevalence, the reduction was estimated to be 0.557 g per bunch (Figure 6b). There was no equation adjustment for flow, which presented an average of 3.31 g per bunch for DMAP.

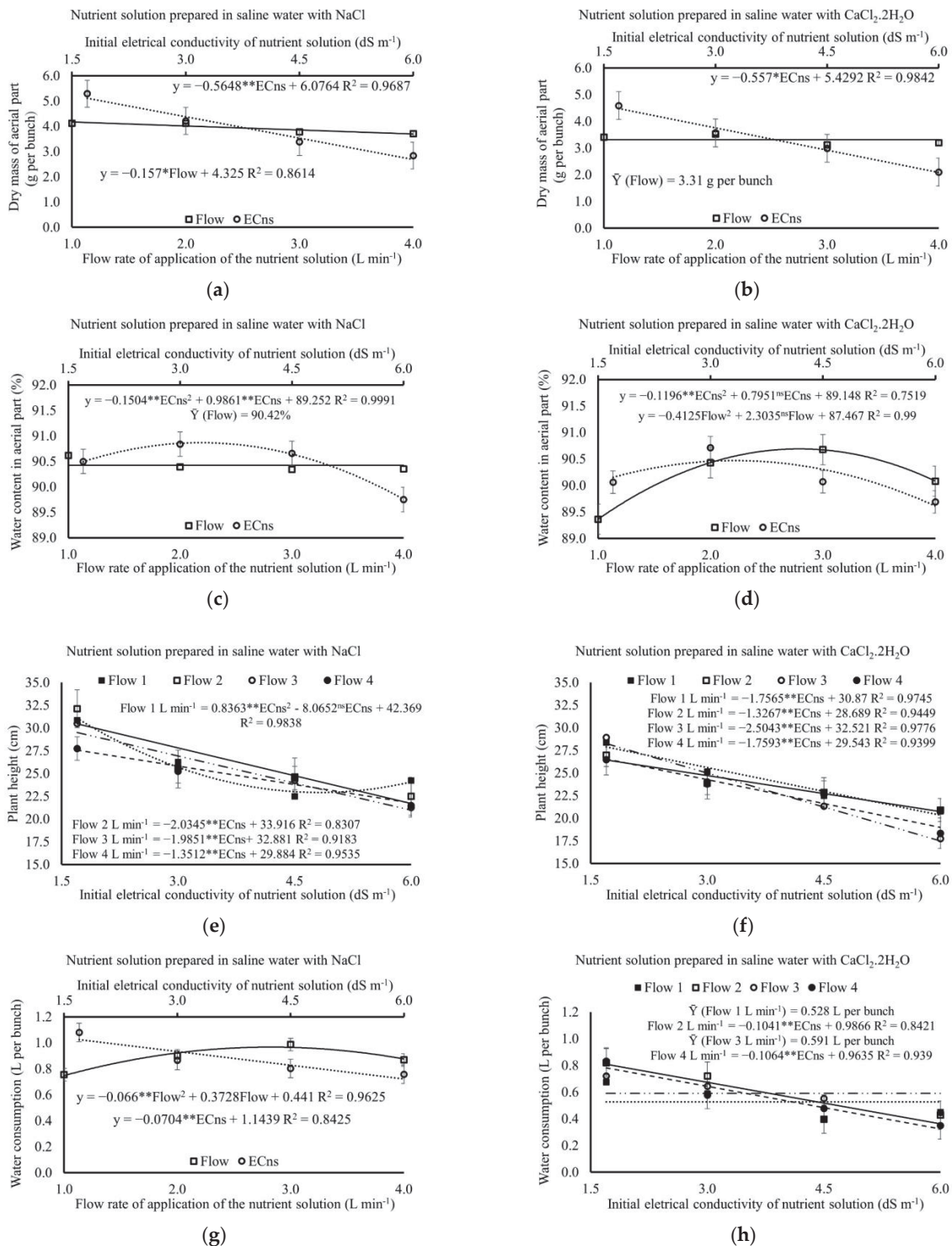


Figure 6. Dry mass (a,b) and water content of aerial part (c,d), average height of bunches (e,f), and total water consumption (g,h) of coriander plants, cv. Verdão, exposed to nutrient solutions prepared in brackish water, salinized with NaCl and $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, and applied in crescent flow rates.

The interaction between the treatments did not influence ($p \geq 0.05$) the WCAP. Under the prevalence of NaCl in the water, the WCAP was at a maximum (90.87%) in the ECns and estimated to be 3.28 dS m^{-1} ; on the other hand, the increases in flow did not affect the WCAP, with an average value of 90.42% (Figure 6c). However, under the $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ prevalence, the WCAP was at a maximum (90.47 and 90.68%) in the ECns, and the flows were estimated to be 3.32 dS m^{-1} and 2.79 L min^{-1} , respectively (Figure 6d).

Regarding the height of the aerial part of plants when the water was salinized with NaCl, at a flow rate of 1.0 L min^{-1} , the height of the bunch was at a minimum (22.92 cm) in the ECns and was estimated to be 4.82 dS m^{-1} , while the flows of 2.0, 3.0, and 4.0 L min^{-1} were estimated to have reductions of 2.03, 1.98, and 1.35 cm for each incremented dS m^{-1} , respectively (Figure 6e). The prevalence of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ resulted in reductions of 1.76, 1.33, 2.50, and 1.76 cm in the height of the bunch per increased dS m^{-1} , under flow rates of 1.0, 2.0, 3.0, and 4.0 L min^{-1} , respectively (Figure 6f).

The highest estimated plant heights were observed in the plants with an ECns of 1.7 dS m^{-1} , independently of the cationic predominance, emphasizing the maximum mean values of 31.08 and 28.26 cm, which were obtained in the first and second cycles with flow rates of 1.0 and 3.0 L min^{-1} , respectively. However, the exception was the treatment under the prevalence of NaCl at a flow rate of 1.0 L min^{-1} ; in all the evaluations, the ECns of 6.0 dS m^{-1} produced the smallest plants. Thus, there was a maximum reduction of 28.93% (Experiment I) and 38.10% (Experiment II) in comparison with the control treatment when 3.0 L min^{-1} of nutrient solution was applied.

When the water was salinized with NaCl, the interaction between the treatments did not influence ($p \geq 0.05$) the water consumption. For each dS m^{-1} increase in the ECns, the plants reduced their water consumption by 0.0704 L per bunch; however, the water consumption was maximum (0.97 L per bunch) at the estimated flow of 2.82 L min^{-1} (Figure 6g).

Under the prevalence of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, it is noteworthy that under the flows of 2.0 and 4.0 L min^{-1} the reduction in water consumption was estimated to be 0.1041 and 0.1064 L per bunch per dS m^{-1} increase in the ECns. When the nutrient solution was applied at flow rates of 1.0 and 3.0 L min^{-1} , the average water consumption for the relative ECns, within the worked interval, was 0.528 and 0.591 L per bunch (Figure 6h).

3.3. Productivity and Water Use Efficiency

The interaction between the treatments (ECns $\times$ flow) affected ($p \leq 0.01$) the water productivity based on the production of the fresh (WP-FMAP) and dry (WP-DMAP) mass of the aerial part under the $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ prevalence. The electrical conductivity of the nutrient solution (ECns) was considered a significant ($p \leq 0.01$) source of variation for all the examined traits, namely WP-FMAP, WP-DMAP, instantaneous (A/E), and intrinsic (A/gS) water use efficiency, in both cycles. The nutrient solution flow rate influenced ($p \leq 0.01$) the WP-FMAP and WP-DMAP under the NaCl prevalence, as well as the WP-DMAP, A/E and A/gS when there was a $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ prevalence in the water. (Table 3).

The amount of fresh mass produced for each liter of nutrient solution consumed by a plant was at the maximum (55.13 g L^{-1}) in the ECns estimated at 2.94 dS m^{-1} , and on the other hand, it was at the minimum (42.00 g L^{-1}) in the estimated flow of 3.20 L min^{-1} , in results obtained under the prevalence of NaCl in the water (Figure 7a).

After analyzing the unfolding of the interaction, it was found that when there was a prevalence of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ in water the WP-FMAP was at a minimum (56.06 g L^{-1}) within the ECns of 4.5 dS m^{-1} for the estimated flow rate of 2.93 L min^{-1} , as well as at a maximum (59.20 g L^{-1}) within the flow rate of 2.0 L min^{-1} for the ECns estimated at 1.88 dS m^{-1} (Figure 7b).

When the waters used to prepare the nutrient solution were salinized with NaCl, the water productivity based on the production of the dry mass of the aerial part was at a maximum (5.03 g L^{-1}) in the ECns estimated at 2.55 dS m^{-1} . Increases in flow promoted

minimum values (3.98 g L^{-1}) in the WP-DMAP, with an estimated flow of 3.12 L min^{-1} (Figure 7c).

After analyzing the unfolding of the interaction under the prevalence of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ in water, it was verified that the productivity of the water in the DMAP was at a maximum (7.47 and 6.49 g L^{-1}) within the flows of 1.0 and 2.0 L min^{-1} for the ECns estimated at 2.45 and 3.87 dS m^{-1} , and it was equal (6.13 g L^{-1}) in the ECns estimated at 4.95 dS m^{-1} . At higher flow levels, the relative values of the water productivity in the DMAP were 5.29 and 5.88 g L^{-1} for flows of 3.0 and 4.0 L min^{-1} (Figure 7d).

With the prevalence of NaCl in the water, the instantaneous (A/E) (Figure 7e) and intrinsic (A/gs) (Figure 7g) efficiency of the water use were at the maximums of $4.35 \mu\text{mol (CO}_2\text{) mmol}^{-1} (\text{H}_2\text{O})$ and $98.05 \mu\text{mol (CO}_2\text{) mol}^{-1} (\text{H}_2\text{O})$ in the ECns estimated at 3.50 and 3.88 dS m^{-1} , respectively. For the flow, there was no significance ($p \geq 0.05$), with the average A/E and A/gs of $3.71 \mu\text{mol (CO}_2\text{) mmol}^{-1} (\text{H}_2\text{O})$ and $81.80 \mu\text{mol (CO}_2\text{) mol}^{-1} (\text{H}_2\text{O})$, respectively.

The prevalence of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ in water implied a reduction in A/E (Figure 7f) and A/gs (Figure 7h), estimated at $0.41 \mu\text{mol (CO}_2\text{) mmol}^{-1} (\text{H}_2\text{O})$ and $5.80 \mu\text{mol (CO}_2\text{) mol}^{-1} (\text{H}_2\text{O})$ for each dS m^{-1} increment in the ECns, respectively. On the other hand, the values of A/E and A/gs were the maximums of $3.41 \mu\text{mol (CO}_2\text{) mmol}^{-1} (\text{H}_2\text{O})$ and $77.92 \mu\text{mol (CO}_2\text{) mol}^{-1} (\text{H}_2\text{O})$ for the estimated flow rates of 3.28 and 2.80 L min^{-1} , respectively.

Nevertheless, the highest values of A/E and A/gs were found for NaCl, and with the prevalence of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ in water, the lowest values were found, at the highest levels of ECns.

Table 3. Mean squares (MS) analysis of variance (ANOVA) for water productivity based on the production of fresh (WP-FMAP) and dry (WP-DMAP) mass of aerial part, instantaneous (A/E), and intrinsic (A/gs) water use efficiency of coriander plants, cv. Verdão, exposed to different levels of electrical conductivity and nutrient solution flow rate under cationic prevalence of NaCl and $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$.

SV	DF	Mean Squares							
		WP-FMAP		WP-DMAP		A/E		A/gs	
		NaCl	CaCl_2	NaCl	CaCl_2	NaCl	CaCl_2	NaCl	CaCl_2
ECns	3	1205.04 **	1064.43 **	6.67 **	8.50 **	6.50 **	9.59 **	3471.45 **	2248.82 **
LR	1	2455.48 **	798.38 **	16.19 **	3.82 ns	4.71 **	27.95 **	11.95 ns	5593.97 **
QR	1	1158.21 **	1531.19 **	3.82 **	7.07 **	14.65 **	0.75 ns	10,267.56 **	1022.25 *
Flow	3	957.51 **	176.81 ns	7.45 **	4.41 **	0.06 ns	3.59 **	36.29 ns	1985.26 **
LR	1	1942.76 **	102.47 ns	14.18 **	6.41 **	0.02 ns	6.76 **	19.11 ns	1097.53 *
QR	1	802.23 **	12.69 ns	7.38 **	3.35 ns	0.17 ns	2.22 *	67.44 ns	2415.60 **
ECns $\times$ Flow	9	76.64 ns	489.83 **	0.71 ns	3.62 **	0.39 ns	0.28 ns	117.70 ns	70.59 ns
Residue	48	60.48	101.63	0.52	0.89	0.31	0.42	177.41	200.79
CV%		16.15	16.51	15.91	15.81	14.90	21.08	16.28	20.33

Notes: SV = source of variation; DF = degrees of freedom; CV% = coefficient of variation; ECns = electrical conductivity of nutrient solution; LR = linear regression; QR = quadratic regression; *, ** significant at $p \leq 0.05$ and $p \leq 0.01$ levels of probability, respectively; ns = not significant.

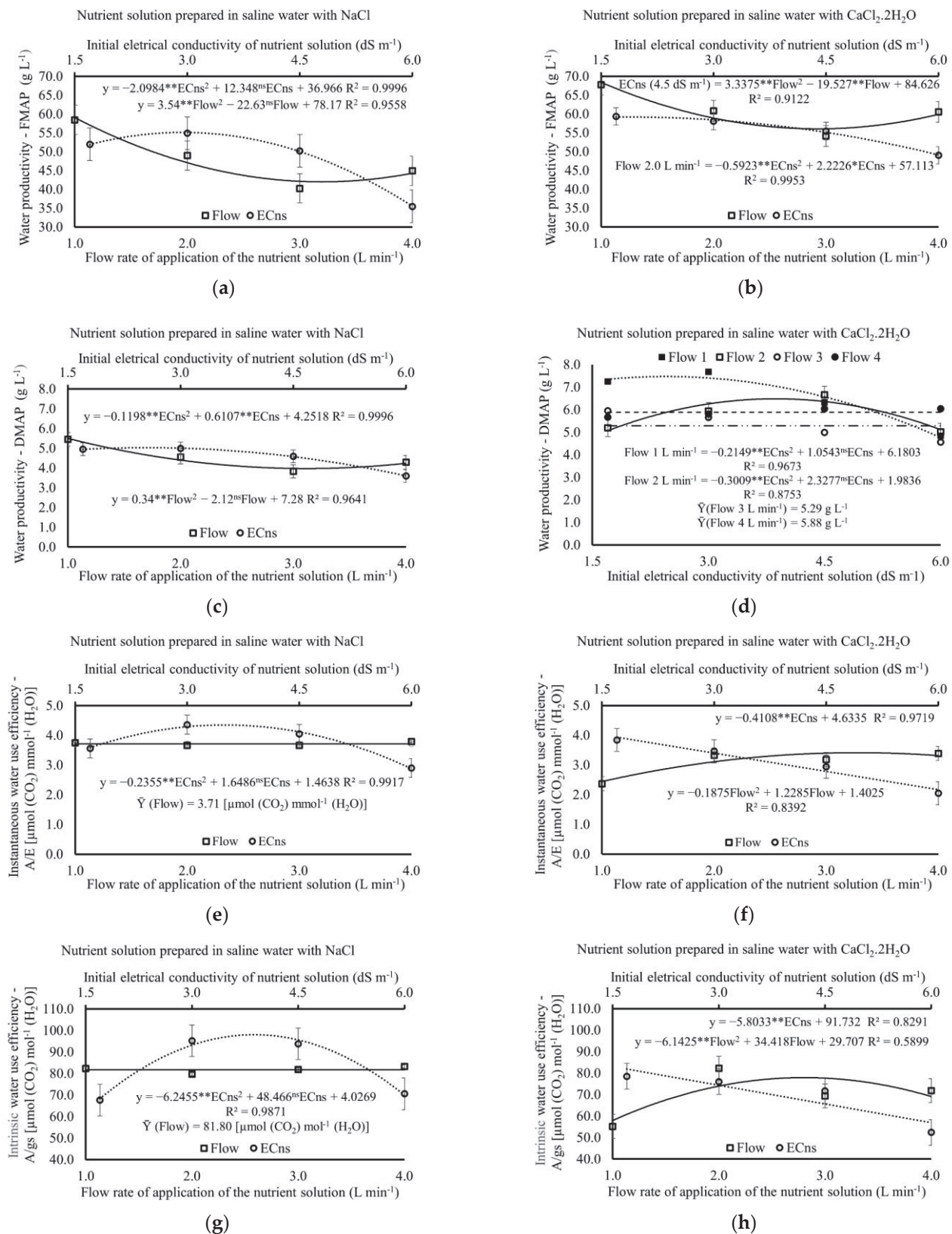


Figure 7. Water productivity, based on fresh (a,b) and dry (c,d) mass shoots; instantaneous efficiency—A/E (e,f) and intrinsic—A/gs (g,h) of water use of coriander plants, cv. Verdão, exposed to nutrient solutions prepared in brackish water, salinized with NaCl and $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$; it was applied in crescents flow rates.

4. Discussion

The electrical conductivity of nutrient solution verified in this study was similar to the trends found in other works developed with leafy vegetables, such as parsley [21] and cauliflower [3]. The reductions observed within the ECns of 1.7 dS m^{-1} were correlated to the initial value, which can be attributed to the natural consumption of nutrients by the plants [22]. In addition, the replenishment of the stock reservoir level was carried out with the water used to prepare the nutrient solution for this treatment ($\text{EC}_w \approx 0.12 \text{ dS m}^{-1}$). However, other cases have shown increases in ECns correlated to the initial value, which may be associated with the concentration of water used to replace the stock reservoir according to each of the treatments.

In both cycles, the pH of the nutrient solution remained within the range that was considered adequate for plant growth in hydroponic systems. Thus, most of the nutrients were available for absorption [5,23]. Considering the predominance of NaCl, similar trends were found in relation to pHns in studies carried out with leafy vegetables [14,23,24], which corroborated the present research. In general, this tendency can be attributed to the stability of NaCl given by different conditions, such as its ion exchange ratios and the other ions present in the nutrient solution.

Increases in the concentration of Na^+ in the nutrient solution can influence the absorption of other ions that are displaced from cells by sodium [25]. As a result, there is nutritional imbalance in the Na^+/K^+ , $\text{Na}^+/\text{Ca}^{2+}$, and $\text{Na}^+/\text{Mg}^{2+}$ ratios [5], which can cause toxicity problems for plants, as a result of the ability to induce the deficiency of other cations [26]. Calcium is an important constituent of plasma membranes; its deficiency in the plant directly affects the absorption of other ions, such as K^+ . Moreover, the integrity of the membranes is affected in conditions in which there is an excess of H^+ ions. Thus, it is important to manage the pH of the solution within the recommended range. Nevertheless, high concentrations of Ca^{2+} in the nutrient solution reduce the absorption of K^+ and Mg^{2+} , as does the excess of these ions, which prejudice the absorption of calcium by the plant [27–29].

Dissolved oxygen values were observed in the nutrient solutions of this study, which corroborate the mean values (6.11 and 6.03 mg L^{-1}) reported for the cultivation of coriander in the conventional DFT system in the morning and afternoon, respectively [30]. It is critical to keep oxygen levels above the minimum limit of the 5 mg L^{-1} recommended for most crops [31]. It occurs because lack of this element reduces the absorption of water and nutrients by plants. Consequently, this affects the development of the aerial part and the yield of the crops [32]. However, reductions in this parameter were verified at the end of cultivation cycle by the predominance of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, which was due to high oxygen demand. Another occurrence is that the volume of the plant roots increases as a function of the growth of the culture [33], as observed in coriander [16,34].

The temperature of the nutrient solution directly affects the absorption of nutrients by the plants [35], and the temperature range of the nutrient solutions was considered suitable for plant growth between 20 and 30°C [36]. However, the temperature of the solutions can exceed 30°C in some regions, which shows the hottest hours of day, as reported by different authors on the hydroponic cultivation of leafy vegetables [15,35,37]. Despite not having been verified in the present study, it is worth noting that increases in flow can decrease the temperature of the nutrient solution, especially during the hottest hours of the day. This occurs because the high volume and short exposure time of the solution during its displacement in the cultivation channel contributes to a small effect on the heat exchange in the plants [11].

Several studies [14,15,38] discuss the hydroponic cultivation of leafy vegetables with brackish water. Moreover, there are losses of DMAP per dS m^{-1} increase in the ECns, which can be attributed to the physiological implications that result in the reduction in the fixation of dry biomass. The reduction in plant dry mass is associated with the osmotic effects of salinity and toxic ions, as well as the ionic imbalance caused by the excess of these ions [39]. However, the reduction in shoot dry biomass which results from increases in flow

can be attributed to a decrease in the solute absorption capacity, due to the time in which the solute remains in solution, which is not long enough for the ions to occupy all available adsorption sites [12].

The water content in the shoots is a fundamental parameter for the commercialization of leafy vegetables. A minimum content of 83.3% is recommended [40]. Thus, all the WCAPs obtained in this research were higher than the reference value.

Salt stress limits the accumulation of essential nutrients in plants, while increasing the ion concentration of sodium, for example, which results in reductions in growth and productivity [41], as seen in the height of the coriander plants. This variable is an important parameter for the commercialization of leafy vegetables, especially for trade in bunches.

In hydroponic crops with coriander cv. Verdão, with plants exposed to an ECns range of 2.28 to 5.51 dS m⁻¹, plant heights of 36.0 cm [42], 37.08 cm [15], and 45.18 cm [16] were confirmed, surpassing the highest values recorded in this work. The negative effects of salinity on plant growth are associated with its interference in the processes of net CO₂ assimilation per unit of leaf area, as well as of the translocation of carbohydrates to the draining tissues and the diversion of energy sources to other processes, such as osmotic adjustment, synthesis of compatible solutes, repair of damage caused by salinity, and maintenance of basic metabolic processes [43].

The type of salt used in the preparation of brackish water influenced the water consumption of the coriander plants. Thus, it was possible to verify that CaCl₂·2H₂O promotes lower water consumption than solutions prepared with NaCl, which may be related to the high absorption rate of monovalent cations compared to bivalent cations [27]. The reduction of water consumption in leafy vegetables exposed to nutrient solutions with increases of electrical conductivities has already been verified for rocket [14], for parsley [21], for green onion [38], and for watercress [44]. For coriander within the range of ECns of 2.05 to 8.26 dS m⁻¹, consumption levels of 1.45 L per bunch were verified for cv. Verdão [42] and 0.89 L per bunch [15]; results similar to those were presented here.

The reduction in water productivity by saline stress conditions can be attributed to the reduction in evapotranspiration and carbon fixation by plants resulting from the increased electrical conductivity of the nutrient solution. However, the trend towards a better relationship between the fresh mass and the water consumption of plants under the prevalence of CaCl₂·2H₂O may be associated with metabolic efficiencies in the use of this nutrient, while under NaCl prevalence the toxic effects of excess sodium in solution may cause reductions in crop yield [21]. Within the range of ECns studied, the water productivity levels of 56.88 g L⁻¹ for parsley [21], 42.6 g L⁻¹ for lettuce [24], and 67.57 g L⁻¹ for chicory [45] has already been confirmed. This corroborates the water productivity values verified in the present work for the flow of 1.0 L min⁻¹ and for ECns levels of 1.7, 3.0, and 4.5 dS m⁻¹.

The best water productivity results were obtained by the lowest flow rates, which was probably due to low water stress in the treatments once the high flows promoted a great flow of salts in the plant rhizospheres [13]. Therefore, the flow can be regulated to improve crop yield. Thus, the ideal applied volume increased the collision frequency between the nutrient ions and the plant roots, promoting nutrient absorption; subsequently, it improved the plant growth [46]. In general, in hydroponic systems, different flow rates of nutrient solution influence plant growth and change the availability of nutrients. Thus, the volume of nutrient solution applied not only affects the diffusion of nutrient ions but can also increase the energy with which these ions are available to plant roots, causing productivity losses [47].

In general terms, within the range of ECns studied, in hydroponic cultures with a prevalence of NaCl in water there was a higher value of the instantaneous efficiency of water use in the order of 1.86 μmol (CO₂) mmol⁻¹ (H₂O) for lettuce [48]; that is, it is a value compatible with that presented here. In both experiments with tomatoes, which were grown in the field and the greenhouse, salt stress reduced A/E and A/gs ranging from 1.50

to 1.95 and 0.9 to 1.28 $\mu\text{mol (CO}_2\text{) mmol}^{-1} \text{ (H}_2\text{O)}$ and 74.5 to 98.9 and 30.3 to 46.7 $\mu\text{mol (CO}_2\text{) mol}^{-1} \text{ (H}_2\text{O)}$ in the first and second cycles, respectively [49].

The intrinsic efficiency of water use in the control plants of *Hebe andersonii* cv. Variegata was similar to the A/gs ratio of the plants exposed to saline stress [50]. According to this study, salinity decreased both A and gs but increased the intrinsic efficiency of the water use. This may be associated with a smaller decrease in the photosynthetic rate than the decreases in stomatal conductance, which are associated with the adaptive mechanisms of plants to stress conditions.

The adjustment of the carbon amount that the plant fixes for each unit of water loss [51] is described by the relationship between liquid photosynthesis and transpiration, which was influenced by the increase in flow only with the prevalence of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ in water. Obtaining high values in the efficiency of water use occurs when the stomata are partially closed; that is, at this point, two diffusion processes are promptly reduced [52].

The rapid acclimatization to salinity, especially in the initial concentrations, explains the best adjustments in both cationic prevalences and is associated with the reduction in cellular osmotic potential caused by the accumulation of organic solutes, which contributes to the maintenance of water absorption and cellular turgor, allowing uninterrupted physiological processes such as stomatal opening, photosynthesis, and cell expansion. On the other hand, this justifies the losses of the instantaneous and intrinsic efficiency of water use by high ECns, once there are decreases in stomatal conductance and transpiration due to the accentuation of induced water stress. This is caused by osmotic effect and the consequent reduction in photosynthetic rate [48].

In general, the concept of efficiency in the use of water is relative, considering that the treatment that obtains the highest efficiency is not always the one with the highest productivity. Generally, the values obtained are linked to the types of treatments adopted and to the way that the culture is managed, which makes it impossible to directly compare results [53].

5. Conclusions

The increase in electrical conductivity of the nutrient solution affected the water productivity, based on the fresh and dry mass of coriander in the two cationic prevalences of brackish water, which was used to prepare the nutrient solution. Otherwise, the increases in flow did not affect the plant height and the water productivity based on fresh mass when there was prevalence of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ in the water with high saline concentrations. The plant's water consumption was affected by increases in salt concentrations under the nutrient solution flows of 2.0 and 4.0 L min^{-1} ; on the other hand, it remained stable under the flows of 1.0 and 3.0 L min^{-1} , within the tested salinity range with the predominance of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$. Increases in the flow rate of nutrient solution influenced the intrinsic water use efficiency of plants which were grown through the cationic predominance of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ in water. In general, despite the effects caused by salinity on the growth parameters and the water relations of the culture, coriander can be grown without major deleterious effects on the mentioned characteristics above, in nutrient solutions of up to 3.0 dS m^{-1} , as well as flow rates of 1.0 and 2.0 L min^{-1} in an NFT hydroponic system with 3 m long profiles.

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Article

Nitrogen Mitigates Salt Stress and Promotes Wheat Growth in the Yellow River Delta, China

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Highlights:

What are the main findings?

- Nitrogen fertilizer (urea) application ameliorated salt damage and promoted the growth of wheat;
- 270 kg/ha nitrogen was the optimal dosage for wheat cultivation in soils of typical agricultural areas of the Yellow River delta.

What is the implication of the main finding?

- The finding is useful for rational utilization of nitrogen fertilizer and coastal saline agriculture development.

Abstract: Salt-affected soils is an important soil resource. Understanding fertilizer and salinity interaction are of great economic importance for improving crop yield and fertilizer use efficiency. A pot experiment was carried out to study the application of nitrogen (N) for ameliorating salt stress in wheat grown in the coastal saline soil of the Yellow River delta. Several controlling levels of salinity and nitrogen (0.7, 1.7, 2.7 g/kg, and 135, 270, and 405 kg/ha) were designed in a pot experiment in a stable water content state to investigate the N and salt interaction on soil properties and winter wheat growth characteristics. The results showed that the dry weight of winter wheat was promoted by salinity in the early growth stage (20 days), then it was gradually inhibited by nitrogen fertilizer. When winter wheat was grown by 54 days, the N and salinity had significant effects on the biomass of winter wheat. The nitrogen content of wheat shoot and root was mainly affected by N addition usage, and the largest value was obtained in 270 kg/ha N dosage treatments. The higher the salt content existed in the soil, the lower the growth rate shown in wheat cultivation. Under saline conditions, the N fertilizer application amount should be controlled to no more than 270 kg/ha, so that it could greatly promote wheat growth. Reasonable fertilizer usage could significantly contribute to crop yield and food quality of the saline agriculture in the Yellow River delta.

Keywords: nitrogen; salt; wheat; the Yellow River delta

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1. Introduction

With global climate change, soil salinization caused more and more attention [1]. At present, more than 20% of the arable land in the world has been affected by salt, which threatens global agriculture's sustainable development [2]. The utilization of saline lands for agricultural development has become a national strategy for ensuring food security in China [3]. The high salinity of groundwater and the shallow water table in the Yellow River Delta has caused soil salinization continued for a long time [4]. The toxic salt could inhibit the germination of seed [5] and the absorption of nutrients while hindering photosynthesis and reducing the metabolic rate [6]. Otherwise, soil salinity also causes crop yield to

decrease and soil quality to decline [7]. The planting acreage of the winter wheat in the Yellow River Delta area was reduced year after year for the salt existence [8]. The answer to this question is going to need further study [9]. A great deal has been done to solve the current difficult problem of soil salinity. Various physical, chemical, and biological measures have been conducted to improve saline soil production [10]. For example, gypsum and other chemical modifiers were also used to improve saline-alkali soil [11]. The development of salt-tolerant varieties, such as biological and ecological measures, were also the means of soil salinization improvement, such as salt tolerant plants [12] and microorganisms. The interaction of water and salt makes it easier to regulate soil through water management [13]. However, the absorption of fertilizer mainly depends on the water, and the salt movement is also dependent on the water. So, it is possible to optimize the regulation of water and salt with the addition of fertilizer [14,15].

Nitrogen fertilizer, particularly urea, has been used to improve soil fertility for thirty years in China. Although the application of fertilizer is beneficial to the growth of crops, the use of much fertilizer also results in decreasing in quality and a series of serious environmental problems [16]. Reasonable control of fertilizer application can not only reduce resource waste but also increase crop yield and improve fertilizer use efficiency [17]. Nitrogen is the primary factor limiting crop growth and yield. It is an important component of many organic compounds in crops. The addition of exogenous nitrogen is often achieved by applying nitrogen fertilizer. Adding nitrogen fertilizer could not only increase the content of chlorophyll and then affect photosynthesis [18] but also improve crop productivity [19] and grain quality [20]. Some studies have reported that nitrogen application affected the accumulation and translocation of nitrogen content and biomass [21] and increased the yield of the crop [22]. Salt could reduce fertilizer recovery and agronomic efficiency [23], so taking reasonable steps to control salinity obstacles is necessary. Nitrogen fertilizer application increases soil acidification [24], but it can be used for ameliorating saline-alkaline soils.

Therefore, a pot experiment was conducted with three levels of soil salinity and four levels of N addition content in saline soil of the coastal area of China. The purpose of this study was to determine the variation of soil physicochemical properties and nitrogen adsorption of winter wheat affected by salinity and nitrogen. Thereby providing the optimal nitrogen fertilizer application amount for wheat production in saline soils. This study could contribute to the goal of reducing the application rate of chemical fertilizer and improving the fertilizer efficiency of agriculture in the Yellow River delta.

2. Materials and Methods

2.1. Sampling Site

The experimental soil was sandy loam collected at Bohai Farm in Lijin County, Shandong province, China (37°41' N, 118°36' E). The sampling site is shown in Figure 1. The sampling site is about 3.5 km from the Yellow River valley and 35 km from the Bohai sea. The climate of the experimental area is warm temperate continental monsoon. The average annual temperature, precipitation, and evaporation were 12.8 °C, 556 mm, and 1755 mm, respectively. The frostless period was 206 d, and the average annual sunshine hours was 2702 h. The main characteristics of the soil are summarized in Table 1.

Table 1. Characteristics of the soil.

Parameter	Value
Sand	67%
Silt	27%
Clay	6%
pH _{1:5}	8.65
Total salt	0.7 g/kg
Bulk density	1.3 g/cm ³

Table 1. Cont.

Parameter	Value
Organic matter	10.35 g/kg
Total N	0.957 g/kg
Available P	11.8 mg/kg
Available K	20 mg/kg

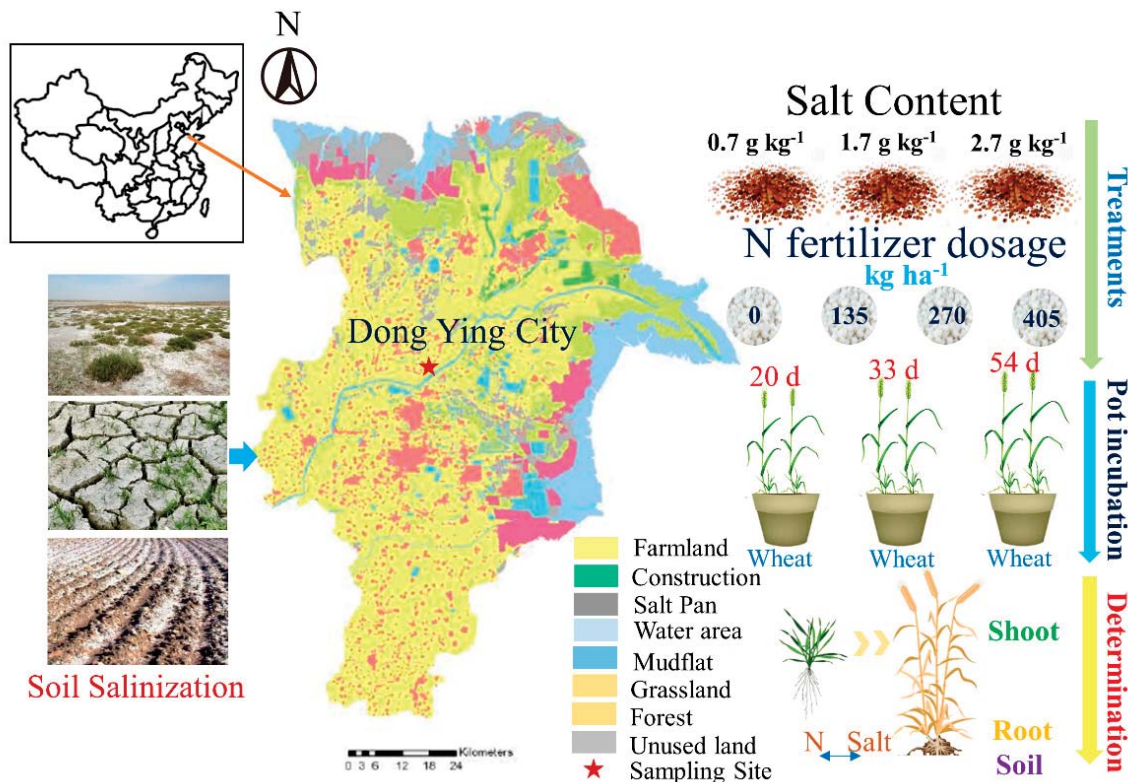


Figure 1. The sampling site and experimental design.

2.2. Experiment Design

The experiment was conducted in the laboratory incubator of the Yantai Coastal Zone Research Institute of the Chinese Academy of Sciences, and two control factors for soil salinity and nitrogen application were set up (Figure 1). The sampling soil was air-dried, removed the pebbles were, and then sieved to pass through a 2 mm mesh for the pot experiment. The cultivar of winter wheat is Shannong 24. The experiment was conducted in a plant growth chamber (Zhonglang RZH 500, Chengdu, China), with the control condition of the temperature of 20/18 °C at day/night, the sunlight/dark time was 16 h/8 h, and the humidity was 60% ± 5%. The nitrogen fertilizer is urea with a nitrogen content of 46%, and the P₂O₅ in phosphate fertilizer is 15%. The pot for the wheat growth was a 5 cm radius at the bottom and 11 cm height. Three levels of salt (0.7, 1.7, and 2.7 g/kg, referred to as S1, S2, and S3, respectively) were regulated in the soil using NaCl solution. While four levels of N application rates consisted of 0 (N0), 135 (N1), 270 (N2), and 405 (N3) kg /ha, respectively. The additional amount of phosphate fertilizer was 105 kg (P₂O₅)/ha. The total treatments were 12 with a randomized block design, and each treatment was repeated 9 times (Table 2).

Table 2. The abbreviations of all treatments.

Number	1	2	3	4	5	6	7	8	9	10	11	12
Treatment	N0S1	N0S2	N0S3	N1S1	N1S2	N1S3	N2S1	N2S2	N2S3	N3S1	N3S2	N3S3

Note(s): S1, S2, and S3 represent 0.7, 1.7, and 2.7 g/kg soil salt content, respectively; N0, N1, N2, and N3 represent 0, 135, 270, and 405 kg/ha N (urea 46%) addition content, respectively.

Each pot was filled with 850 g soil and covered the bottom hole with orchid stones. The hole supplied air exchange and prevented anoxia of the soil. The different salt solutions and fertilizers of all treatments were added to the soil and combined uniformly. The wheat seeds were soaked in 100 mL/L NaClO solution for 10–15 min. After washing with deionized water until the bleach's smell disappeared, the seeds were placed in Petri dishes to germinate for 20 min in the dark conditions at the temperature was 26 ± 1 °C. The 10 seedlings were transplanted at a depth of 2 cm in every pot. In order to maintain the soil salinity at stable levels, the soil water holding capacity in each pot was maintained at $65\% \pm 5\%$ by adjusting the whole weight with deionized water throughout the experiment. Plants were grown in a glasshouse with the illumination setting parameters of 16 h/8 h (Light/Dark) and the air humidity maintained at 55–65%. The temperature was set at 20 °C by day and 18 °C by night). Plant samples and soil samples were taken at 20, 33, and 54 days during the cultivation, respectively.

2.3. Data Collection

Basic parameters of the soil: The soil particle size composition was determined by a laser particle analyzer (Mastersizer 2000, Malvern, UK). The soil pH was measured in 1:5 soil-water suspension using a pH meter (Leici PHSJ-4F, Shanghai City, China) after 1 h shaking at 25 °C in an incubator shaker. The total salt was measured by the oven-drying method. The bulk density was tested by cutting the ring. The soil organic matter was determined by a total organic carbon analyzer (Thermo Fisher LH-SOC350, New York, NY, USA).

Plant sampling: The whole winter wheat plant was removed from the pot at each sampling time. Shoots were cut off then roots were washed with distilled water 3 times.

Chlorophyll content: In each pot, three leaves were cut and soaked in Anhydrous ethanol, then determined the Chlorophyll by spectrophotometry (Puxi T6, Beijing, China).

Stem height, stem, and root weight: Pseudo stem height of winter wheat seedlings was measured by a ruler. The fresh samples of the stem and root were baked in a dryer (DHZ-9140A electrothermal constant temperature blast drying box, Shenxian, Tianjin, China) at the temperature of 85 °C for 15 min. Then the samples were baked for 12 h at 70 °C. Finally, they were weighed with High Precision Electronic Balances (with a precision of 0.1 µg) (Mettler Toledo XPR2U, Greifensee, Switzerland).

Total nitrogen of plant and soil: The dried samples were digested with the H₂SO₄-H₂O₂ method (SH220 graphite digestion apparatus), then determined the N content was by the Kjeldahl method (Huawei KDY-9840 Kjeldahl apparatus, Wuhan, China).

Soil inorganic nitrogen: The fresh soils were extracted with 2 mol/L KCl solution, and the leaching solutions were measured by a continuous flow analyzer (German Seal Company AutoAnalyzer III, Hamburg, Germany) for NO₃[−]. In addition, a part of the soil samples was dried in the oven for water content measurement.

2.4. Statistical Analysis

All data were analyzed using SPSS (Statistical Product and Service Solutions) 19.0 (IBM Company, New York, NY, USA) for Windows software. Significant differences for all data were tested with two-way ANOVA analysis followed by least significant differences (LSD) at $p < 0.05$.

3. Results

3.1. Soil pH

The N addition contents, and soil salt had significant effects on the soil pH_{1.5} (Table 3). At the early growth stage of winter wheat (20 days), increased nitrogen fertilizer addition content significantly reduced soil pH_{1.5}, and the difference between N2 and N3 levels was not significant. The higher the soil salinity, the lower the pH_{1.5}. The sequence of pH value in treatments was S1 > S2, S3. On the 33rd day of winter wheat growth, the soil pH_{1.5} decreased significantly with the increased addition of nitrogen and salinity. The sequence was N0 > N1 > N2 > N3 and S1 > S2 > S3. When winter wheat grew after 54 days, N and salinity addition significantly decreased soil pH_{1.5}, and pH in treatments that included N3 were significantly lower than other N addition levels (N0, N1, and N2). The order of soil pH_{1.5} in different soil salinity was S1 > S2 > S3. The contribution rates of nitrogen and salt to soil pH_{1.5} was various in different periods. The contribution rate of nitrogen fertilizer was stronger than that of salt at 20 and 33 days, and the contribution rate of salt was stronger than that of nitrogen fertilizer at 54 days. Although the application of N significantly reduced soil pH_{1.5}, the soil pH_{1.5} showed an overall increase during the growth of winter wheat. The soil pH_{1.5} of N0S1 increased by 0.14, while the soil pH_{1.5} of N0S3 increased by 0.14. In addition, the soil pH_{1.5} of N1S3 increased by 0.19, while the soil pH_{1.5} of N3S3 increased by 0.11. Therefore, the amount of nitrogen and salt affected soil pH_{1.5}. They significantly decreased soil pH_{1.5}. In the early stage of winter wheat growth (33 days), nitrogen fertilizer was key influencing factor on soil pH. When the winter wheat grew to 54 days, the nitrogen fertilizer affected little soil pH_{1.5}, and it was mainly affected by soil salinity. The lowest pH in the three levels of salinity was obtained in N3 treatments, and there was no significant difference between N2 and N3 treatments.

Table 3. Effects of nitrogen application on soil pH_{1.5} at different growth stages of winter wheat in various salinity level soils.

pH/Time	N Rate	20 Days			33 Days			54 Days		
		S1	S2	S3	S1	S2	S3	S1	S2	S3
Soil pH	N0	8.45 a	8.407 ab	8.40 ab	8.60 a	8.46 bc	8.37 e	8.59 def	8.52 ef	8.43 f
	N1	8.40 ab	8.33 bc	8.24 cd	8.48 d	8.42 cd	8.37 e	8.65 cdef	8.51 def	8.43 ab
	N2	8.34 b	8.23 cd	8.18 d	8.40 de	8.36 e	8.29 f	8.64 ab	8.47 ab	8.41 cd
	N3	8.32 bc	8.24 cd	8.22 d	8.37 e	8.30 f	8.28 f	8.56 bc	8.39 ab	8.33 cde
	N rate		0.000			0.000			0.001	
	Salinity		0.000			0.000			0.000	
	N rate × salinity		0.556			0.003			0.601	

Note(s): N0, N1, N2, and N3 represent nitrogen fertilizer amounts of 0, 135, 270, 405 kg (N)/ha, S1, S2, and S3 represent soil salt content of 0.7, 1.7, 2.7 g/kg. Different letters in the same column indicate significant differences ($p < 0.05$) between the treatments.

3.2. Soil Total N and NO₃[−]

As shown in Table 4, the salt had no significant effect on soil total N during the 54 days of cultivation of winter wheat, while the N addition rate had a significant effect on soil total N before 33 days of growth and the interaction of them had a significant effect on soil total N. The more N addition, the higher NO₃[−] in the soil. With the experiment going on, the NO₃[−] decreased significantly until there was no difference between all treatments after 54 days of cultivation. Soil salinity increased soil NO₃[−] at 33 days but showed no significant effects at 20 days and 54 days. Nitrogen and salt showed obvious interaction on soil N content. There was no significant difference between N2 and N3 treatments in the three levels of soil salinity after 54 days of cultivation.

Table 4. Effects of nitrogen application rates on soil total N and soil NO₃[−] in different growth stages of winter wheat in various salinity level soils.

Soil N	N Rate	20 Days			33 Days			54 Days		
		S1	S2	S3	S1	S2	S3	S1	S2	S3
Total N (g/kg)	N0	0.92 cde	0.904 e	0.912 de	0.933 c	0.937 c	0.926 c	0.643 e	0.617 e	0.663 e
	N1	0.94 c	0.930 cd	0.929 cd	0.941 bc	0.941 bc	0.972 ab	0.844 d	0.847 d	0.809 c
	N2	1.00 b	1.04 a	1.02 ab	0.974 a	0.972 ab	0.974 a	0.659 c	0.844 b	0.861 b
	N3	1.03 ab	1.03 a	1.02 ab	0.989 a	1.00 a	0.997 a	1.07 a	1.075 a	1.06 a
	N rate		0.000			0.000			0.001	
	Salinity		0.000			0.595			0.033	
	N rate × salinity		0.556			0.520			0.005	
NO ₃ [−] (mg/kg)	N0	13.6 d	11.5 d	12.4 d	1.99 e	2.68 e	3.89 d	1.25 a	1.91 a	1.95 a
	N1	28.5 c	31.7 c	30.7 c	14.8 c	17.4 c	17.4 c	8.95 a	8.96 a	7.96 a
	N2	54.53 ab	50.2 b	48.3 b	24.0 b	29.8 b	36.7 a	19.0 a	16.9 a	19.0 a
	N3	66.8 a	70.8 a	60.5 ab	44.5 a	43.5 a	45.1 a	31.0 a	31.0 a	28.9 a
	N rate		0.000			0.000			0.598	
	Salinity		0.642			0.001			0.775	
	N rate × salinity		0.771			0.132			0.998	

Note(s): N0, N1, N2, and N3 represent nitrogen fertilizer amounts of 0, 135, 270, 405 kg/ha (N), S1, S2, and S3 represent soil salt content of 0.7, 1.7, 2.7 g/kg. Different letters in the same column indicate significant differences ($p < 0.05$) between the treatments.

3.3. Wheat Chlorophyll Content

The chlorophyll content of winter wheat was significantly affected by salinity and N application rate in different growth stages (Table 5). When winter wheat was grown for 20 days, the chlorophyll content of winter wheat was significantly affected by salinity and N application rate. The application of N increased the chlorophyll content, but there was no significant difference between all levels of N application. The increase in soil salinity simulated the generation of chlorophyll in winter wheat (S3, S2 > S1). There was a significant interaction between the salinity and N application rate, and the contribution rate of this interaction was greater than the main effect of soil salinity and nitrogen fertilizer. At 54 days, salinity and N rate had a significant effect on the chlorophyll of winter wheat, while the interaction between the salinity and N rate was not significant. What's more, chlorophyll content was increased by 58.89% in N3S1 treated posts at 54 days. The application of nitrogen fertilizer promoted the formation of chlorophyll, but there was no significant effect between the various nitrogen application treatments. The chlorophyll content was promoted by salinity (S3 > S2 > S1). Therefore, the chlorophyll content of winter wheat was affected by soil salinity and N rate, and both of them showed significantly promoted effects. The contribution rate of salinity was less than that of nitrogen fertilizer. When the salinity was higher than 1.7 g/kg, the salt hardly increased chlorophyll, and there was no significant correlation between nitrogen usage and chlorophyll during the whole cultivation period. N treatments increased Chlorophyll content compared to N0, and there was no significant difference between all N treatments after 54 days of planting.

Table 5. Effects of nitrogen application rates with different soil salinity levels on chlorophyll content in different growth stages of winter wheat.

Parameter	N Rate	20 Days			33 Days			54 Days		
		S1	S2	S3	S1	S2	S3	S1	S2	S3
Chlorophyll content (mg/g)	N0	0.033 c	0.097 b	0.097 a	0.299 a	0.266 a	0.232 a	0.169 f	0.216 e	0.253 cd
	N1	0.097 a	0.097 a	0.097 a	0.242 a	0.277 a	0.276 a	0.249 de	0.292 abc	0.329 a
	N2	0.096 a	0.096 a	0.097 a	0.249 a	0.239 a	0.222 a	0.250 de	0.303 ab	0.305 ab
	N3	0.097 a	0.096 a	0.096 a	0.2263 a	0.224 a	0.242 a	0.269 bcd	0.326 a	0.317 a
	N rate		0.000			0.303			0.000	
	Salinity		0.000			0.844			0.000	
	N rate × salinity		0.000			0.659			0.255	

Note(s): N0, N1, N2, and N3 show nitrogen fertilizer amounts of 0, 135, 270, 405 kg (N)/ha, S1, S2, and S3 show soil salt content of 0.7, 1.7, 2.7 g/kg. Different letters in the same column indicate significant differences ($p < 0.05$) between the treatments.

3.4. N Concentration of Winter Wheat

As shown in Table 6, the N dosage had significant effects on the total N content of the shoot of wheat at different growth stages (within 54 days). When wheat was grown after 20 days, the N application significantly increased the total N in the shoot, but there was no significant difference between the different N treatments. When winter wheat grew to 33 days, the N levels showed significant differences, which showed $N1 > N2$, $N3 > N0$. However, when winter wheat grew until 54 days, the N addition levels showed significant differences among the treatments, showing a tendency of $N2, N3 > N1 > N0$. The amount of N fertilizer merely had significant effects on the total N of the root when the winter wheat grew up to 54 days (Table 6), with the sequence of N content $N2, N3 > N1 > N0$. A similar variation tendency was found in N application on the total N of the shoot (54 days). During the cultivation period, soil salinity had no significantly improved effect on the total N of shoot and root. At 54 days, the total N of the shoot was increased by 103.18% in N3S1 treatment, and the total N of the root was increased by 122.06% in N2S1 treated pots. After 54 days of cultivation, the highest total N in the shoot and root was obtained in the N2 treatment.

Table 6. Total N of shoot and root in different growth stages of winter wheat.

Total N (g/pot)	N Rate	20 Days			33 Days			54 Days		
		S1	S2	S3	S1	S2	S3	S1	S2	S3
Shoot	N0	0.034 d	0.038 cd	0.038 cd	0.036 d	0.038 cd	0.040 bcd	0.016 e	0.018 de	0.020 cde
	N1	0.042 abc	0.042 abc	0.040 bcd	0.050 abc	0.045 abc	0.043 bcd	0.025 abcd	0.027 abc	0.028 ab
	N2	0.049 a	0.043 abc	0.044 abc	0.044 a	0.042 abc	0.041 abc	0.030 a	0.031 a	0.032 a
	N3	0.046 ab	0.041 bcd	0.039 bcd	0.043 ab	0.043 bcd	0.040 bcd	0.032 a	0.032 a	0.022 bcde
	N rate		0.679			0.622			0.000	
	Salinity		0.684			0.267			0.922	
	N rate $\times$ salinity		0.356			0.030			0.147	
Root	N0	0.018 a	0.019 a	0.020 a	0.010 c	0.012 abc	0.011 bc	0.007 d	0.007 d	0.007 d
	N1	0.019 a	0.020 a	0.018 a	0.011 bc	0.012 abc	0.012 abc	0.011 c	0.012 bc	0.014 ab
	N2	0.020 a	0.016 a	0.017 a	0.0140 a	0.011 bc	0.011 bc	0.016 a	0.015 a	0.015 a
	N3	0.019 a	0.016 a	0.020 a	0.013 ab	0.011 bc	0.010 c	0.015 a	0.014 ab	0.014 ab
	N rate		0.679			0.622			0.000	
	Salinity		0.684			0.267			0.922	
	N rate $\times$ salinity		0.356			0.030			0.147	

Note(s): N0, N1, N2, and N3 represent nitrogen fertilizer amounts of 0, 135, 270, 405 kg (N)/ha, S1, S2, and S3 represent soil salt content of 0.7, 1.7, 2.7 g/kg. Different letters in the same column indicate significant differences ($p < 0.05$) between the treatments.

3.5. Plant Height of Wheat

The additional amount of N and salt had significant effects on the pseudo stem height (PSH) of winter wheat, which showed different characteristics at different times (Table 7). At the early growth stage of winter wheat (20 and 33 days), salt had a significant effect on the pseudo stem height. While N application played its role in the growth of winter wheat at 54 days, the PSH increased by 17.14% in N3S1 treatment. However, there were obviously interactive effects between N rate and soil salinity. Salt inhibited the growth of winter wheat in the early growth stage, and the inhibitory effect decreased as the plant grew. On the 20-day, salt effects on PSH showed $S1 > S2 > S3$, while the values in the order of PSH on the 33-day were $S1, S2 > S3$. The effect of adding N on the PSH in winter wheat was later than that of salinity. The inhibitory effect of salt on wheat growth was mainly shown at the beginning stage of the plant growth (33 days), and the N application on the PSH was mainly presented after 54 days of growth. The interaction between salinity and N application on winter wheat growth was mainly shown on the 54 days. N2 treatments showed a higher PSH value than N3 treatment, which reflected the lower N addition with the higher productivity.

Table 7. Effects of nitrogen application rates with different soil salinity levels on Pseudo stem height (PSH) in different growth stages of winter wheat.

Parameter	N Rate	20 Days			33 Days			54 Days		
		S1	S2	S3	S1	S2	S3	S1	S2	S3
PSH (cm)	N0	5.74 abc	5.08 cde	5.08 de	7.55 abcd	7.26 abc	7.02 abcd	7.12 def	6.99 ef	6.92 f
	N1	6.13 a	5.51 abcd	4.728 e	7.24 abc	7.22 abc	6.85 bc	7.18 cdef	7.99 def	8.07 ab
	N2	5.89 ab	5.34 bce	4.75 e	7.26 abc	7.18 abcd	6.58 d	8.09 ab	7.51 ab	7.63 cd
	N3	5.67 abcd	5.43 cd	4.79 e	7.41 ab	7.07 abcd	6.71 cd	8.34 bc	7.46 ab	7.25 cde
	N rate		0.85			0.43			0.000	
	Salinity		0.000			0.002			0.16	
	N rate $\times$ salinity		0.55			0.95			0.00	

Note(s): N0, N1, N2, and N3 represent nitrogen fertilizer amounts of 0, 135, 270, 405 kg (N)/ha, S1, S2, and S3 represent soil salt content of 0.7, 1.7, 2.7 g/kg. Different letters in the same column indicate significant differences ($p < 0.05$) between the treatments.

3.6. Wheat Weight

The results showed that salt and N application rate significantly affected shoot and dry root weight in different growth periods (Table 8). While the salt and N addition rate had no significant effect on the shoot dry weight, the salinity had a significant effect on the root dry weight at 20 days. With the increase in soil salt, the dry weight of winter wheat increased, and the root dry weight in S2 and S3 treatments was significantly higher than in S1. At 33 days after wheat sowing, the salinity had a significant effect on shoot dry weight ($S1 < S2 < S3$), while the N addition rate had no significant effect on the dry weight of winter wheat. The interaction of N rate and salinity had a significant effect during this period. The dry shoot weight of N2S1 was the highest, and the dry shoot weight of N2S3 was the lowest. When winter wheat grew up to 54 days, the amount of N and salinity had significant effects on the shoot and root dry weight of winter wheat. The shoot dry weight increased by 44.96% in the N2S1 treatment, and the root dry weight increased by 10.42% in the N2S1 treatment after the 54 days plant. The addition of N increased the shoot and root dry weight, but the dry weight decreased as the dosage improved. The effect of salt on the shoot and root dry weight was significant, and the root dry weight of S3 was significantly lower than that of S1 and S2. Therefore, the dry weight of different parts of the winter wheat was significantly affected by salinity and nitrogen fertilizer. However, the nitrogen fertilizer exerted its influence after the salt effects. The different wheat parts' weight was mainly affected by different factors, and the dry shoot weight of winter wheat was affected by salt, which was stronger than the amount of nitrogen. The root dry weight was principally impacted by the N dosage than the salt content. N2 treatments obtained the highest shoot and root weight, and it was more than the higher N addition N3 treatment.

Table 8. The dry weight of shoot in different growth stages of Winter Wheat under different salinity and N application rates.

Dry Weight (g/pot)	N Rate	20 Days			33 Days			54 Days		
		S1	S2	S3	S1	S2	S3	S1	S2	S3
Shoot	N0	0.023 ab	0.020 bc	0.022 abc	0.079 abc	0.066 cde	0.076 abcd	0.176 de	0.195 bcde	0.179 cde
	N1	0.023 ab	0.028 a	0.021 bc	0.080 abc	0.083 ab	0.067 cde	0.234 abc	0.225 abcd	0.176 cde
	N2	0.026 ab	0.025 ab	0.021 abc	0.090 a	0.078 abcd	0.059 e	0.255 a	0.247 ab	0.204 abcd
	N3	0.022 abc	0.021 bc	0.017 c	0.088 ab	0.074 bcd	0.064 de	0.226 abcd	0.213 abcd	0.136 c
	N rate		0.069			0.918			0.019	
	Salinity		0.074			0			0.003	
Root	N rate × salinity		0.519			0.041			0.457	
	N0	0.010 cd	0.012 abcd	0.009 d	0.041 a	0.031 a	0.035 a	0.097 abc	0.103 ab	0.106 a
	N1	0.010 cd	0.013 abcd	0.013 abc	0.035 a	0.033 a	0.032 a	0.105 a	0.087 abcde	0.058 ef
	N2	0.009 d	0.013 abc	0.014 ab	0.037 a	0.040 a	0.033 a	0.108 a	0.091 abcd	0.062 def
	N3	0.010 bcd	0.0120 bcd	0.014 a	0.042 a	0.038 a	0.036 a	0.074 bcdef	0.070 cdef	0.045 f
	N rate		0.175			0.501			0.001	
	Salinity		0.007			0.341			0.002	
	N rate × salinity		0.35			0.851			0.193	

Note(s): N0, N1, N2, and N3 represent nitrogen fertilizer amounts of 0, 135, 270, 405 kg (N)/ha, S1, S2, and S3 represent soil salt content of 0.7, 1.7, 2.7 g/kg. Different letters in the same column indicate significant differences ($p < 0.05$) between the treatments.

4. Discussion

Soil salinity adversely affects crop productivity and agricultural sustainability, and plant growth can be inhibited by high salt concentrations through nutritional imbalance, osmotic stress, and specific ion toxicity [25]. Understanding N-Salt relationships is of great economic and social importance [26]. Many studies have been conducted to investigate N and other nutrient application effects on saline soil [16,27–29]. The effects of salinity and/or nitrogen on soil properties and plant growth have been recognized in many crops; however, their interaction effect, especially in different addition levels of N and various soil salinity levels, is still not fully understood. Our study has added a new perspective on the common perception of the N rate, salt content or their interactions affected saline soil properties and plant growth.

4.1. Effects of N Addition on Saline Soil Properties

Soil fertility is the capacity to support and coordinate plant growth. Long-term fertilization might change the nutrient status of the soil, and soil N is essential for plant growth. In saline soil, salinity has a negative effect on plant–the nutrient–salinity relationship. In China, fertilizer application has been commonly used for improving crop production and soil fertility in the last three decades [30]. Reports showed that overuse of nitrogen fertilizer is poisoning the country's air, soil, and water and that farmers could reduce its use without compromising crop yields [31]. Otherwise, applying the N fertilizer could cause soil pH to decrease and accelerate soil acidification [32]. The result of the study showed that soil pH decreased with increasing N addition. Similar results have been reported in many studies [33,34]. Although soil pH increased in the seedling stage, salinity and N addition slowed down its rising trend. Effects of N addition are greater than salinity on soil pH in 33 days, but salinity affected more when wheat grew to 54 days. The soil water content was contained at $65\% \pm 5\%$ in the experiment, and that reduced experimental error to ensure the accuracy of the results. Soil total N is usually used to measure the basal fertility of the soil. Proper N addition rate improved total N increasing, but greater soil salinity caused marked inhibition of the early step of nitrification [35]. The increased soil salinity could affect the nitrification process adversely, and nitrification of NH_4^+ to NO_3^- was reduced by salinity treatments [36]. In our study, when N addition is lower than 270 kg/ha, soil total N increases with increasing N addition. N application rate had no effect until 54 days. This may be caused by the fact that the soil total N was close to the background value (0.957 g/kg) in all treatments. The lower content of NO_3^- in soil was mainly affected by salinity, and there should be greater NH_4^+ accumulation in the soil at the greatest salinity level. The more nitrogen added, the more NO_3^- in the soil during the

experimental cultivation (Table 4). The findings agree with those observed by Izsaki [37] and Lu [38], who demonstrated that increasing the application of N fertilizer could increase NO_3^- content. So nitrogen application could change saline soil pH and then accelerate the N fertilizer nitrification process in soil [39]. The moderate N application rate N2 treatment not only decreased fertilizer consumption but also ameliorated the soil situation, which was beneficial to improve resource utilization.

4.2. Effects of N on Wheat Growth and Plant Nutrition in Saline Soil

The pseudo stem height in the seedling stage is the distance between the plant's basal part and the top part of the expanded leaf sheath. It is one of the most basic indexes in plant morphology [40]. Photosynthesis is an important basis for the synthesis of organic compounds, and chlorophyll plays an important role in the absorption, transmission, and transformation of light energy [41]. N application rate, nitrogen time, and N form all affect plant growth. N exists in protein and chlorophyll in wheat, and the distribution of nitrogen in plants is affected by N application rate and nitrogen time. The yield of crops that grow in saline soil is significantly lower than that in Non-saline soil, so salinity is harmful to crop growth. Winter wheat is a kind of plant which excludes salt while it can adjust biomass distribution to adapt to salt stress [42]. Plant height, biomass, and Morphological characteristics are affected by salinity [43]. Chlorophyll, Photosynthetic rate, and root activity are limited by salinity [44–46]. The study showed that the addition of N and salinity had a significant effect on the shoot and root dry weight, and the effects of salinity accrued earlier than the N addition treatments. The influence of salinity on dry shoot weight was more significant than N addition. While the effect of root dry weight is the opposite. Salinity is the major factor limiting winter wheat growth in the seedling stage (33 d). Similar results were reported by Ray [47], Ghafoor [48], and Liu [49]. The soil water content also affects the yield, but the water maintained a constant content during the experiment, so nitrogen and salinity were the main influence factors. The effect of the N application rate played a key role in pseudo stem height after 54 days of cultivation. So, the effect of salinity on pseudo stem height was earlier than the effect of the addition of N, and the interaction between salinity and the addition of N was significant. Salinity and N rate had a positive effect on chlorophyll improvement, and the chlorophyll content was higher in N addition treatments, the same as that reported in [14,50]. When the soil salinity was 1.7 g/kg, salinity decreased wheat leaf chlorophyll contents. N application rate had no significant effect on chlorophyll content. N concentration in wheat increased with N addition, but an excessive supplement of N might not improve N concentration in wheat. Salinity had no significant negative effects on the total N of each part of the wheat (Table 8). The lower N addition treatment N2 showed a better plant growth promotion effect than the N3 treatment, so the proper utilization of fertilizer in saline soil planting is essential.

5. Conclusions

During the first 20 days of the wheat cultivation, root dry weight was promoted by salinity, and the total N of the shoot was improved by the addition of N. After 33 days of planting, the dry shoot weight of wheat was limited by salinity, and the total N of the shoot was promoted by the addition of N. On the 54 days, shoot dry weight, total N of shoot and root, and chlorophyll content were promoted by the addition of N, while shoot and root dry weight and chlorophyll content were inhibited by different levels of salinity.

The shoot dry weight was increased by 44.96% in the N2S1 treatment, and the root dry weight increased by 10.41% in the N2S1 treatment after 54 days of growth. The addition of N was not only beneficial for reducing the harmful effects of soil salt but also for decreasing soil pH. Soil total N increased gradually with the increase in N application rate when the N rate was less than 270 kg/ha. During the experimental time (within 54 days), the interaction between salinity and N application rates significantly increased shoot dry weight, and the total N of the root lasted for 33 days. During the wheat seedling growth stage, 270 kg N/ha

application was the optimal measurement for crop growth and soil regulation when the salt content is less than 1.7 g/kg.

Consequently, it is necessary that how to apply fertilizer rationally and improve the utilization ratio of fertilizer for the sustainable development of saline agriculture in the Yellow River delta.

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Article

Fertilizer ^{15}N Fates of the Coastal Saline Soil-Wheat Systems with Different Salinization Degrees in the Yellow River Delta

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Abstract: In order to clarify the fates of fertilizer N in coastal saline soil-wheat systems with different salinization degrees, this study was conducted to determine the ^{15}N uptake rates in various parts of wheat plant at maturity stage and the residual ^{15}N in three different saline soils and the ^{15}N loss of soil-wheat systems by using the ^{15}N -labeled urea N tracing method in the Yellow River Delta. The results showed that: (1) The increase of soil salinity from 0.2‰ to 1‰ promoted the wheat plant to absorb N from soil and not from fertilizer and significantly inhibited the dry matter mass accumulation and ^{15}N uptakes of each wheat parts and whole plant, but especially increased the total N concentration of wheat roots, stems, leaves, and grains. The aggravation of soil salinity significantly enhanced the distribution ratios of ^{15}N uptakes and Ndfs in the wheat roots, stems, and leaves to depress the salt stress. (2) The ^{15}N residues were mainly concentrated in the 0–20 cm saline soil layer and decreased as the soil profile deepened from 0 to 100 cm; the ^{15}N residues decreased in the 0–40 cm soil profile layer and accumulated in the 40–100 cm with the increase of soil salinization degrees significantly. (3) The fates of ^{15}N applied to the coastal saline soil-wheat system were wheat uptakes 1.53–13.96%, soil residues 10.05–48.69%, losses 37.35–88.42%, with the lowest ^{15}N uptake and utilization in the three saline soils, the highest residual rate in lightly saline soils, and the highest loss in moderately and heavily saline soils. The increase of soil salinity inhibits wheat uptakes and soil residues and intensifies the losses from fertilizer ^{15}N . Therefore, the fate of fertilizer N losses significantly increased as the degree of soil salinity increased. The conventional N management that was extremely inefficient for more N loss should be optimized to enhance the N efficiency and wheat yield of the coastal saline soil-wheat system in the Yellow River Delta.

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Keywords: fertilizer ^{15}N fate; coastal saline soil-wheat system; N uptake; N residue; N loss

1. Introduction

Soil salinization is a widespread problem on more than 25% of the global soil area, and more than 36 million hectares of land in China are affected by salinization, representing about 4.9% of all available land [1–7]. The Yellow River Delta, located in the warm temperate subhumid continental monsoon climate zone, has experienced serious soil salinization from the coastline to the interior over the past 20 years due to seawater intrusion [8–12]. The coastal saline soils in the Yellow River Delta are an important back-up land resource for food production in China [13]. However, shallower saline groundwater, high soil pH and salinity, poor soil nutrients and structure, low water retention capacity, and other problems of the coastal saline soils reduce crop growth and yields [14–17], ultimately constraining sustainable development of agriculture and food security of the Yellow River Delta.

Nitrogen is a basic nutrient required for plant growth and development, and it is one of the especially deficient nutrients in the coastal saline soil of the Yellow River Delta [18].

Nitrogen fertilizers have been widely applied to increase crop yields in the coastal saline soil to address the pressure on the increasing food security due to the population boom in this century [19]. Urea is commonly used as a source of nitrogen fertilizer for its high nitrogen content and stability [20,21]. The conventional amount of urea application in Chinese crop production is 2–3 times higher than that of the world averagely [22]. However, less than 30% of urea nitrogen is absorbed by crops in China, while more than 70% leaches into the soil profile and groundwater with rainfall and irrigation, or runoffs into surface water resulting in eutrophication of water bodies [23,24].

Wheat is one of the major food crops grown in the coastal saline soil of the Yellow River Delta and its growth is affected by both N deficiency and salt stress [25]. Currently, many studies have focused on increasing the application amount of the nitrogen fertilizer to close yield gaps in the saline soil, but the effect may be limited by the soil saline environment. Meanwhile, nitrogen deficiency of coastal saline soil increases the severity of salt stress [26–28]. So, nitrogen fertilizer management is an important and urgent task of agricultural production in coastal saline soil.

Stable ^{15}N isotope labeling is a well-established technique for tracking and quantifying N transformations mostly applied in various ecosystems and in non-saline soil environment [29–32]. This technique is also used in some studies of saline soil, but mainly applied to specific saline soil [33], and less used in different saline soils, especially in soil-wheat systems with different degrees of salinization, which has less been reported.

Compared to most of previous studies, which are still confined to indoor pot conditions, this technique with ^{15}N -labeled urea in field is more reflective of the actual fate of urea N in coastal saline soil-wheat systems with different salinization degrees [34]. Therefore, the objectives of this research are to quantify the N uptake by wheat plants at maturity, the N residual distribution and the N loss in the coastal saline soil-wheat system with different degrees of salinity by ^{15}N -labeled urea tracing method, and to provide a theoretical basis for improving nitrogen management in the wheat planting process which may contribute to the sustainable agriculture development of the Yellow River Delta.

2. Materials and Methods

2.1. Experimental Site and Soil Properties

The experimental site is located in Bohai farm, Dongying City, Shandong Province ($37^{\circ}47' \text{ N}$, $118^{\circ}36' \text{ E}$), which is in the hinterland of the Yellow River Delta. The topography of the area is flat, and the degree of soil salinization is unevenly distributed. The soil types are mainly coastal chloride saline fluvo-aquic soils with loamy and clay loamy textures. The burial depth of groundwater is 0.8–1.2 m with salinity $12.69\text{--}20.08 \text{ g L}^{-1}$, which is highly mineralized and not suitable for irrigation. The region has a warm temperate semi-arid continental monsoon climate with an average annual temperature of 13.3°C , an average annual frost-free period of 206 days, an average annual precipitation of 537 mm and an average annual evaporation of 1885 mm. There is light-saline and medium-salinity land, heavy-saline land, and salty wasteland in this area, accounting for 66%, 18%, and 16% respectively, wheat-corn rotation and cotton are cultivated in saline land except for salty wasteland. The natural vegetation is dominated by halophytes, such as *Suaeda salsa* (*Suaeda salsa* L.), reeds (*Phragmites australis* L.), and tamarisk (*Tamarix chinensis* L.).

The three different salinization experimental coastal saline soils were the light (LS), medium (MS), and heavy (HS) salinity with the classification of the soil water-soluble salt contents: 0.2%–0.4%, 0.4%–0.6%, and 0.6%–1.0%, respectively (China Soil Census Office, 1992), and the basic physicochemical properties are shown in Table 1.

Table 1. Properties of light-salinity soil (LS), medium-salinity soil (MS), and heavy-salinity soil (HS).

Soil	pH	EC (dS m ⁻¹)	TS (g kg ⁻¹)	BD (g cm ⁻³)	OM (g kg ⁻¹)	TN (g kg ⁻¹)	AP (mg kg ⁻¹)	AK (mg kg ⁻¹)
LS	7.90 ± 0.01	0.42 ± 0.02	2.97 ± 0.28	1.38 ± 0.05	15.23 ± 0.19	1.05 ± 0.01	18.75 ± 0.49	185.70 ± 0.80
MS	7.98 ± 0.01	1.24 ± 0.01	5.02 ± 0.24	1.32 ± 0.05	12.72 ± 0.09	0.93 ± 0.03	12.08 ± 0.10	227.05 ± 3.15
HS	7.99 ± 0.02	2.97 ± 0.03	6.91 ± 0.55	1.30 ± 0.09	7.99 ± 0.07	0.76 ± 0.02	9.33 ± 0.10	250.30 ± 8.70

Note: EC, soil electrical conductivity; TS, soil total salt; BD, soil bulk density; OM, soil organic matter; TN, soil total nitrogen; AP, soil available phosphorus; and AK, soil available potassium.

2.2. Experimental Design

The field experiment of wheat (*Triticum aestivum* L., Jimai 23) was conducted from October 2017 to June 2018 with a field micro-zonal randomized block trial design. The treatments consisted of three fields with different salinization degrees: LS (light-salinity soil), MS (medium-salinity soil), and HS (heavy-salinity soil) and each treatment was repeated three times. The field micro-zones with 1 m² square area were delimited in the middle area of each field and were separated by 1.5 m distance. The plastic cloth was buried into a ditch dug 0.2 m wide and 0.6 m deep to form a ridge 0.2 m wide and 0.05 m high above the soil surface and surrounding every micro-zone, which prevented the ¹⁵N-labeled urea run off from each micro-zone.

The conventionally chemical fertilizers were applied with 225 kg N hm⁻² (urea, N ≥ 46.4%)-150 kg P₂O₅ hm⁻² (superphosphate, P₂O₅ ≥ 18%)-75 kg K₂O hm⁻² (potassium sulfate, K₂O ≥ 50%) in the experimental fields. All the superphosphate, potassium sulfate and 1/2 amount of urea were basely applied and mixed with topsoil before wheat sown, another 1/2 amount of urea was top-dressed at the jointing stage of wheat. The amount and method of the chemical fertilizers applied in each micro-zone were as the same as the outside fields except for the ¹⁵N labeled urea (N ≥ 46.4%, 2.0% ¹⁵N abundance, produced by Shanghai Research Institute of Chemical Industry, Shanghai, China) which was applied plot by plot before the application of outside field. All the other management measures were consistent with the local farmer practices.

2.3. Sampling, Measurement Methods and Assessment of Nitrogen Accumulation

Plant and soil samples were collected during wheat harvest stage in June 2018. All wheat plant samples in the micro-zone were harvested, and the roots, stems, leaves, sheaths, and grains were separated and dried at 60 °C to determine the dry matter masses. Soil samples were collected in 5 layers: 0~20 cm, 20~40 cm, 40~60 cm, 60~80 cm, 80~100 cm.

Soil total salt content was measured with the drying residue method (water-soil ratio 5:1), and soil total N content was determined with the semi-micro Kjeldahl method. Plant total N concentration was determined by H₂SO₄-H₂O₂ digestion and the Kjeldahl method. Soil and plant ¹⁵N abundance was determined using a mass spectrometer (Isoprime, Manchester, UK).

The percentage of plant nitrogen derived from fertilizer nitrogen (Ndff, %) was calculated as

$$\text{Ndff} = (\text{N}_P - \text{N}_A) / (\text{N}_f - \text{N}_A) \times 100 \quad (1)$$

where N_P represents the ¹⁵N abundance (%) in plant samples, N_A represents the natural abundance of ¹⁵N (N_A = 0.365%), and N_f represents the ¹⁵N abundance (%) in fertilizer.

The percentage of plant nitrogen derived from soil nitrogen (Nd_{fs}, %) was calculated as

$$\text{Nd}_{fs} = 1 - \text{Ndff} \quad (2)$$

The plant ¹⁵N uptake (F_N, g m⁻²) was calculated as

$$F_N = \text{Ndff} \times D_M \times N_C \quad (3)$$

where D_M is plant dry matter mass (g m⁻²) and N_C is plant total nitrogen concentration (%).

The ^{15}N fertilizer utilization efficiency (^{15}NUE , %) in the current season was calculated as the wheat ^{15}N uptake, dividing the amount of N applied, which is the ^{15}N uptake rate:

$$^{15}\text{NUE} = F_{\text{N}} / ^{15}\text{N}_{\text{AP}} \times 100 \quad (4)$$

where $^{15}\text{N}_{\text{AP}}$ is the amount of ^{15}N applied per square of wheat (g m^{-2}).

Soil ^{15}N residue (R_{N} , g m^{-2}) was calculated as

$$R_{\text{N}} = D_{\text{MS}} \times N_{\text{CS}} \times (^{15}\text{N}_{\text{S}} - N_{\text{A}}) \times 100 \quad (5)$$

where D_{MS} is dry weight of soil sample (g), N_{CS} is total soil nitrogen content (%), and $^{15}\text{N}_{\text{S}}$ is soil ^{15}N abundance (%).

Soil ^{15}N residual rate (R_{Nr} , %) was calculated as

$$R_{\text{Nr}} = R_{\text{N}} / ^{15}\text{N}_{\text{AP}} \times 100 \quad (6)$$

^{15}N loss (L_{N} , g m^{-2}) was calculated as

$$L_{\text{N}} = ^{15}\text{N}_{\text{AP}} - F_{\text{N}} - R_{\text{N}} \quad (7)$$

^{15}N loss rate (L_{Nr} , %) was calculated as

$$L_{\text{Nr}} = 100\% - \text{NUE} - R_{\text{Nr}} \quad (8)$$

2.4. Statistical Analysis

The data of wheat plant and soil properties from the experimental field were analyzed by one-way analysis of variance (ANOVA) using SPSS 19.0 software (IBM Corporation, Armonk, NY, USA), and multiple comparisons of means were performed using Duncan's test ($p < 0.05$). Data calculation and graphing were respectively implemented with Excel 2016 software (Microsoft Corporation, Redmond, WA, USA) and Origin 2019 software (Origin Lab Corporation, Northampton, MA, USA).

3. Results

3.1. Dry Matter Mass of Each Wheat Parts

With the aggravation of soil salinization, the dry matter masses of the same wheat parts and whole plant of different salinization soil treatments showed a downward trend (Table 2). There were significant differences of the dry matter masses of the wheat root and stem between MS and LS treatments, HS and LS treatments with no significant differences of these between MS and HS treatments. However, there were significant differences of the dry matter masses of the wheat leaf, sheath, grain, and whole plant among the three treatments.

Table 2. Dry matter mass (g m^{-2}) of each wheat parts in different treatments.

Treatment	Root	Stem	Leaf	Sheath	Grain	Whole Plant
LS	22.63 ± 0.93 a	125.60 ± 7.64 a	94.69 ± 3.83 a	103.26 ± 2.19 a	222.83 ± 25.61 a	569.02 ± 18.97 a
MS	3.40 ± 0.43 b	18.85 ± 1.41 b	15.37 ± 0.26 b	29.13 ± 3.34 b	82.64 ± 6.40 b	149.38 ± 4.44 b
HS	1.75 ± 0.02 b	6.95 ± 0.24 b	6.33 ± 0.13 c	7.69 ± 0.15 c	14.80 ± 0.59 c	37.51 ± 0.52 c

Note: The values in the table are the mean ± standard error and different letters in each column indicate significant difference ($p < 0.05$).

Compared with LS treatment, HS treatment and MS treatment significantly reduced the dry matter masses of the wheat root, stem, leaf, sheath, grain, and whole plant by 92.28%, 94.47%, 93.32%, 92.56%, 93.36%, and 93.41%; and by 84.97%, 84.99%, 83.77%, 71.79%, 62.92%, and 73.75%, respectively ($p < 0.05$). The dry matter masses of the wheat leaves, sheaths, grains, and whole plants in HS treatment significantly decreased than those

of corresponding parts of wheat plants in MS treatment by 58.83%, 73.61%, 82.09%, and 74.89%, respectively ($p < 0.05$).

The order from high to low of each wheat part dry matter mass in the same saline soil treatment with the same salinization degree were basically in accordance with the order of grain, sheath, stem, leaf, and root, and the dry matter mass of the wheat grain was higher than those of the other parts with 77.41~2328.79%. So, the dry matter masses of wheat plants in saline soils were mainly concentrated in wheat grains than the other wheat parts, and the increase of soil salinization would inhibit the accumulation of the dry matter masses in various wheat parts and the whole plants.

3.2. Total N Concentration, ^{15}N Uptake, Distribution Ratio of ^{15}N Uptake, Ndff and Ndfs in Wheat Parts

With the increase of soil salinization, the total N concentrations in all wheat parts and the whole wheat plant showed an upward trend (Table 3).

Table 3. Total N concentration, ^{15}N uptake, distribution ratio of ^{15}N uptake, Ndff, and Ndfs in wheat parts of different treatments.

Item	Treatment	Root	Stem	Leaf	Sheath	Grain	Whole Plant
Total N Concentration/%	LS	0.74 ± 0.02 c	0.47 ± 0.02 c	0.80 ± 0.02 c	0.84 ± 0.01 b	1.87 ± 0.01 b	1.15 ± 0.04 b
	MS	1.02 ± 0.02 b	0.60 ± 0.02 b	1.27 ± 0.01 b	1.33 ± 0.05 a	2.34 ± 0.11 a	1.78 ± 0.03 a
	HS	1.13 ± 0.01 a	0.93 ± 0.03 a	1.32 ± 0.00 a	1.47 ± 0.10 a	2.49 ± 0.19 a	1.74 ± 0.07 a
^{15}N Uptake/(g m ⁻²)	LS	0.05 ± 0.01 a	0.15 ± 0.01 a	0.32 ± 0.01 a	0.36 ± 0.01 a	2.28 ± 0.30 a	3.15 ± 0.28 a
	MS	0.01 ± 0.00 b	0.04 ± 0.00 b	0.08 ± 0.00 b	0.17 ± 0.01 b	1.09 ± 0.13 b	1.39 ± 0.12 b
	HS	0.01 ± 0.00 b	0.02 ± 0.00 b	0.04 ± 0.00 c	0.05 ± 0.00 c	0.23 ± 0.01 c	0.35 ± 0.01 c
Distribution Ratio of ^{15}N Uptake/%	LS	1.59 ± 0.18 ab	4.88 ± 0.72 ab	10.23 ± 1.26 a	11.66 ± 1.13 a	71.64 ± 3.17 ab	/
	MS	0.70 ± 0.09 b	2.73 ± 0.45 b	5.94 ± 0.57 b	12.59 ± 2.04 a	78.04 ± 3.06 a	/
	HS	2.16 ± 0.45 a	7.12 ± 1.11 a	10.84 ± 1.33 a	13.97 ± 1.77 a	65.91 ± 1.66 b	/
Ndff/%	LS	25.52 ± 0.55 b	28.16 ± 1.00 c	36.85 ± 0.44 b	41.56 ± 1.30 a	47.05 ± 2.21 b	45.63 ± 1.72 a
	MS	29.53 ± 1.53 ab	32.89 ± 0.86 b	40.28 ± 0.97 b	43.50 ± 2.02 a	55.47 ± 1.39 a	45.42 ± 1.54 a
	HS	37.44 ± 3.93 a	37.79 ± 0.56 a	44.76 ± 1.46 a	46.13 ± 1.09 a	57.62 ± 3.15 a	50.42 ± 2.48 a
Ndfs/%	LS	74.48 ± 0.55 a	71.84 ± 1.00 a	63.15 ± 0.44 a	58.44 ± 1.30 a	52.95 ± 2.21 a	54.37 ± 1.72 a
	MS	70.47 ± 1.53 ab	67.11 ± 0.86 b	59.72 ± 0.97 a	56.50 ± 2.02 a	44.53 ± 1.39 b	54.58 ± 1.54 a
	HS	62.56 ± 3.93 b	62.21 ± 0.56 c	55.24 ± 1.46 b	53.87 ± 1.09 a	42.38 ± 3.15 b	49.58 ± 2.48 a

Note: The values in the table are the mean $\pm$ standard error and different letters in each column indicate significant difference ($p < 0.05$).

The total N concentration of the wheat roots, stems and leaves were significantly different among the three treatments ($p < 0.05$). Compared with those of LS treatment, the total N concentrations of the wheat roots, stems, leaves, sheaths, grains, and the whole wheat plant in HS and MS treatments significantly increased by 33.22~98.73% and 25.47~59.12%, respectively ($p < 0.05$). The total N concentrations of the wheat roots, stems, and leaves in HS treatment were higher than those of the corresponding wheat parts in MS treatment with 11.55%, 56.51% and 4.10% ($p < 0.05$). In the three saline soil treatments, the total N concentrations order of each wheat parts in the same soil treatment were obtained according with grain, sheath, leaf, root and stem. Therefore, compared with the other wheat parts, the total N concentrations in wheat grains were significantly highest. The increase of soil salinization increased the total N concentrations in all wheat parts, especially in the wheat root, stem, and leaf in the highest salinization soil to resist salt stress.

The ^{15}N uptake per unit area of the same wheat parts or the amounts of fertilizer nitrogen absorbed by the same wheat parts were different in different salinization soil treatments (Table 3). Compared with the ^{15}N uptakes per unit area of each wheat parts in LS treatment, the ^{15}N uptakes per unit area of the wheat roots, stems, leaves, sheaths, grains, and the whole plants in MS and HS treatment significantly decreased by 80.32% and 84.94%, 75.30% and 83.59%, 74.19% and 88.16%, 52.80% and 86.63%, 51.93% and 89.98%, and 55.82% and 89.03% ($p < 0.05$). In the three saline soil treatments, the ^{15}N uptake order of each wheat parts in the same soil treatment were all obtained according with grain,

sheath, leaf, stem, and root. The ^{15}N uptake of wheat grains was higher than that of other wheat parts by 3.72~111.00 times ($p < 0.05$). So, compared with the other wheat parts, the ^{15}N uptake of wheat grains were all significantly highest in the three saline soil treatments. With the aggravation of soil salinization, the amount of fertilizer nitrogen absorbed by each wheat part and the whole plant decreased significantly.

The distribution ratios of ^{15}N uptakes (the ratio of ^{15}N uptakes in each part of wheat to ^{15}N uptakes in whole wheat plant) in various wheat parts were different in different salinization soil treatments (Table 3). Although the distribution ratio of ^{15}N uptakes of the wheat leaf in LS treatment was significantly higher than that in MS treatment by 72.22%, those of the wheat roots, stems, sheaths, and grains in LS treatment were not significantly different between MS treatment and HS treatment ($p < 0.05$). The distribution ratios of ^{15}N uptakes in the wheat root, stem and leaf in HS treatment were significantly higher than those of the corresponding wheat part in MS treatment by 207.91%, 160.68% and 82.37% except for that of the wheat sheath between HS and MS. Meanwhile, that of wheat grain in HS treatment was significantly lower than that in MS treatment by 15.54% ($p < 0.05$). The order from high to low of the ^{15}N uptakes distribution ratios of various wheat parts in the same saline soil treatment was accordance with the grain, sheath, leaf, stem, and root. Hence, when the degree of soil salinization increased to HS level, the ^{15}N uptakes distribution ratio of the wheat root, stem, and leaf increased significantly. Meanwhile, there was no effect on the wheat sheath, but that in the wheat grain decreased significantly. The changes of soil salinization degree had no significant effects on the high and low order of the ^{15}N uptakes distribution ratio in each part of wheat plant.

The Ndffs of the same wheat parts in different saline soil treatments were different (Table 3). The wheat root Ndff of HS treatment was significantly higher than that of LS treatment, but the wheat root Ndff of MS treatment was not significantly different from those of LS treatment and HS treatment ($p < 0.05$). The Ndffs of wheat stem and leaf in HS treatment were significantly higher than those in MS and LS treatments, and the Ndffs of wheat stem of MS treatment was significantly higher than that of LS treatment except for the wheat leaf Ndff ($p < 0.05$). There were no significant differences of the Ndffs in wheat sheath and whole plant among LS, MS, and HS treatments and of the wheat grain Ndff between HS and MS, but the wheat grain Ndffs of HS and MS treatments was significantly higher than that of LS treatment ($p < 0.05$).

Compared with those of the corresponding wheat parts in LS treatment, the Ndffs of the wheat root, stem, leaf, and grain in HS treatment were significantly increased by 46.70%, 34.21%, 21.48%, and 22.46%, respectively ($p < 0.05$). Meanwhile, the trends of the Ndffs in various wheat parts of different saline soil treatments were opposite to those of Ndff. Above all, the Ndffs of each wheat parts in different saline soil treatments showed an upward trend with the increase of soil salinization degrees, except for the wheat sheath and the whole plant, indicating that the increase of soil salinization degree improved the more N absorption of wheat roots, stems, leaves, and grains from fertilizer source and not from soil source to depress salt stress.

3.3. ^{15}N Residues and Distribution in Each 20 cm Soil Layer in 0~100 cm Soil Profile

The soil ^{15}N residues in three different saline treatments decreased significantly with the increase of soil profile depth (Figure 1).

The ^{15}N residues in the 0~20 cm soil layer were higher than those in 20~100 cm soil profile by 0.20~317.08 times ($p < 0.05$). Compared with the upper layer (0~20 cm, 20~40 cm, 40~60 cm and 60~80 cm), the ^{15}N residues of the lower layer (20~40 cm, 40~60 cm, 60~80 cm and 80~100 cm) in the same treatment decreased by 16.68~74.16%, 26.43~95.91%, 0.92~74.81%, 13.19~56.73%, respectively ($p < 0.05$). The ^{15}N residues of the 0~20 cm soil layer were significantly different among LS, MS and HS treatments which decreased significantly with the increase of soil salinization.

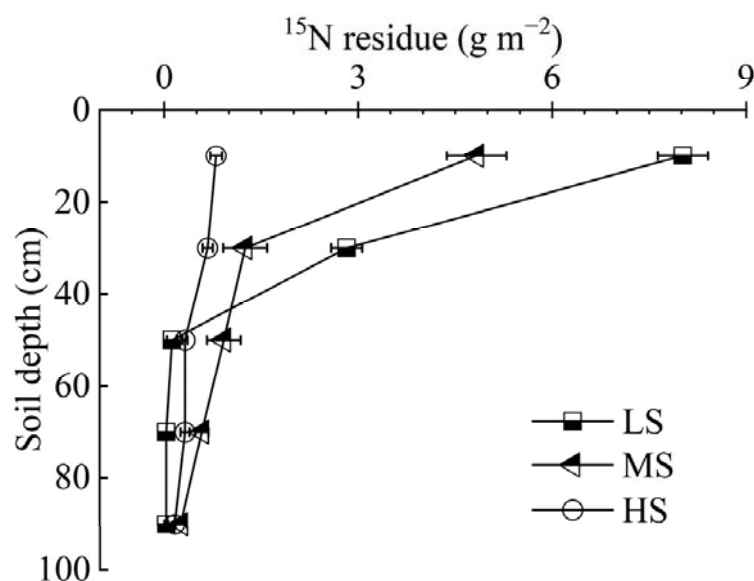


Figure 1. ¹⁵N residues in different depth soil layers of different treatments.

The ¹⁵N residues of 0~20 cm soil layer in MS and HS treatments were significantly lower than those in LS treatment by 39.73% and 90.01%, and the ¹⁵N residues of 0~20 cm soil layer in HS treatment were significantly lower than those in MS treatment by 83.42% ($p < 0.05$). The ¹⁵N residues of 20~40 cm soil layer had no significant difference between MS and HS treatments, but both treatments were significantly lower than LS treatment by 55.70% and 76.32% ($p < 0.05$). There was no significant difference in ¹⁵N residues of 40~60 cm soil layers between LS and HS treatments, and both treatments were significantly lower than those of MS treatment respectively by 87.45% and 65.03% ($p < 0.05$). The ¹⁵N residues of 60~80 cm soil layer in MS treatment were higher than those of LS and HS treatments with 1896.16% and 82.07%, and those in HS treatment were higher than those in LS treatment by 996.39% ($p < 0.05$). The ¹⁵N residues of the 80~100 cm soil layer in MS treatment were higher than those in LS treatment by 895.05% except for between both treatments and HS treatment ($p < 0.05$).

Compared with other corresponding treatments at different soil profile depths, the significantly highest ¹⁵N residues in 0~20 cm and 20~40 cm soil layers and in 40~60 cm and 60~80 cm soil layers were LS treatment and MS treatment respectively, but the ¹⁵N residues in 80~100 cm soil layers were not significantly different between HS and LS, and between HS and MS. The above showed that the ¹⁵N residues of different salinization degrees soil treatments mainly remained in 0~20 cm and 20~40 cm, which in other soil layers was significantly reduced. The soil salinization mainly affected the ¹⁵N residues in 0~20 cm and 20~40 cm. With the increase of soil salinization, the ¹⁵N residues in different soil layers also increased significantly with the increase of soil profile depth.

The ¹⁵N residue distribution ratios of 0~20 cm soil layer in three soil treatments with different salinization degrees were significantly higher than those of other soil layers and decreased with the increase of soil profile depth (Figure 2).

With the increase of soil salinization, the ¹⁵N residue distribution ratios in the upper soil layers of 0~100 cm soil profile decreased while those in the lower soil layers increased. However, the ¹⁵N residue distribution ratios in the 0~100 cm soil profile were mainly concentrated in the 0~20 cm soil layer of LS treatment with 72.82%, in the 0~40 cm soil layer of MS treatment with 77.69%, and in the 0~60 cm soil layer of HS treatment with 78.91%, respectively.

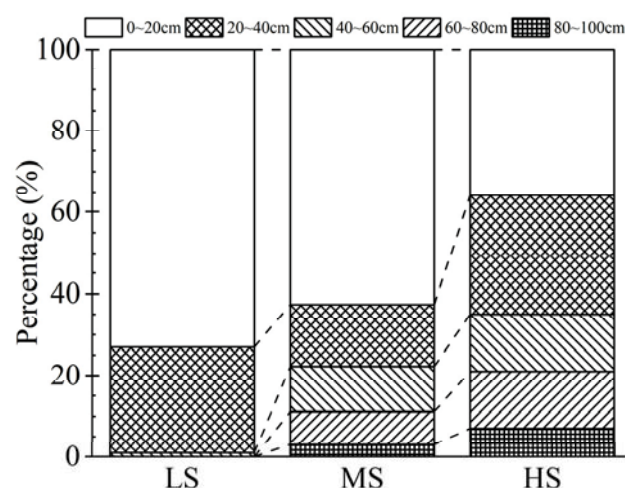


Figure 2. ¹⁵N residues distribution ratios in different depth soil layers of different treatments.

The ¹⁵N residue distribution ratio of 0~20 cm soil layer in LS treatment was significantly higher than those in MS and HS treatments respectively by 16.97% and 104.74%, and which in MS treatment was significantly higher than that of HS treatment by 75.04% ($p < 0.05$). The ¹⁵N residue distribution ratio of 20~40 cm soil layer in LS treatment was not significantly different from that in HS treatment, but those of both treatments were significantly higher than that in MS treatment respectively by 66.16% and 89.61% ($p < 0.05$). The ¹⁵N residue distribution ratios of the 40~60 cm soil layer in LS treatment were significantly lower than those in MS and HS treatment respectively by 90.63% and 92.46%, except for that between MS and HS treatment ($p < 0.05$). The ¹⁵N residue distribution ratios of 60~80 cm and 80~100 cm soil layers in LS treatment were significantly lower than those in MS and HS treatments respectively by 96.62% and 98.10%, 93.42% and 97.08%, and those in MS treatment were significantly lower than those in HS treatment respectively by 43.75%, 55.62% ($p < 0.05$). With the aggravation of soil salinization, the ¹⁵N residue distribution ratios of different soil layers in 0~100 cm soil profile increased significantly with the increase of soil profile depth.

The above showed that fertilizer N in saline soil mainly remained in the upper soil layers, such as the topsoil and subsurface layers. However, with the aggravation of soil salinization, the ratio of fertilizer N moving to the deeper soil layer in the 0~100 cm soil profile increased significantly, while the upper soil layer decreased correspondingly.

3.4. ¹⁵N Fate in Coastal Saline Soil-Wheat System

After wheat harvest in the field micro-zone, the fates of wheat uptake, soil residue, and system loss of fertilizer nitrogen (¹⁵N) applied to different saline soil-wheat systems were significantly different (Table 4).

Table 4. Balance of ¹⁵N fate in soil-wheat systems of different saline soils treatments.

Treatment	¹⁵ N Input (g m ⁻²)	Plant ¹⁵ N Uptake		Soil ¹⁵ N Residue		System ¹⁵ N Loss	
		Uptake (g m ⁻²)	Uptake Rate (%)	Residue (g m ⁻²)	Residual Rate (%)	Loss (g m ⁻²)	Loss Rate (%)
LS	22.60	3.15 ± 0.28 a	13.96 ± 1.22 a	11.00 ± 0.42 a	48.69 ± 47.15 a	8.44 ± 0.70 c	37.35 ± 3.08 c
MS	22.60	1.39 ± 0.12 b	6.17 ± 0.51 b	7.83 ± 0.98 b	34.65 ± 4.33 b	13.37 ± 1.04 b	59.19 ± 4.60 b
HS	22.60	0.35 ± 0.01 c	1.53 ± 0.04 c	2.27 ± 0.25 c	10.05 ± 1.11 c	19.98 ± 0.25 a	88.42 ± 1.09 a

Note: The values in the table are the mean ± standard error and different letters in each column indicate significant difference ($p < 0.05$).

The soil ¹⁵N residues and residual rates were significantly higher than the wheat ¹⁵N uptakes and uptake rates by 248.89%, the system ¹⁵N losses and loss rates by 30.38% in LS

treatment ($p < 0.05$). The system ^{15}N losses and loss rates in MS and HS treatments were significantly higher than the soil ^{15}N residues and residual rates of them respectively by 70.84% and 779.78%, and these in MS and HS treatments were significantly higher than wheat ^{15}N uptakes and uptake rates respectively by 8.60 and 56.73 times, 4.62 and 5.56 times ($p < 0.05$). Therefore, the wheat ^{15}N uptakes and uptake rates in the different saline soil-wheat systems were all significantly lower than the soil ^{15}N residues and residual rates and the system ^{15}N losses and loss rates. The soil ^{15}N residues and residual rates in lightly salinity soil were significantly higher than the system ^{15}N losses and loss rates. However, the trend was contrary in medium-salinity and heavy-salinity soils. The aggravation of soil salinization promoted the ^{15}N loss fate from the saline soil-wheat system.

The wheat ^{15}N uptakes or uptake rates, the soil ^{15}N residues or residual rates in HS treatment were significantly lower than those in LS and MS treatment respectively by 89.03% and 75.16%, 79.36% and 70.99%; and those in MS treatment were significantly lower than those in LS treatment respectively by 55.82%, 28.85% ($p < 0.05$). The system ^{15}N losses or loss rates in HS treatment were significantly higher than those in LS and MS treatment by 136.74% and 49.39%, and this in MS treatments were significantly higher than those in LS treatment by 58.48% ($p < 0.05$). The above showed that with the increase of soil salinization, the system ^{15}N losses and loss rates increased significantly, while the wheat ^{15}N uptakes and uptake rates, the soil ^{15}N residues, and residual rates decreased significantly. With higher degree of soil salinization, the fates of wheat ^{15}N uptake and soil ^{15}N residue were reduced, and the fate of ^{15}N loss was significantly promoted.

4. Discussion

The uptake and utilization of nitrogen was an important factor affecting wheats dry matter mass forming through photosynthesis [35]. Our results showed that the order of total N concentration in each part of wheat plant at maturity stage under different salinization degrees soil treatments from high to low was grains, sheaths, leaves, roots, and stems, which was consistent with the result in non-saline soil studied by Wang et al. [36–38]. Our research further found that the total N concentration of wheat roots was between that of leaves and stems, and the order of dry matter masses of wheat plants from high to low was basically as the same as that of total N concentration of wheat plants. Akhtar et al. and Bassil et al. found that the uptake of potassium by crops promoted the N uptake by crops through the joint application of nitrogen and potassium fertilizers [39,40]. Because saline soil has a greater ability to supply potassium, which is rich in available potassium, the total N concentration of each wheat part and the whole plant in our research increased significantly with the aggravation of soil salinization degree.

Our results showed that the dry matter mass accumulation of all wheat parts and the whole plant was inhibited with the fertilizer ^{15}N uptakes decreased. Soil salinity has adverse effects on crops through two processes: osmotic stress and ion toxicity. Osmotic stress delayed seeds germination, reduced seedling emergence rate and inhibited seedling growth. The high concentration of sodium ions in saline soil rhizosphere resulted in ion imbalance. Sodium and Chloride ions respectively competed with NH_4^+ and NO_3^- for crop uptake, inhibited leaves development and photosynthesis, affected the dry matter mass accumulation of crops, and reduced the number and weight of grains [41–45]. When the nitrogen supply of each plant part was limited due to insufficient nitrogen uptake of crops, the dry matter mass of grains might be reduced [46]. Wang et al. found that salt stress inhibited the transport of nitrogen nutrients from vegetative organs (roots and stems) to reproductive organs (grains and sheaths) of crops at maturity, resulting in a decrease of crop grain yield in saline soil [25], which was consistent with the results of our research that the fertilizer ^{15}N uptakes and its distribution ratios of wheat roots, stems and leaves increased and those of grains decreased in saline soil with aggravation of soil salinization.

Our results showed that the Ndff of wheat grains was 47.1–57.6%, so about half of the N uptake came from fertilizer ^{15}N . The Ndff of other wheat parts was 25.5–46.1%, and the wheat ^{15}N uptake mainly came from soil nitrogen. Davis et al. found that the ratio

of fertilizer nitrogen absorbed by crops in the current season was only about 20% in the field crop nitrogen balance experiment [47], and the results of crops preferring to absorb soil nitrogen rather than fertilizer nitrogen were consistent with that of wheat parts except grains in our study. Our study also found that with the aggravation of soil salinization, the ratio of total nitrogen from fertilizer nitrogen in each wheat part increased, while the ratio from soil nitrogen in each wheat part decreased.

Previous studies on the fertilizer nitrogen residue distribution in soil profile showed that the residual rate in different soil layers was inversely proportional to the depth of the soil layer, and the residue of fertilizer nitrogen was mainly concentrated in 0~20 cm soil layer [22], which was consistent with our results. Our study also found that the aggravation of salinization significantly reduced the residues of fertilizer nitrogen in 0~100 cm soil profile and promoted the migration of fertilizer nitrogen to deeper soil layer, which might be one of the reasons for the reduction of fertilizer nitrogen residue in the heavy-salinity soil. Miller et al. had found that the nitrogen accumulation in the soil layer below 20 cm was related to the soil texture [48]. The higher the soil salinity was, the heavier the soil texture was, and the more soil cracks easily resulted in fertilizer nitrogen leaching into the deep soil layer with water [26], which illustrated the results of our study that the fertilizer nitrogen increased significantly with the increase of soil profile depth with the aggravation of soil salinization.

Fertilizer nitrogen applied to saline soil has three main destinations: plant uptake, soil residue, and nitrogen loss in various ways, such as ammonia volatilization, nitrification denitrification, surface runoff, and leaching. Through the study on the fates of fertilizer nitrogen in the saline soil-wheat system, our results found that the current season wheat plants uptake rate of fertilizer nitrogen was only 1.53~13.96% of saline soil in the Yellow River Delta, which was far lower than the average utilization rate of wheat nitrogen in China of 28.2% and the global utilization rate of wheat nitrogen of 30~50% [49]. Our research also found that the utilization of fertilizer nitrogen in the current wheat season was far lower than soil residue and system loss of fertilizer nitrogen, and the aggravation of soil salinization reduced the uptake and residue of fertilizer nitrogen and increase its loss. The above results were because denitrification of nitrogen, volatilization of ammonia, and intensified leaching and migration were the main reasons for less residue and higher loss of fertilizer nitrogen in saline soil [50], and N₂O emission and ammonia volatilization were significantly increased after nitrogen application in saline soils with the aggravation of soil salinity [51].

Therefore, the characteristic of the conventional nitrogen fertilizer application method in the coastal saline soil of the Yellow River Delta was higher nitrogen loss and lower crop uptake and soil residue, which resulted in insufficient nitrogen nutrition for regional crop growth and high yield. Hence, it is recommended to scientifically improve the nitrogen fertilizer application method and strengthen nitrogen management in the coastal saline soil area, so as to reduce fertilizer nitrogen loss, increase crop uptake and soil residue, improve soil nitrogen fertility and crop yield, and achieve high efficiency, high yield, and sustainable development in the coastal saline soil region. Whereas the grades of different soil salinization degrees in our study were relatively less, the fates of fertilizer nitrogen of more soil salinization grades should be deeply studied in order to establish the optimal mode of the utilization and management of fertilizer nitrogen in the coastal saline soil-wheat system in the Yellow River Delta.

5. Conclusions

Under the coastal saline soil conditions in the Yellow River Delta, the aggravation of soil salinity from 0.2% to 1% significantly inhibited the dry matter masses accumulation and the ¹⁵N uptakes of various wheat parts and whole plant but promoted the total N concentrations of various wheat parts, especially in wheat roots, stems, and leaves parts absorbed from soil. The dry matter masses and total N concentrations of wheat grains in saline soil were significantly higher than those in other wheat parts. The aggravation of soil

salinity significantly increased the ^{15}N distribution ratios of wheat roots, stems, and leaves, but decreased that of wheat grains, and significantly increased the Ndfs of wheat roots, stems, leaves, and grains, but had no significant effects on the order from high to low of ^{15}N distribution ratios in various wheat parts. The fates of ^{15}N applied in the coastal saline soil-wheat system were wheat uptake 1.53~13.96%, soil residue 10.05~48.69%, and ^{15}N loss 37.35~88.42%. Compared the lighter salinity soil, the heavier salinity soil reduced the ^{15}N fate of wheat uptakes and soil residues by 89.03% and 79.36%, but significantly increased the ^{15}N fate of losses by 136.74% in the coastal saline soil-wheat system. Therefore, the conventional nitrogen management of the coastal saline soil in the Yellow River Delta should be optimized to reduce the nitrogen loss and to improve the productivity of the soil-wheat system to ensure food security.

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Article

Regulation of Abiotic Factors on Aboveground Biomass and Biodiversity of Ditch Slope in Coastal Farmland

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Abstract: Ditch plant biomass and diversity play an important role in maintaining ditch ecosystem structure and function stability, which are subject to environmental changes. However, the regulation of abiotic factors on the aboveground biomass and diversity of plants on the slopes of coastal agricultural ditches remains unclear. In this study, the spatial distribution of soil physicochemical properties, aboveground biomass, and diversity of vegetation on different slope positions (upper slope, middle slope, and lower slope) and slope aspects (north-south direction) of farmland drainage ditches and their correlations were investigated through field surveys of vegetation on the slopes of coastal farmland drainage ditches at different sampling sites. First, water content and bulk density) decreased with the increase of slope position, while the salinity showed the opposite spatial distribution characteristics and the distribution of soil nutrients in space was mainly concentrated in the 0–20 cm soil layer. Second, the aboveground biomass of vegetation was significantly higher on the south slope than on the north slope, with the highest biomass at the lower slope on the south slope and higher aboveground biomass on the north slope at the upper and middle slopes. The Shannon-Wiener index, Pielou index, and Margalef index of ditch slope vegetation in Dongying and Binzhou farmland ditch slopes showed the same pattern of change at different slope positions and directions, which were significantly higher at the upper and middle slopes than at the lower slopes. In contrast, the Simpson index showed the opposite pattern, decreasing with the increase in slope position. Further, WC, BD, organic matter content, and total nitrogen content had positive effects on vegetation aboveground biomass, while soil pH, salinity, and available potassium content hindered vegetation growth. Finally, the Shannon-Wiener index and Pielou index were positively correlated with soil BD and available phosphorus content, and negatively correlated with organic matter and total nitrogen content, while the Simpson index was positively correlated with soil BD and WC, and had a significant negative correlation with soil salinity.

Keywords: ditch slopes; aboveground biomass; plant diversity; spatial distribution

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1. Introduction

The Yellow River Delta is one of the nascent terrestrial ecosystems in China and is also the most active area of sea-land change. Subject to seawater erosion, the soils there have been accumulating salts on the surface, resulting in the gradual development of coastal saline soils under the influence of rainwater and microorganisms [1]. The salinization, poor permeability, and low nutrient content of agricultural soils in the Delta are not conducive to agricultural production [2]. The agricultural drainage ditch is an important engineering measure for saline soil improvement, which regulates the distribution of water and salt in agricultural fields through irrigation and then discharges through a drainage

ditch, thus reducing the salinity of coastal agricultural fields and improving their farming conditions [3]. As a marginal part of the farmland ecosystem, farm drains carry salts, nutrients, and residual pesticides from the farmland with varying degrees of adsorption, forming a unique ecological landscape. Meanwhile, the slope vegetation of the drainage ditch can prolong the residence time of agricultural drainage in the ditch, and improve the desalination rate of the soil surface layer in the ditch and the purification rate of the drainage. Moreover, rich vegetation can also increase the content of soil organic matter, total nitrogen, and other nutrients, with a positive impact on the improvement of the soil [4].

The aboveground biomass and diversity of plants are important evaluation indicators for the composition and function of plant communities [5]. As the total aboveground organic matter accumulation of an organism or community in a certain period of time, aboveground biomass is usually used to evaluate vegetation community productivity and population function. Species diversity not only describes the abundance, degree of variation, and evenness of species in a community or habitat, but also reflects the interrelationship between different physical geographic conditions and communities [6]. The influencing factors of vegetation aboveground biomass and diversity are very complex. Various factors such as site conditions, environmental factors, disturbance characteristics, restoration degree, isolation degree, etc., may have an impact on species biomass and diversity. Environmental factors are usually considered to affect the growth of vegetation, and research on the effect of environmental factors has been a research hotspot, attracting the attention of ecologists [7]. Liu et al. [8] studied the influence of elevation-induced hydrothermal conditions and the spatial distribution of their combinations on vegetation structure, and found a positive correlation between elevation and vegetation diversity index and Margalef index. Yang et al. [9] found that vegetation diversity increased with the increase of restoration degree by analyzing the diversity characteristics of vegetation in different restoration stages of rocky slopes. Sewerniak et al. [10] deemed soil fertility as the most critical environmental factor affecting vegetation richness by analyzing the influence of topography-induced microclimate and soil conditions on vegetation diversity in Scottish pine woodlands. Xiao et al. [11] argued that environmental factors exerted an important influence on vegetation diversity.

Soil is the material basis for the occurrence and development of plant communities, with critical effects on plant community composition, community diversity, and biomass size [12]. Studies on the characteristics of plant community species diversity with different soil factors can reveal the interrelationship between biodiversity and soil factors, which has been a key area in ecological research [13]. Previous studies have mostly focused on grassland communities [5,14], forest communities [15], degraded sandy grasslands, roadside slopes, but less research has been conducted on saline drainage ditches. Therefore, the typical agricultural drainage ditches in the Yellow River Delta were selected as the research object in this study to investigate the spatial distribution characteristics of soil physicochemical properties, aboveground biomass, and diversity of vegetation in different slope positions (upper slope, middle slope, and lower slope) and slope aspects (north-south direction) of the ditch slopes. Because the elevation of the two sampling sites in the study area did not vary much and the climatic environment of the sites was similar, the influence of climatic factors such as temperature and precipitation on the aboveground biomass and diversity of vegetation was relatively small. In this paper, the vegetation index changes caused by soil factors were analyzed to explore the regulation of vegetation biomass and diversity on slopes by soil factors in coastal wetlands, which is expected to provide basic data and a theoretical basis for ecological restoration of saline soil on drainage ditch slopes.

2. Study Area Overview and Methodology

2.1. Study Area Overview

Bohai Farm, Lijin County, Dongying City, Shandong Province, and Huanghedao Island, Wudi County, Binzhou City, Shandong Province were selected as sample sites. The location and climatic conditions of sampling points are shown in Figure 1.

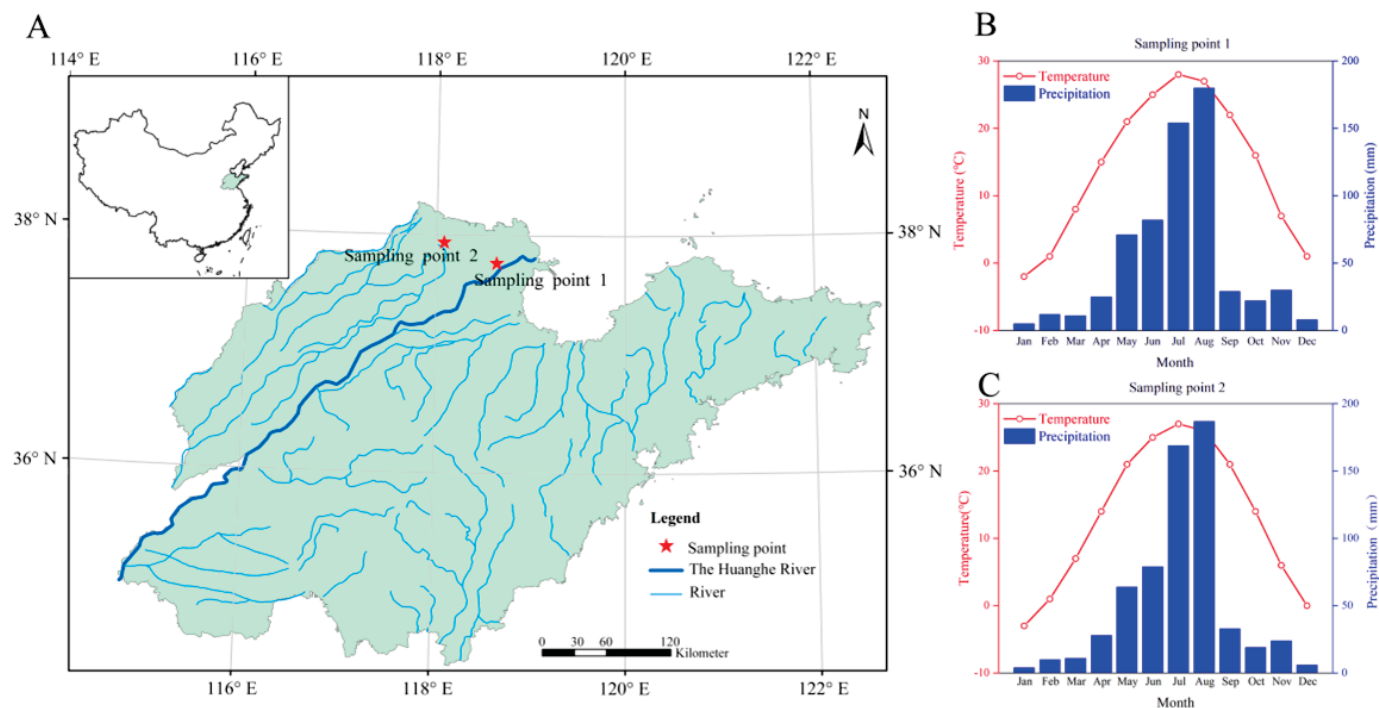


Figure 1. Sampling location and climate in 2020. Note: (A) is the location of the two sampling sites; (B) is the monthly average precipitation and temperature of sampling site 1 in 2020; (C) is the monthly average precipitation and temperature of sampling site 2 in 2020.

Lijin County is located in the northeastern part of Shandong Province, on the southwestern coast of the Bohai Sea, and on the left side of the near-mouth section of the Yellow River. The terrain of the whole territory slopes to the northeast; high in the southwest, low in the northeast, high near the Yellow River, and low at the far Yellow River. Given the frequent breach of the Yellow River, the area is subject to repeated punching by both flooding and sedimentation, thus forming a complex micro-land with interlocking hills, slopes, and depressions [16]. The average annual temperature is 14.2 °C, and the average precipitation is about 634.4 mm. It belongs to the continental monsoon region. The soil texture is mainly silting loam, a coastal saline Chao soil, and the farmland is a typical saline soil farmland [16]. Bohai Farm has formed a complete irrigation and drainage system after years of development, mainly planting corn, rice, and cotton. The self-sow herbaceous plants mainly include suaedasalsa (*Suaeda glauca* Bunge), reeds (*Phragmites australis*), *Miscanthus sacchariflorus* (*Triarrhena sacchariflora* Nakai), and cogon grass (*Imperata cylindrica* Beauv) [17,18].

Huanghedao Island, located in the transitional zone between the coastal plain and coastal mudflats, is the alluvial plain formed by the ancient Yellow River. Under the influence of river siltation and sea tide overflow, the area has formed a strip-like terrain surrounded by water on all sides, with a north-south direction and high and low. The soil is mainly silt loam, a typical coastal solonchak and coastal saline Chao soil with serious soil salinization. The annual average temperature is 13.6 °C, and the average rainfall is about 600 mm, a continental monsoon climate. The island has a wide variety of wildlife and plants, and self-sow vegetation mainly includes reeds (*Phragmites australis*), *Tamarix* (*Tamarix chinensis* Lour), *Pyrus betulaefolia*, and *Suaeda glauca* Bunge, etc.

2.2. Sampling Design

A total of nine east-west aligned bucket ditches with typical vegetation were selected at each of the two sampling sites, with an average length of 1.7 km, an average depth of 2.0 m, a bottom width of 1.5 m, an upper width of 9.5 m, and a slope of 2:1. The north slope of the ditches faced the sun and had denser vegetation than the south slope. The bottom of the ditch was waterlogged all year round and covered by tall reeds with a coverage of 85%, and the vegetation diversity was higher on the middle and upper slopes, mainly growing with *Suaeda salsa* (*Suaedaphysophora*), *artemisia annua* (*Artemisia annua* L.), *Apocynumvenetum* (*Apocynumvenetum* L.), and *chenopodium glaucum* (*Chenopodium glaucum* L.).

Field surveys and sampling were conducted in July 2020 (peak growth period), when the biomass in the ditch was at its maximum. The ditch was divided into three equal parts from the top down to the bottom of the ditch, marked as upper slope, middle slope, and lower slope; the ditch profile is shown in Figure 2A. An amount of 3 sample plots were selected as replicates (with an interval of 20 m) at the same slope position and slope aspect, and 18 sample plots were taken for each ditch, with 108 sample plots for 6 ditches slope sampling, as shown in Figure 2B. For good sample collection and vegetation survey, a random sample plot with the size of 1 m × 1 m was established. Four inflection points in the sample plot were marked with eye-catching markers. The names and basic traits of all plants in the sample plots: species composition, cover, height, abundance, and aboveground biomass, were measured as follows.

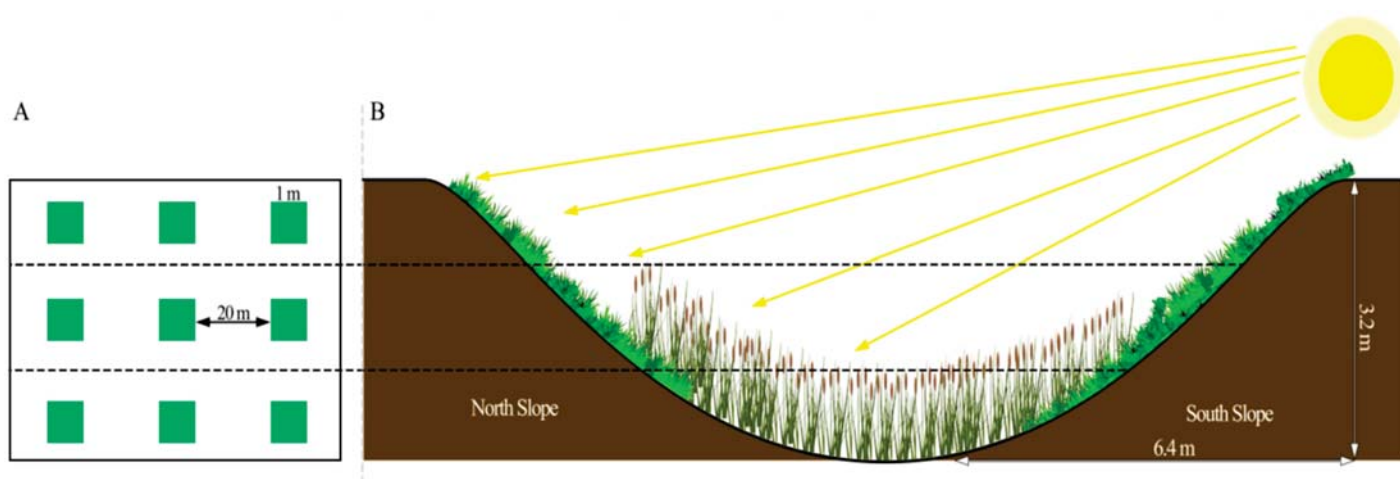


Figure 2. Schematic diagram of ditch section and slope sampling location. Note: (A) is the distribution of sampling points on the slope, (B) is the profile of the trench.

Height: Expressed as the average height of 10 random individuals.

Coverage: Expressed as the projected area on the ground of all individuals in the quadrant.

Abundance: Expressed as the average number of clumps of a species in the quadrant.

Aboveground biomass: The above-ground parts of the plants in 1 m² were completely mowed and then killed at 105 °C for 30 min and dried to constant weight.

After harvesting the aboveground plants, soil samples from 0–20 cm and 20–40 cm soil layers were taken in self-sealing bags with an earth-boring auger in each quadrant, providing 216 bags in total, which were brought back to the laboratory, dried naturally in a place protected from light, the plant roots, residues, and gravels were removed, along with other debris from the soil, and were then sieved through 100 mesh for later use.

2.3. Determination of Soil Properties and Species Diversity

Soil indicators were determined according to the method of Yang et al., as follows: soil bulk density was determined with the cutting ring method; soil salt content and water

content were determined with the oven drying method; bulk density was the ratio of water in the soil to the total weight of the soil; the soil-water suspension was prepared at a 5:1 (*v/w*) water-to-soil ratio and soil pH was determined by a pH meter (PHS-3C, Shanghai INESA Scientific Instruments Co., Ltd., Shanghai, China); soil organic matter content was determined by concentrated sulfuric acid-potassium dichromate oxidation-outer heating; total nitrogen content was determined by Kjeldahl apparatus (KDN-9820, Wuxi Chemical Equipment Co., Ltd., Wuxi, China) after the addition of boiled soil by concentrated sulfuric acid; available phosphorus content was extracted with 0.5 mol/L NaHCO₃ solutions, and then colorimetry was conducted with spectrophotometer; and available potassium content was extracted with 1 mol/L NH₄OAc solution, and then measured with a flame photometer (FP6430, Shanghai INESA Scientific Instruments Co., Ltd., Shanghai, China).

In this study, the importance values of the plant species were used as the basis for species diversity calculation. The importance value reflects the comprehensive quantitative index of the role and status of a species in the forest community, and is critical in determining the dominant species and constructive species, identifying the community type, and investigating the structure and function of ecological communities [19]. Different scholars have different approaches to calculating importance values, mainly differing in the combinations of relative density, relative dominance, relative height, relative coverage, and relative frequency. Because the number of individuals of species in the scrub and herbaceous layers is difficult to count compared to the tree layer, and Cr (relative coverage) and Hr (relative height) are the most readily available data in field surveys, relative height and relative cover are often used to calculate importance values for the shrub and herbaceous layers. In this study, the formula $Iv = (Hr + Cr)/2$ was used to calculate the importance value of each species. Four categories of species diversity measures were chosen: diversity index (Shannon-Wiener index), evenness index (Pielou index), richness index (Margalef index), and ecological dominance index (Simpson index); calculated as follows [14]:

Shannon-Wiener index (H):

$$H = \sum_{i=1}^S P_i \ln P_i \quad (1)$$

Pielou index (E):

$$E = H / \ln S \quad (2)$$

Margalef index (M):

$$M = (S - 1) / \ln S \quad (3)$$

Simpson index (C):

$$C = \sum_{i=1}^S (P_i)^2 \quad (4)$$

where H is the species Shannon-Wiener index, P_i is the dominance of the species in the sample plot, and S is the number of species in the sample plot.

2.4. Data Processing

The data were statistically sorted using Microsoft Excel and then processed and analyzed with SPSS to explore the correlations between vegetation biomass, species diversity, and soil factors. PCA analysis was performed and the correlation diagram was plotted using Origin 2019b (Origin Lab, Northampton, MA, USA). Finally, an SEM model was constructed using AMOS 22.0 to explain the effects of soil characteristics on plant biomass and vegetation diversity.

3. Results

3.1. Spatial Distribution Characteristics of Soil Physical and Chemical Properties

As can be seen in Table 1, the bulk density and pH of soil in the two slopes of sampling site 1 in the south and north were not significantly different in different soil depths, with the highest BD value found in the 20–40 cm soil layer in the lower slope of 1.56 g/cm³ and

1.52 g/cm³, respectively. The variation pattern of soil pH at different slope levels in both slope aspects was: lower slope position > middle slope position > upper slope position. Soil salt showed a pattern of upper slope position > middle slope position > lower slope position in both slope aspects, where the upper slope of the north slope showed significant surface aggregation with 4.03 g/kg in the 0–20 cm soil layer, 30% higher than that in the 20–40 cm soil layer, while the upper and middle slopes of the south slope both showed different degrees of surface aggregation with 4.14 g/kg and 2.7 g/kg, respectively. There was no significant difference in the total salt content of the soil at different soil depths on the other slope positions. The soil water content in both slopes showed a pattern of upper slope position > middle slope position > lower slope position, and the soil contents in the 0–20 cm soil layer were higher than those in the 20–40 cm soil layer in different slopes. The soil organic matter, total nitrogen, available phosphorus, and available potassium contents of soils on the north slope all exhibited the surface aggregation phenomenon, and the phenomenon in the 0–20 cm soil layer was significantly higher than that in the 20–40 cm soil layer. The contents of organic matter, total nitrogen, and available phosphorus did not significantly differ among the same soil layers at different slope positions, while the available potassium content showed a pattern of upper slope position > middle slope position > lower slope position. The organic matter content of the soil in the 0–20 cm soil layer on the lower slope position of the south slope was significantly higher than that in the 20–40 cm soil layer, while the differences in organic matter content between other slopes and soil layers were not significant. The total nitrogen and available phosphorus content were both highest in the 0–20 cm soil layer on the south slope, with 0.6 g/kg and 6.36 mg/kg, respectively.

Table 1. Spatial distribution characteristics of soil physical and chemical properties.

Sampling Point	Slope Direction	Slope Position	Soil Depth cm	Bulk Density g/cm ³	pH	Total Salt Content g/kg	Water Content %	Soil Organic Matter Content g/kg	Total Nitrogen Content g/kg	Available Phosphorus Content mg/kg	Available Potassium Content mg/kg
Sampling point 1	North	Upper	0–20	1.50 ± 0.03 b	8.17 ± 0.11 bc	4.03 ± 0.42 a	17.97 ± 2.42 c	7.09 ± 0.88 a	0.57 ± 0.08 a	4.29 ± 0.38 a	185.67 ± 19.45 a
			20–40	1.52 ± 0.05 ab	8.11 ± 0.10 c	3.12 ± 0.43 b	22.71 ± 3.08 b	4.61 ± 0.64 b	0.35 ± 0.04 b	2.58 ± 0.25 c	99.67 ± 9.24 cd
		Middle	0–20	1.51 ± 0.05 ab	8.13 ± 0.11 bc	2.71 ± 0.36 bc	23.87 ± 2.36 b	6.41 ± 0.68 a	0.55 ± 0.07 a	4.09 ± 0.49 a	138.33 ± 18.47 b
	South	Upper	0–20	1.54 ± 0.05 ab	8.29 ± 0.17 ab	2.25 ± 0.27 d	30.74 ± 3.03 a	6.33 ± 0.73 a	0.52 ± 0.05 a	3.23 ± 0.32 b	110.78 ± 9.48 c
			20–40	1.56 ± 0.03 a	8.35 ± 0.19 a	1.95 ± 0.25 d	30.95 ± 2.91 a	3.96 ± 0.47 b	0.29 ± 0.04 b	2.81 ± 0.33 bc	65.33 ± 6.94 e
		Middle	0–20	1.46 ± 0.03 b	8.15 ± 0.17 b	4.14 ± 0.34 a	21.60 ± 2.55 c	4.57 ± 0.63 b	0.45 ± 0.06 b	4.29 ± 0.42 b	139.56 ± 16.99 a
Sampling point 2	North	Upper	0–20	1.48 ± 0.03 ab	8.14 ± 0.14 b	3.97 ± 0.47 a	22.60 ± 2.22 c	4.41 ± 0.57 b	0.29 ± 0.03 c	1.79 ± 0.21 d	88.44 ± 8.18 c
			20–40	1.47 ± 0.03 b	8.28 ± 0.13 ab	2.72 ± 0.38 b	26.95 ± 2.45 b	5.58 ± 1.10 b	0.49 ± 0.06 b	2.81 ± 0.30 c	135.44 ± 12.72 a
		Middle	0–20	1.50 ± 0.03 ab	8.26 ± 0.13 ab	2.10 ± 0.25 c	27.38 ± 3.81 b	4.51 ± 0.44 b	0.35 ± 0.03 c	1.85 ± 0.21 d	94.11 ± 11.60 c
			20–40	1.49 ± 0.04 ab	8.34 ± 0.09 a	2.16 ± 0.28 c	30.48 ± 2.59 ab	7.20 ± 0.86 a	0.60 ± 0.08 a	6.36 ± 0.59 a	120.11 ± 8.69 b
		Bottom	0–20	1.52 ± 0.03 a	8.37 ± 0.11 a	2.08 ± 0.26 c	32.36 ± 3.29 a	5.30 ± 0.65 b	0.31 ± 0.03 c	2.89 ± 0.32 c	81.44 ± 7.57 c
			20–40	1.50 ± 0.06 a	8.65 ± 0.40 a	5.64 ± 0.57 a	9.89 ± 1.30 d	6.88 ± 0.78 a	0.54 ± 0.06 a	8.41 ± 1.16 b	599.33 ± 58.88 a
	South	Upper	0–20	1.52 ± 0.03 a	8.54 ± 0.24 a	5.44 ± 0.44 ab	15.51 ± 1.74 c	5.10 ± 0.48 b	0.31 ± 0.04 c	3.75 ± 0.51 e	517.00 ± 51.67 bc
			20–40	1.49 ± 0.02 a	8.51 ± 0.17 a	5.73 ± 0.52 a	16.81 ± 2.21 c	4.89 ± 0.46 b	0.34 ± 0.04 c	9.45 ± 1.03 a	470.78 ± 63.89 a
		Middle	0–20	1.53 ± 0.06 a	8.56 ± 0.20 a	4.85 ± 0.30 bc	19.81 ± 2.34 bc	2.18 ± 0.29 b	0.31 ± 0.03 c	4.78 ± 0.47 d	380.89 ± 41.05 d
			20–40	1.52 ± 0.03 a	8.55 ± 0.32 a	5.79 ± 0.44 a	17.26 ± 2.37 b	5.07 ± 0.51 b	0.40 ± 0.05 b	8.40 ± 0.27 b	594.78 ± 63.36 a
		Bottom	0–20	1.54 ± 0.02 a	8.53 ± 0.22 a	4.60 ± 0.57 d	23.38 ± 1.91 a	4.88 ± 0.51 c	0.31 ± 0.04 c	6.62 ± 0.64 c	557.78 ± 67.88 ab
			20–40	1.40 ± 0.05 d	8.75 ± 0.50 a	5.75 ± 0.77 a	9.76 ± 1.09 d	6.75 ± 0.61 b	0.45 ± 0.05 b	6.36 ± 0.50 b	491.33 ± 34.79 ab
Sampling point 2	North	Upper	0–20	1.45 ± 0.06 cd	8.64 ± 0.35 a	5.02 ± 0.63 b	13.49 ± 1.36 cd	4.66 ± 0.43 c	0.29 ± 0.03 c	4.39 ± 0.42 c	479.50 ± 51.30 abc
			20–40	1.46 ± 0.05 c	8.55 ± 0.36 a	5.72 ± 0.54 a	12.07 ± 1.62 c	9.12 ± 1.07 a	0.54 ± 0.06 a	4.45 ± 0.33 c	520.89 ± 58.34 a
		Middle	0–20	1.49 ± 0.03 bc	8.55 ± 0.36 a	4.52 ± 0.15 bc	18.30 ± 1.78 b	3.13 ± 0.39 d	0.25 ± 0.03 c	3.66 ± 0.34 c	459.44 ± 39.15 bc
	South	Upper	0–20	1.53 ± 0.03 ab	8.35 ± 0.36 a	3.65 ± 0.49 d	22.59 ± 2.70 a	3.76 ± 0.53 d	0.26 ± 0.03 c	9.69 ± 1.26 a	440.00 ± 41.15 bc
			20–40	1.55 ± 0.03 a	8.45 ± 0.40 a	3.97 ± 0.27 cd	22.73 ± 2.64 a	3.56 ± 0.47 d	0.25 ± 0.03 c	5.78 ± 0.70 b	431.00 ± 52.93 c

Note: Data in the table are mean ± standard deviation, and same lowercase letter indicates no significant difference between soil factors with different slope direction, slope position, and soil depth ($p < 0.05$).

As can be seen in Table 1, bulk density and pH at sampling site 2 on both south and north slopes were not significantly different in different soil layers on the same slope, and soil water content on different slopes showed the pattern of upper slope < middle slope < lower slope, with the soil water content in the 20–40 cm soil layer higher than that in the 0–20 cm soil layer. The soil organic matter content of the 0–20 cm soil layer on the north slope was the highest at 6.88 g/kg, significantly higher than that of the other slopes. The soil organic matter content of the 20–40 cm soil layer on the lower slope was the lowest at 4.88 g/kg, and the difference between the other slope layers was not significant. The highest

soil organic matter content of 9.12 g/kg was found in the 0–20 cm soil layer on the south slope at the mid-slope, and the lowest organic matter content of 4.66 g/kg was found in the 20–40 cm soil layer on the upper slope. Total nitrogen content showed 0–20 cm > 20–40 cm on the upper and lower slopes of the northern slope, with no significant differences between different soil layers on the middle slope, while its content showed 0–20 cm > 20–40 cm on the upper and middle slopes of the southern slope, with no significant differences between different soil layers on the lower slope. The content of available phosphorus on the north slope showed a pattern of middle slope position > lower slope position > upper slope position, with the highest value of 9.45 mg/kg in the 0–20 cm soil layer of the middle slope position and the lowest value of 3.75 mg/kg in the 20–40 cm soil layer of the upper slope position. The content of available phosphorus in the south slope showed a pattern of lower slope position > upper slope position > middle slope position, in which the content in the 0–20 cm soil layer in the upper and lower slope positions was significantly higher than that in the 20–40 cm soil layer, and the difference between different soil layers in the middle slope was not significant. The content of available potassium showed a pattern of 0–20 cm > 20–40 cm on different slope aspects and slope positions, lower slope position > upper slope position > middle slope position on the north slope, and middle slope position > upper slope position > lower slope position on the south slope. As can be seen in Figure 3, soil physicochemical properties greatly varied on different slopes of the ditch, and nutrient mineralization also greatly varied between slope aspects under the influence of physical factors, such as soil temperature and soil moisture.

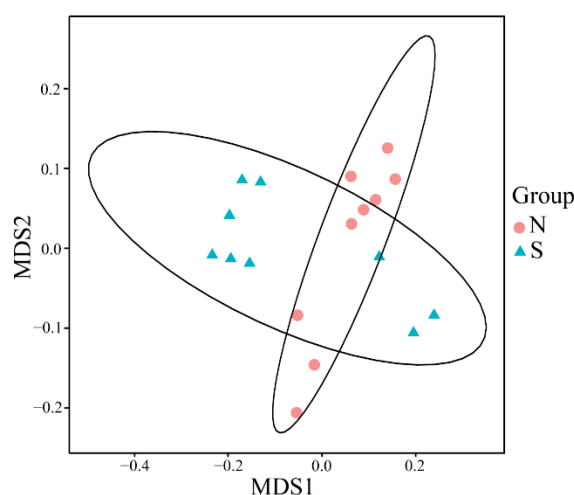


Figure 3. NMDS ranking of soil indicators. Note: N is the north slope of the ditch, S is the south slope of the ditch. The blue triangles and red squares represent the differences in soil physicochemical properties between the south and north slopes in the nine sampling sites (in this study, nine ditches were selected for sampling in two sampling sites).

3.2. Spatial Distribution Characteristics of Vegetation Biomass and Diversity

The analysis of the aboveground biomass of vegetation on the slope at different positions and aspects (Figure 4) revealed that the average aboveground vegetation biomass at site 1 was significantly higher than that at site 2, with the average vegetation biomass on the southern slope of the two sites, 0.70 kg/m², substantially higher than the northern one. At site 1, the north slope with the order of middle slope position > upper slope position > lower slope position witnessed the mid-slope displaying 1.36 kg/m² aboveground biomass on average; unquestionably higher than the other two. The average aboveground biomass on the south slope represented the highest in the lower slope position, followed by the upper slope position, and with that in the middle slope being the lowest. At site 2, the distribution of different slope positions on the north slope turned into the upper slope position > lower slope position > middle slope position, while the vegetation biomass of

the lower slope position on the south slope was 0.53 kg/m^2 ; significantly higher than that of the upper and middle counterparts.

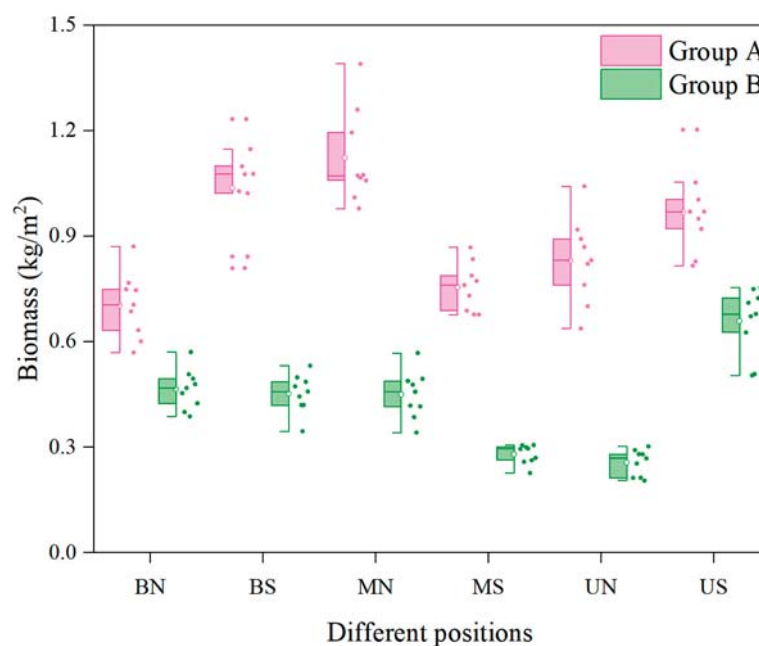


Figure 4. Spatial distribution of biomass on the ground of vegetation on ditch slope. Note: The four lines on the left of each graph are the maximum, upper quartile, median, lower quartile, and minimum values from top to bottom, with the circle being the mean, and the values of the nine sampling points on the right. BN—lower position of the north slope, BS—the lower position of the south slope, MN—the middle position of the north slope, MS—middle position of the south slope, UN—upper position of the north slope, US—lower position of the south slope. Group A is Dongying, northeastern Shandong Province, China; Group B is Binzhou, northern Shandong Province, China.

As can be observed in Figure 5, the species diversity exhibited distinct changes in different aspects and positions, with the same laws discovered on the indexes of species diversity, Margalef, and Pielou of the two sites: the upper position on the south slope was significantly higher than other slope positions with the middle on the north greater than other counterparts. The indexes of species diversity, Margalef, and Pielou showed upper slope position > lower slope position > middle slope position at the south slope of site 1 with middle slope position > upper slope position > lower slope position on the north. They surfaced upper slope position > middle slope position > lower slope position, with middle slope position > lower slope position > upper slope position on the north. The Simpson index saw the uniform law on the two site slopes: the lower slope position, the highest on the southern slope, swelled with the slope position climbing with lower slope position > upper slope position > middle slope position on the north.

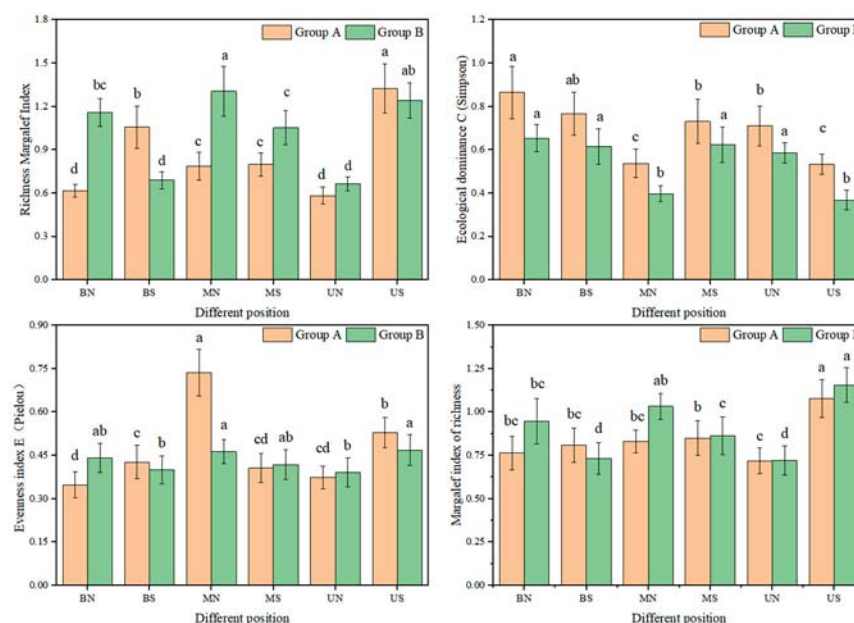


Figure 5. Spatial distribution characteristics of vegetation diversity on ditch slope. Note: BN—lower position of the north slope, BS—the lower position of the south slope, MN—the middle position of the north slope, MS—middle position of the south slope, UN—upper position of the north slope, US—lower position of the south slope. Group A is Dongying, northeastern Shandong Province, China; Group B is Binzhou, northern Shandong Province, China. Same lowercase letter indicates no significant difference between soil factors with different slope direction and slope position ($p < 0.05$).

3.3. Correlation Analysis of Plant Diversity and Soil Properties

The accumulation and consumption of nutrients by plants on the slopes of coastal wetlands is a dynamic process. The close correlation between plant species diversity and soil properties indicates more than a simple and direct relationship. More importantly, species diversity could be affected through the integration of various soil characteristic factors, and therefore, both single- and multi-factor analyses are required for various influencing factors of soil. Principal component analysis (PCA) was performed on the 12 variables reflecting the soil characteristics of lateral ditches in the coastal wetland to determine the correlation between the variables and the aboveground vegetation biomass and diversity. The results are shown in Figure 5. The PC1 axis mainly reflected the soil chemical properties accounting for 37.3% of the overall change in the standard soil variables, with the PC2 axis mainly reflecting the soil physical properties, explaining 18.1% of the standard deviation. The cumulative variance contribution rate of the two was 55.4%, a primary mirror of the variation information of the soil characteristic factor system. Figure 6 presents a positive correlation between vegetation biomass and soil organic matter content, water content, and total nitrogen content, and a negative correlation between the former and soil salt content, pH, available phosphorus content, and available potassium content. The Shannon-Wiener index and Pielou index were positively correlated with soil bulk density and available phosphorus, with apparent negative correlation with soil organic matter content and total nitrogen content, while the Margalef index enjoyed visible positive correlation with soil organic matter content and total nitrogen content, with Simpson index buffeted hardest by soil bulk density and water content.

The structural equation model (SEM) is a technique suitable to evaluate the relations between variable networks that can be used as both predictive and response variables to study the direct and indirect effects of factor combination on variables. This paper adopted SEM in order to quantify the impact of physical and chemical soil properties on the diversity and aboveground biomass of the vegetation (Figure 7). The analysis results displayed a more significant impact of the latter than the former, whose influence on biomass was

negligible, with a total effect of -0.85 . Both physical and chemical soil properties exerted significant effects on vegetation diversity with the effects -1.06 and -1.01 , respectively.

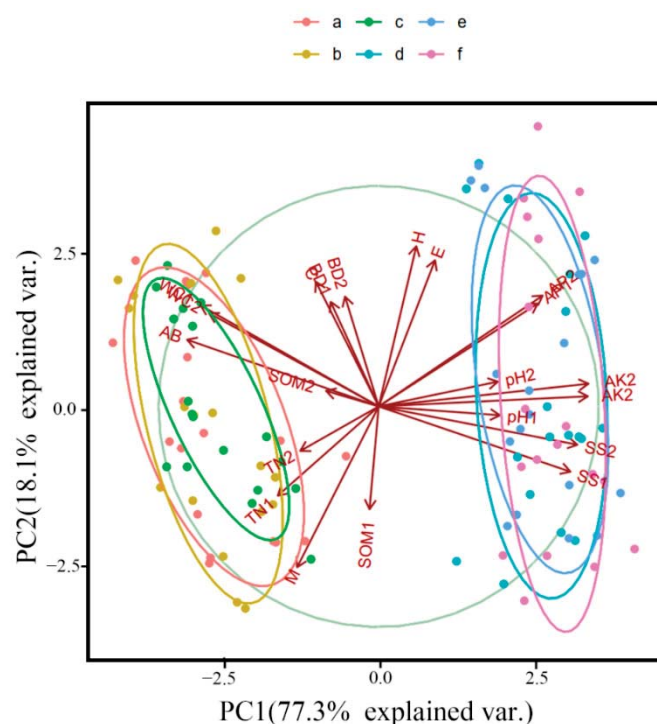


Figure 6. Principal component analysis. Note: a—South Slope direction, Upper Slope position; b—South Slope direction, Middle Slope position; c—South Slope direction, Bottom Slope position; d—North Slope direction, Upper Slope position; e—North Slope direction, Middle Slope position; f—North Slope direction, Bottom Slope position; 1 denotes 0–20 cm soil layer, 2 denotes 20–40 cm soil layer; SS—soil salt; WC—water content; BD—bulk density; SOM—soil organic matter; TN—total nitrogen; AP—available phosphorus; AK—available potassium; H—Shannon-Wiener index; E—Pielou index; M—Margalef index; C—Simpson index.

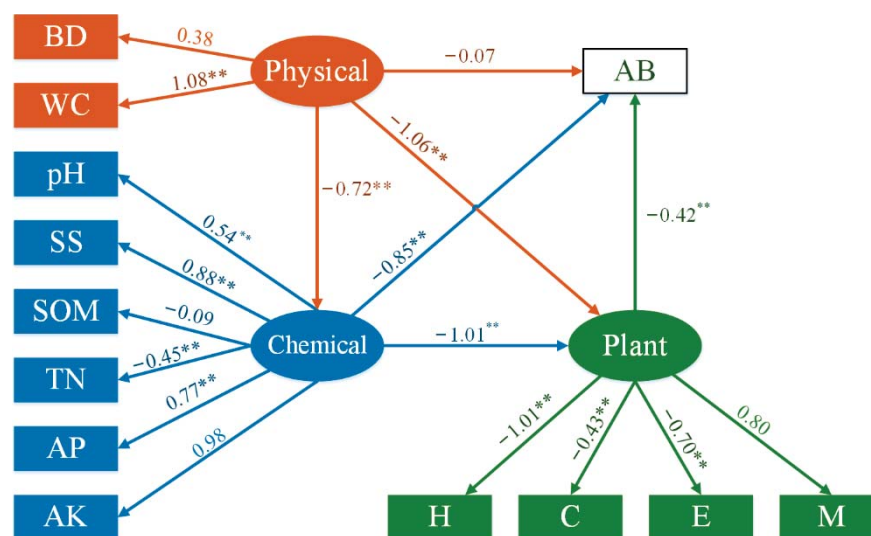


Figure 7. The structural equation model (SEM) of biomass, soil physical properties, chemical properties, and plant biomass and diversity. Note: SS—soil salt content; WC—water content; BD—bulk density; SOM—soil organic matter content; TN—total nitrogen content; AP—available phosphorus content; AK—available potassium content; AB—aboveground biomass; H—Shannon-Wiener index; E—Pielou index; M—Margalef index; C—Simpson index; ** represents a significant correlation at $p < 0.01$.

4. Discussion

In coastal farmland drainage ditches, the diminutive reshaping of soil formation and vegetation growth by the slope aspect and position indicate the primary source of the spatial heterogeneity of soil and vegetation properties in the same altitude zone. Studies have revealed that aspect and position changes represented the ecological sequence of light, water, and nutrient conditions. This study signified that the lower slope with high vegetation coverage boasted higher soil water content and bulk density, as well as better water-holding and storage capacities. While the swelling slope position signals a poorer performance of the four indicators mentioned, with increased soil porosity and salt content. All these agreed with results obtained by Zhang [20], who studied the distribution characteristics of physical and chemical soil properties of desert riparian forests in the middle reaches of the Tarim River. In addition, the contents of soil organic matter, total nitrogen, available phosphorus, and potassium in the 0–20 cm soil layer, at different slope positions and aspects of the two sites, were all higher than those in the 20–40 cm counterparts. This could be explained by the fact that the more outstanding nutrient content was discharged from litter and irrigation water than the value absorbed by vegetation growth engendered nutrient enrichment in topsoil. In comparison, the 20–40 cm soil layer was less affected by the outside world, with a more minor change in nutrient content than the surface one. Slope aspect, as a pivotal topographical factor in ditches, can exert important effects on biodiversity, plant growth and development, productivity, and ecosystem functions by changing ecological factors, such as light, temperature, moisture, and soil [21]. The analysis of the nonmetric multidimensional scaling (NMDS) discovered significant distinctions in the soil physical and chemical properties on different slopes with a greater soil water content in the southern slope (shady slope) than that in the northern slope (sunny slope). This could be attributed to strong sunlight and high soil temperature, resulting in colossal evaporation accompanied by the moving up and surface concentration of salt, giving higher soil salt content from the northern slope than that in the southern counterpart. Maren [22] pointed out that the difference in soil temperature and soil moisture will also cause disparities in nutrient mineralization in various slope directions. Moreover, the fact that the northern slope boasted a remarkably higher bulk density than that of the southern agreed with the study results obtained by Schittko [23], the consequence of greater biomass, denser grassroots, and sparser soil in the southern slope. Analysis revealed lower soil water content of the farmland ditch slopes in site 2 compared with that of site 1, with the former assailed by more severe salinization, lower organic matter, and total nitrogen content, but supplied with more available nutrients. All these were possibly connected with the diversified irrigation volumes and modes in distinct areas.

The indexes of diversity, Pielou, and Margalef, in the different slope positions and aspects of the farmland ditch slopes in Dongying and Binzhou, witnessed significantly higher degrees in the upper and middle positions in comparison to the lower positions. Ricotta [24] indicated the close connection between species Margalef and Pielou and the diversity index, a statistic that combines the first two indexes, the diverse expression of the two-index combination. The vegetation Simpson index of the lower slope position in this study was significantly higher than that of the upper and middle slopes, in opposition to the other three indexes. That could be explained by the fact that the lower position was tormented by perennial flooding and laborious absorption of soil organic matter and other nutrients; therefore, the position was only suited for the emergent aquatic plants like reeds to form a single superior community [25]. In a community with obvious dominance where the dominant plant occupies more living conditions, other non-dominant species have little access to re-enter the community and be repulsed by them, with its species diversity reduced. The increased slope position of the ditch meant a gradual improved flooded environment, swelled soil aeration, and better mineralization of surface soil organic matter [26]. This possibly resulted in competition between individual plants and species for limited soil resources and affected the species composition of plant communities. At the same time, Harpole [27] also pointed out that in the absence of a dominant species, the

number of species in the corresponding community could be increased, and so could its species diversity.

Through principal component analysis, it was determined that the soil water content of the coastal farmland ditch slopes exerted a significant positive effect on the vegetation aboveground biomass, which was in line with most research results on the relationship between vegetation biomass and soil [28]. Water represented a key factor in curbing plant growth, as declined soil moisture will severely limit vegetation growth with dropped plant height, leaf area, number of leaves, and other traits, clouding plant biomass accumulation [29]. Romina et al. [30] determined that slight differences in soil water content can also engender significant distinctions in seed germination and changes in vegetation biomass. In addition to water content, soil organic matter content and total nitrogen content are also positively correlated with aboveground biomass of vegetation, agreeing with the research results of Zhang [31]. It is generally believed that higher soil nutrients can promote vegetation growth with more litter produced by vegetation with high-ground biomass, along with soil organic matter and total nitrogen content. The negative correlation between Soil SS and pH, two factors curing aboveground biomass, is a result of high soil salinization in the coastal farmlands, with the plants being forced to become saline and alkali resistant. Furthermore, such a relation can also be applied to the connection between available phosphorus, available potassium, and the biomass previously mentioned. That is because excessive available nutrients fall heavily on plants; even moderate available phosphorus and available potassium can provide the necessary nutrients for vegetation growth.

Soil organic matter and total nitrogen, the leading nutrient indicators of the soil, directly affect soil fertility, water holding capacity, anti-erodibility, soil bulk density [22], and pH. The complex relationship between plants and soil nutrients is supported by the mixed research results of scholars in different regions [20]. Yang [32] et al. discovered a positive correlation between the species diversity index and organic matter and total nitrogen, after having studied the community diversity and soil nutrients of various vegetation types in the hilly region of Loess Plateau. Wang et al. [33] uncovered zero significance among organic matter, total phosphorus, and species diversity and plant quantitative features when studying the plant diversity and soil environmental factors in the Qinghai Lake area. Through principal component analysis, a negative correlation was found between organic matter, TN content, and the Shannon-Wiener index and Pielou index of vegetation with various negative correlations between the first two and the indexes of Margalef and dominance. This was in line with the research outcome of Al-Munqedhi [33]. The experimental results of Kejian [34] revealed raised soil nutrients indicated reduced species diversity. It is generally believed that the former leads to the rapid expansion of the dominant species population, with the growth of other plants being curbed, leaving simplistic community structures with decreased vegetation diversity, and improving the ecological dominance of dominant species. Lifted slope positions indicated ballooned plant community diversity; as the aquatic environment shifted to the wet, mesic, and xeric, so did the diversification and structure complexity of the plant community [35]. Alongside that, the substance decomposition rate and biological return rate of soil, fueled by promoted nutrient utilization, dwindled soil organic matter and total nitrogen content as the plant diversity enriched. This could help to explain the positive correlation between the ecological advantage of vegetation on the ditch slope and soil moisture.

In addition, through SEM analysis, it was revealed that changes in soil chemical properties cast more uncertainly on vegetation biomass than its physical counterparts. The soil chemical properties were the main limiting factor for the aboveground biomass of vegetation on the slopes of coastal ditches, as the properties disrupted biomass with indirect influence through confusing plant diversity on the aboveground biomass of vegetation, while the physical counterparts invisibly acted. Both soil physical and chemical properties can have a significant impact on vegetation diversity. In addition to directly affecting

plant diversity, soil physical properties can also indirectly affect vegetation diversity by influencing soil chemical properties.

5. Conclusions

The analysis of the two sites shed light on the prominent spatial distinctions in the soil physical and chemical properties, vegetation biomass, and diversity of the slopes of the farmland drainage ditches in the Yellow River Delta on the diversified slope positions, aspects, and tops, with similar change patterns found in both sites.

(1) Soil nutrient content at the same slope and soil depth was higher on the north slope than on the south slope, and higher in the 0–20 cm soil layer than in the 20–40 cm soil layer, and the salt content also showed the same pattern. Soil water content was higher on the south slope than on the north slope and higher in the 20–40 cm soil layer than in the 0–20 cm soil layer at the same slope and soil depth.

(2) The vegetation biomass on the south slope of the same slope position of the ditch was higher than that on the north slope; on the south slope of the ditch, the biomass was highest on the upper slope; and on the north slope, the biomass was highest on the middle slope. The vegetation diversity, Margalef, and Pielou indices showed the same pattern on the north and south slopes; that is, the highest on the upper slope in the south slope and the highest on the middle slope in the north slope. The Simpson index of vegetation gradually increased with the increase in slope position.

(3) The physical and chemical properties of soil exert varying degrees of influence on the vegetation biomass and diversity of ditch slopes. Among them, soil water content, soil bulk density, organic matter content, and total nitrogen content have a positive influence on the aboveground biomass of vegetation, whose growth is impeded by soil pH and salinity content, and available potassium content. The Shannon-Wiener index and Pielou index of coastal ditch slope vegetation are positively correlated with soil BD and available phosphorus content, with a negative correlation with organic matter and total nitrogen content. The Simpson index is most affected by soil bulk density and water content.

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Article

The Temporal–Spatial Dynamic Distributions of Soil Water and Salt under Deep Vertical Rotary Tillage on Coastal Saline Soil

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Abstract: Different from the traditional deep tillage, deep vertical rotary tillage can smash deep soil without disturbing the soil layer, which improves soil water infiltration and promotes salt leaching. This has gradually been applied in the research into saline alkali improvements. However, there is limited knowledge about the effect of deep vertical rotary tillage on the temporal–spatial distributions of soil water and salt under the shallow underground water level. Therefore, a preliminary soil column experiment was carried out to explore the results of water and salt movement under three different tillage methods: traditional rotary tillage depth of 20 cm (XG–20), deep vertical rotary tillage depth of 20 cm (FL–20) and deep vertical rotary tillage depth of 40 cm (FL–40). The temporal–spatial variation in soil water and salt was analyzed. The results showed that the average infiltration rate of FL–40 increased by 1.25 and 0.46 cm h^{−1} in 0–40 cm soil layer compared with that of XG–20 and FL–20. At the same time, soil water content was also increased, and the order of soil water content was FL–40 > FL–20 > XG–20. With the increase in tillage depth, the desalinization rate and the soil electric conductivity (EC) of FL–40 were increased and decreased, respectively. The FL–40 treatment's average desalinization rates increased by 16.32% and 13.99% compared with XG–20 and FL–20 treatments' in 0–60 cm soil layer. In conclusion, FL–40 had a better effect on regulating water and salt. The deep vertical rotary tillage provided an effective method for the control and optimization of water and salt in coastal saline soil.

Keywords: deep vertical rotary tillage; temporal–spatial dynamic distributions of soil water and salt; coastal saline soil

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1. Introduction

Soil salinization and secondary salinization in coastal area are serious issues due to the influence of topography and climate and improper field management. Reasonable water and salt regulation measures are important ways to improve the saline alkali barrier in this region [1]. The aim is to control the water and salt in the root zone of crops within a certain tolerance range, avoid water and salt stress, and increase crop yield.

Previous studies have shown that tillage methods can control the dynamics of water and salt by changing soil's physical structure to inhibit soil evaporation and improve the infiltration and leaching of salinity [2]. Therefore, tillage can be considered as one of the most important agricultural management measures to improve saline alkali land. However, many previous studies have shown that soil bulk density and soil water can be significantly affected by various tillage methods, thus affecting soil surface water migration [3–7]. Cai et al. (2014) [8] found that the average tillage depth was 16.5 cm in China. A shallow and dense tillage layer deteriorates soil's physical and chemical properties such as aeration, water permeability, water storage and fertilizer storage, which can restrict the growth and development of crop roots, creating a limiting factor for crop yield and harvest [9]. As

can be seen from the above studies, the plough layer formed by traditional tillage reduces water infiltration and hinders salt leaching. The dense soil layer reduces soil water storage capacity and increases water and salt stress. Therefore, it is crucial to further optimize tillage measures to improve the saline alkali barrier and water-use efficiency in coastal saline soil.

In recent years, the deep vertical rotary tillage technology developed has improved this situation. This is different from the two common deep tillage methods. One is deep ploughing, which pushes fertile soil into the lower layer, reducing soil fertility [10]. The other is deep pine, which has a limited area of loose soil. Soil block is larger after tillage, affecting crop growth [11]. However, deep vertical rotary tillage overcomes these problems. The machine includes six vertical spiral drills, which can vertically smash up to a maximum soil depth of 1 m without disturbing the soil layer [12]. After tillage, the soil clods were crushed to a higher degree, forming a thick loose layer. Therefore, without the hindrance of the topsoil, the soil water permeability increases, and the topsoil salt is more likely to be washed into the deep soil. The upward movement of salinity in the lower layers is reduced by the cutting of capillaries [13]. Previous studies have shown that deep tillage increases soil porosity, water conductivity and infiltration rate by reducing soil bulk density and penetration resistance, leading to a higher water content in deep loosening layers and reducing soil salinity [14–18]. Therefore, deep vertical rotary tillage has potential advantages in the improvement and utilization of mildly saline alkali land. Although there have been a lot of studies on the water–salt rule under deep vertical rotary tillage, they were all concentrated in the arid area of Northwest China, where the groundwater level is deep and the distribution of soil water and salt is affected by rainfall and surface irrigation. However, the factors affecting the distribution of soil water and salt in coastal areas are complex. The groundwater level in this area is shallow and highly mineralized, and groundwater and soil water frequently interact. It is very important to clarify the dynamics of water and salt at a shallow groundwater level for the further optimization regulation of water and salt. Under shallow-groundwater-level conditions, the dynamic distribution of water and salt under deep vertical rotary tillage has rarely been studied.

This study's ultimate aim was to evaluate the effect of deep vertical rotary tillage on water and salinity regulation in saline alkali soil with a shallow underground water level. In this paper, it was hypothesized that deep vertical rotary tillage could improve soil water infiltration performance, increase soil water storage capacity and increase salt leaching efficiency. The above effects were more significant with the increase in tillage depth. Therefore, a soil column experiment was carried out to study the characteristics of the temporal–spatial dynamic distributions of water and salinity under different tillage methods on coastal saline soil. This provided a basis for the study and regulation of water and salinity movement under deep vertical rotary tillage on coastal saline soil.

2. Materials and Methods

2.1. Study Area, Sampling Sites and Sample Analysis

Saline soil was sampled from a depth of 0–30 cm at the Dong Tai Ecological Research Station of Coastal Wetland (Figure 1), Chinese Academy of Sciences, located in Yan Cheng, Jiangsu Province, China. This area is a subtropical monsoon maritime climate, with distinct seasons and rain and heat over the same period. The annual average air temperature and rainfall are 15.0 °C and 1061.2 mm, raining enough, with 220 frost–free days and 2130.5 h sunshine time. The region is severely affected by soil salinization.

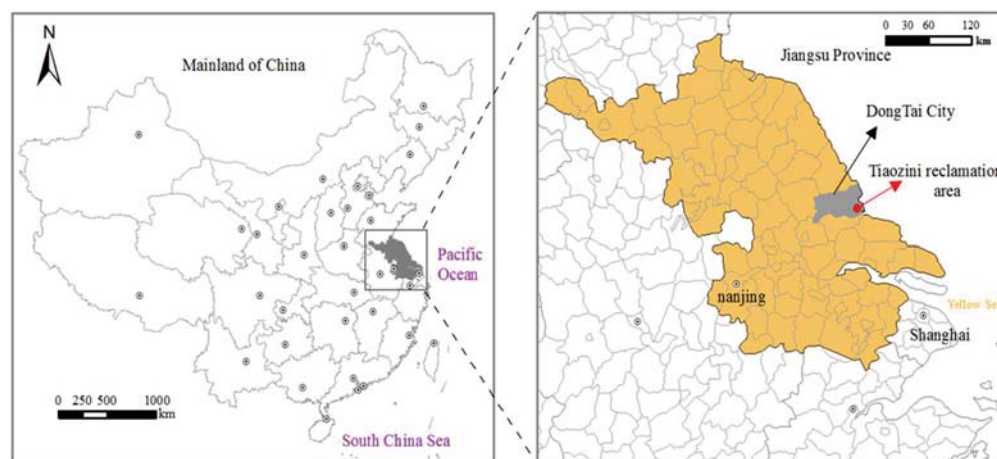


Figure 1. Study area location.

Soil samples were air-dried at room temperature (25 °C) and then sieved using a 2 mm sieve to remove coarse debris and stones. The initial analysis indicated a medium soil salinity; soil water content was determined by drying method; soil pH and soil electrical conductivity (EC) were measured in a supernatant of 1:5 (*w/v*). Soil-water mixtures were measured using a pH meter and an electronic conductivity meter (Mettler Toledo, OH, USA). The total salinity content was measured as residue drying (Table 1). The desalination rate was calculated as the percentage difference between salinity values measured before and after the experiments.

Table 1. The physical and chemical properties of soil were tested.

pH	EC ($\mu\text{s cm}^{-1}$)	Salinity Content (g kg^{-1})	Sand Content (%)	Silt Content (%)	Clay Content (%)	Soil Texture
7.98	1600	3.35	13.2	61.5	25.3	Silt loam

Note: EC, soil electrical conductivity of soil extract with a soil–water ratio of 1:5.

2.2. Soil Column Experiment

Soil columns were prepared using transparent polymethyl methacrylate (PMMA) cylinders (15 cm diameter, 130 cm height). Prior to filling the column, a 5 cm thickness of fine quartz sand was placed at the bottom. To obtain homogenous soil bulk density (1.35 g cm^{-3}), the sieved dry soil was poured into each column in 10 cm sections; the soil surface of each packed layer was stirred before adding the next to prevent stratification. The soil was packed in each column until a height of 110 cm was achieved. Soil columns were irrigated according to the water content suitable for cultivation, and soil was cultivated after irrigation. After tillage, the soil columns were placed under infrared and the soil was allowed to dry so that wettability peaks could be observed. A tape measure (length, 110 cm) was vertically fixed to the outer wall of each soil column; this was used to record the location of the wetting front during infiltration. The sampling holes were distributed at 10, 20, 40, 60, and 80 cm vertically downward from the soil surface. Four groups of the sampling holes were set on the bottle body. Three treatments were established, and each treatment was repeated three times: traditional rotary tillage 20 cm (XG–20), deep vertical rotary tillage 20 cm (FL–20) and 40 cm (FL–40). The schematic diagram of experimental treatment is shown in Figure 2. To simulate the field cultivation as closely as possible, a small rotary cultivator (helix blade diameter of 10 cm) was used to simulate field rotary tillage, and a hand electric drill with auger (helix blade diameter of 4 cm; the machine's speed was the same as that of the field deep vertical rotary machine: 460 r min^{-1}) was used to simulate deep vertical rotary tillage. To avoid marginal effects, tillage was carried out in the center of the soil column without touching the wall.

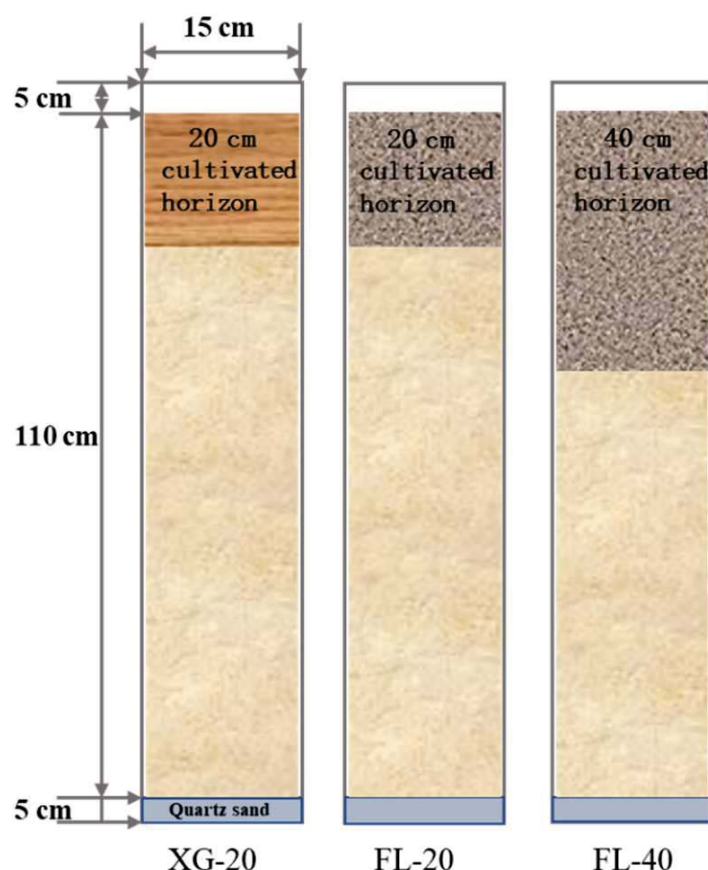


Figure 2. Schematic diagram of soil column experiment (traditional rotary tillage 20 cm (XG–20), deep vertical rotary tillage 20 cm (FL–20) and 40 cm (FL–40)).

The infiltration experiment was carried out at the time of the first irrigation. The wetting peak was observed every five minutes at the beginning of the infiltration, then every half hour, and every hour after the infiltration stabilized. A 37-day simulation test was conducted after the end of the infiltration experiment, during which two irrigations were carried out. The average soil water content in 0–60 cm soil layer of the three treatments before irrigation was 0.285 g g^{-1} . The time of the first irrigation was selected as the first day of the simulation, and the second irrigation was carried out on the 21st day. The meteorological data of the meteorological station in the test site from 2000 to 2012 were used as reference. The average monthly precipitation of 140 mm in the maize growing season from April to August was used as the irrigation amount for the experiment. The irrigation amount was 1.24 L for both times, and variable pressure head irrigation was adopted. On the 0, 4, 19 and 37 days, samples were taken from 10, 20, 40 and 60 cm soil layers, respectively. Approximately 10 g of soil was removed from the sampling hole and then backfilled with moist mother soil. Meanwhile, water samples from Mariotte's bottles were taken to determine soil water content and electric conductivity.

Mariotte's bottle was used at the 110 cm layer to measure the underground water depth. After irrigation, the infrared lights were placed 20 cm from the soil surface to simulate evaporation. The irradiation lasted for eight hours each day from 10:00 a.m. to 18:00 p.m. Evaporation was weighed at 10 a.m. every day, and the difference between the two weights was the daily evaporation (Figure 3).

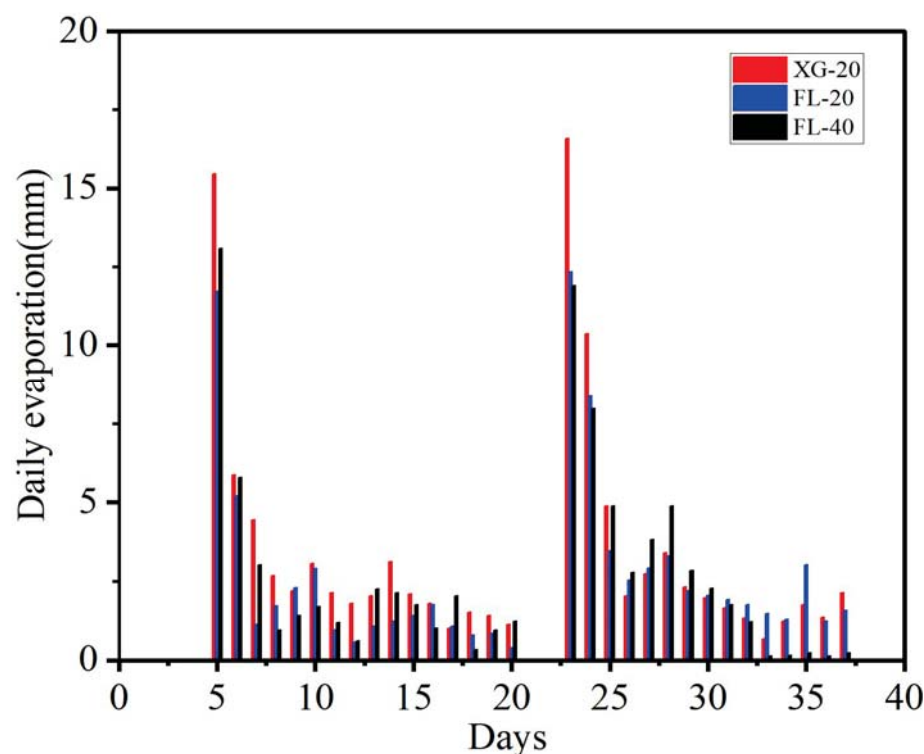


Figure 3. Daily evaporation under different tillage treatment methods.

3. Statistical Analysis

Microsoft Excel 2019 was used to calculate the means and standard deviations. SPSS was used to analyze the mean values of the data by one-way ANOVA (Analysis of Variance) with Student–Newman–Keuls multiple-comparison test at the level of $p < 0.05$. Before the ANOVA, the data were tested for equality of variances by Levene’s test. The figures were drawn using Origin 2022b and Microsoft Excel 2019.

4. Results and Discussion

4.1. Effect of Deep Vertical Rotary on Soil Water Infiltration

Soil water infiltration is an important process of soil water and salt distribution [19]. Figure 4 shows the dynamic changes in the wetting front with time under different treatments. It can be seen that different tillage methods have a significant influence on soil infiltration. By comparing the soil infiltration of 0–40 cm soil layers, it can be seen that the infiltration difference between different treatments gradually increases over time, and then gradually decreases until it becomes stable. The Table 2 shows the average infiltration rate of each soil layer under different treatments. It can be concluded that the infiltration rate of the XG–20 treatment was significantly lower than that of the other two treatments in 0–20 cm soil layer. In 20–40 cm soil layer, the infiltration rate of FL–40 treatment was significantly higher than that of FL–20 and XG–20. Although the tillage depth of FL–20 was the same as XG–20, the infiltration rate of FL–20 was still higher than XG–20. As the saturated water content of FL–20 was higher than that of XG–20, the higher water potential increased the infiltration rate into the underlying soil [19]. The average infiltration rate was FL–40 > FL–20 > XG–20 in 0–40 cm soil layers. The results showed that tillage depth was an important factor affecting soil infiltration, and the soil infiltration rate increased with the increase in tillage depth. When the vertical rotation depth is 40 cm, the soil infiltration performance can be significantly improved.

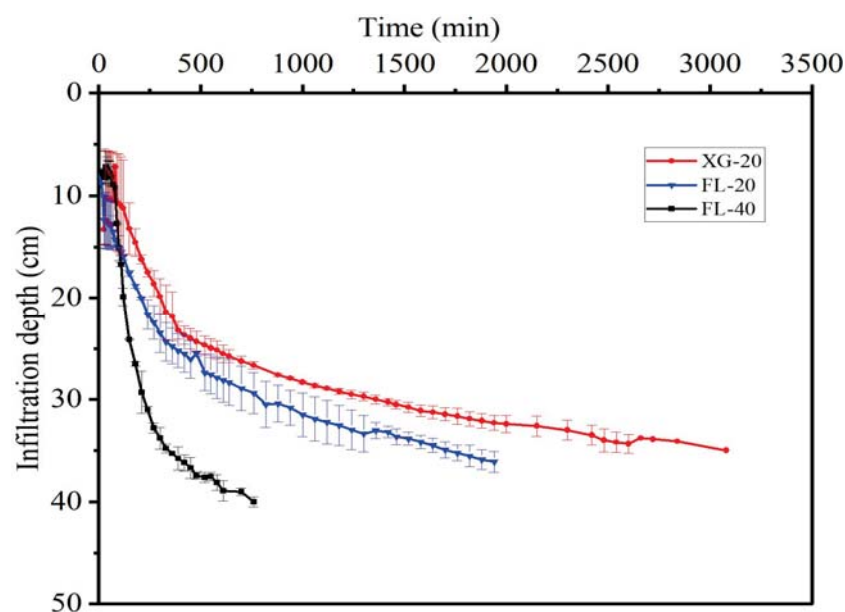


Figure 4. Wetting front under different treatments.

Table 2. The infiltration rate at different layers.

Treatments	XG-20 ($\text{cm} \cdot \text{h}^{-1}$)	FL-20 ($\text{cm} \cdot \text{h}^{-1}$)	FL-40 ($\text{cm} \cdot \text{h}^{-1}$)
0–20 cm	1.12	2.19	2.62
20–40 cm	0.27	0.47	1.28

In this study, we found that deep vertical rotary tillage improved soil infiltration performance in the cultivated layer. This was consistent with the results of Jiang et al and Wei et al. [20,21]. The soil structures of saline–alkali land and the soil water infiltration capacity were poor. This was an important problem in the process of saline–alkali land improvement. Water infiltration performance played an important role in the leaching of soil salt. Deep vertical rotary tillage can loosen the soil, make the soil particles fine and even, and promote water infiltration. Compared with the treatment of different tillage depths, the water infiltration of the FL–40 treatment was the fastest. The results of this study are consistent with those of previous studies. Yang and Ma et al. proved, through both laboratory and field experiments, that the water infiltration rate of deep vertical rotary tillage was significantly higher than that of traditional rotary tillage. Other studies have found that when the depth of traditional cultivation reaches 20 cm, it cannot break through the plough plate formed by years of cultivation, which hinders soil water infiltration and salt leaching [15,22]. In this study, deep vertical rotary tillage was used to reduce soil bulk density and increase soil infiltration rate in topsoil. Soil water infiltration rate increased with increasing tillage depth.

4.2. Temporal–Spatial Dynamic Distributions of Soil Water

During the two irrigation and evaporation processes, there were differences in the temporal–spatial dynamic distribution of soil water on 0–60 cm layers in each treatment (Figure 5). With the occurrence of irrigation and evaporation, the water content of 20 cm soil in each treatment fluctuated greatly and showed significant differences. Compared with the water content on the 4th day after irrigation, the range of decrease in soil water content (19 and 37 days) in 20 cm were both FL–40 > FL–20 > XG–20, and the reductions were 13.74%, 8.36%, and 7.86% and 17.19%, 14.44%, and 2.81%, respectively. The reduction in soil water content in the FL–40 treatment was significant ($p < 0.05$) on the 37th day. The soil water content of FL–40 decreased faster due to evaporation. However, in the 40 and 80 cm soil layers, the water content of the FL–40 treatment was always higher than that

of other treatments. The average soil water content at 40–60 cm significantly increased ($p < 0.05$) with FL-40 treatment. The average water contents of FL-40, FL-20 and XG-20 in 40–80 cm soil layers were 0.428, 0.415 and 0.412 cm cm^{-3} , respectively.

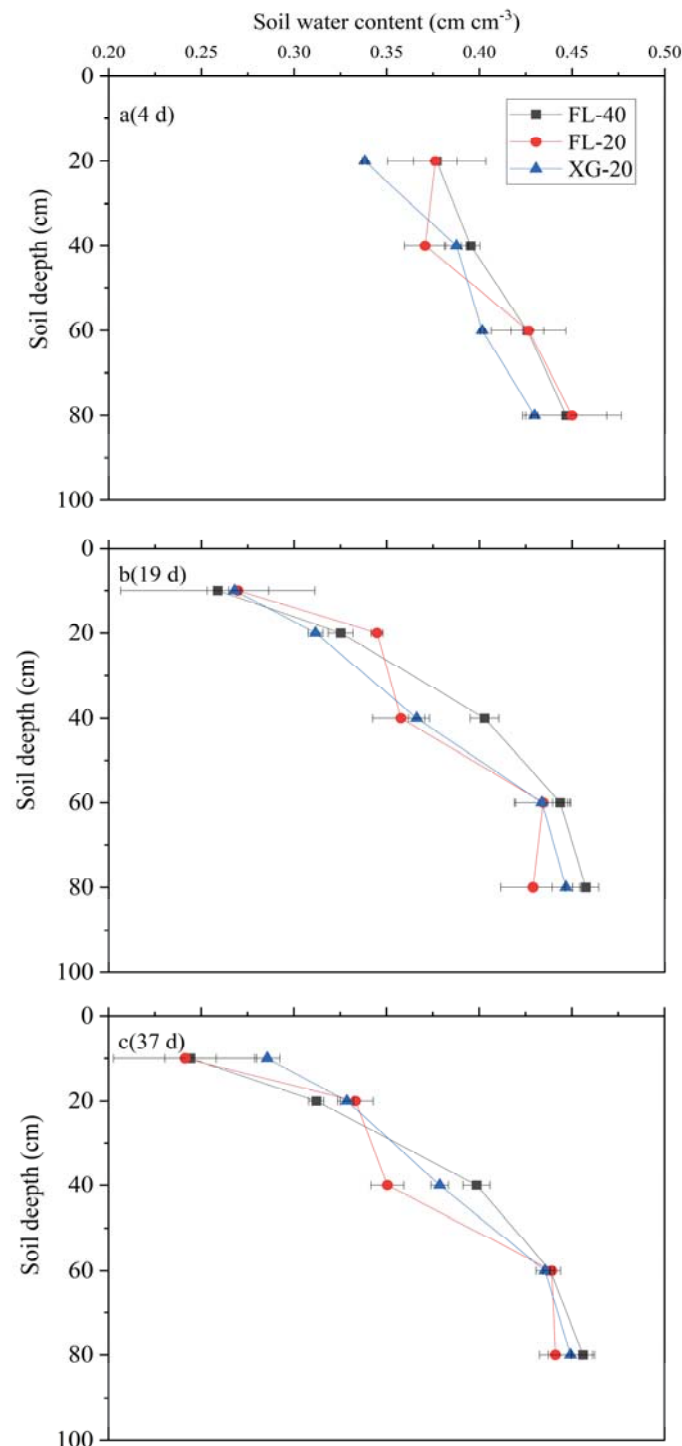


Figure 5. Dynamic distributions of soil water content in the soil profiles under different treatments.

In salinized soil improvement process species, soil water management is an important process to alleviate salt stress [23]. Soil water distribution was significantly affected by deep vertical rotary tillage. Our study found that the soil that was loose after deep vertical rotary tillage had better air permeability. When there was no land cover, the soil water content in the 0–10 cm surface layer, subject to high atmospheric evaporation force, rapidly decreased to form a dry soil layer, which was consistent with the study of Li et al. In the

20–40 cm soil layer, the water content of the FL–40 treatment was always higher than that of the other treatments. The deep vertical rotary tillage can crush the bulk soil to form a uniform and fine granular structure, increasing the porosity. When supplied with water, the water storage will be higher than other treatments [24–27]. In addition, the presence of a dry soil layer in the top layer could block the rise in capillary water in the lower layer, so the soil water content in the 40–60 cm layer was increased. Due to the separation of soil particles from the underlying soil structure, the capillary tube is interrupted, the rising of the capillary water to the surface soil is reduced, the evaporation loss of water is reduced, and the water in the deep soil is preserved at the same time [27].

The force between soil particles and water molecules determines the water-holding capacity of soil, which is affected by soil porosity, soil texture and other factors [18,28–31]. The soil was porous, with a reduced bulk density, increased porosity, and expanded soil water storage capacity, which was an important reason for the increase in soil water content in 40 and 60 cm deep layers. A high number of studies have shown that deep vertical rotary tillage can improve soil structure and increase soil water-stable aggregate content [30,32,33]. Wang et al. [34] observed, using scanning electron microscope, that the soil micromorphology after silty ridge cultivation had the characteristics of a smooth surface, larger specific surface area and richer pore distribution. Fine soil particles have a large pore surface area and adsorption capacity [35], which can improve soil water-holding capacity. This was also an important reason for the increase in soil water content. With a water supply, compared with the traditional rotary tillage, when the deep vertical rotary tillage layer is 40 cm, the deep and loose tillage layer was conducive to water infiltration; thus, more water is stored [23,31]. When continuous evaporation occurred, the deep soil moisture was less affected by evaporation, and the deep soil moisture was more conducive to preservation, thus increasing the deep soil moisture contents at 40 and 60 cm. The results were consistent with those of previous studies. A large number of studies showed that deep vertical rotary tillage could reduce soil bulk density and increase soil water content [20,31,36]. When drought persists in the field, the deep water stored in the deep vertical rotary tillage will play an important role in crop growth and development. However, traditional rotary tillage can further aggravate salt stress during droughts [37,38]. In conclusion, deep vertical rotary tillage can increase the water content in soil at 40 and 60 cm depths, and water storage can be effectively carried out during droughts.

4.3. Temporal–Spatial Dynamic Distributions of Soil Electric Conductivity

Throughout the whole experiment, the dynamic changes in EC under different treatments were significantly different (Figure 6). The EC of XG–20 greatly fluctuated in the 20 cm soil layer. On the first four days after the first irrigation, the ECs of XG–20, FL–20 and FL–40 treatments were significantly reduced by 13.8%, 25.1% and 36.7%, respectively. The reduction in FL–40 was significantly ($p < 0.05$) higher than that of the other two treatments. After 19 days, the EC of XG–20 increased by 6.4% compared to after four days. FL–20 and FL–40 treatments decreased by 6.0% and 7.1%. After the second irrigation, the EC of the 0–40 cm soil layer further decreased in each treatment. However, in the 60 cm soil layer, the salt from each treatment began to accumulate, and the cumulative degree was XG–20 > FL–20 > FL–40. This showed that the desalinization effect of FL–40 is better than the other two treatments when using the same irrigation amount. It may be that FL–40 treatment reduced bulk density and cut off the capillary, promoting salt leaching and inhibiting salt reductions in the 0–40 cm soil layer. The results showed that deep vertical rotary tillage could reduce the surface soil salt compared with XG–20 treatment, and the salt desalinization rate increased with the increase in tillage depth. Due to the loosened soil structure, tillage can promote the soil vertical infiltration of water and salt. At the same time, the salt reduction caused by the capillary effect was inhibited [13,18,39].

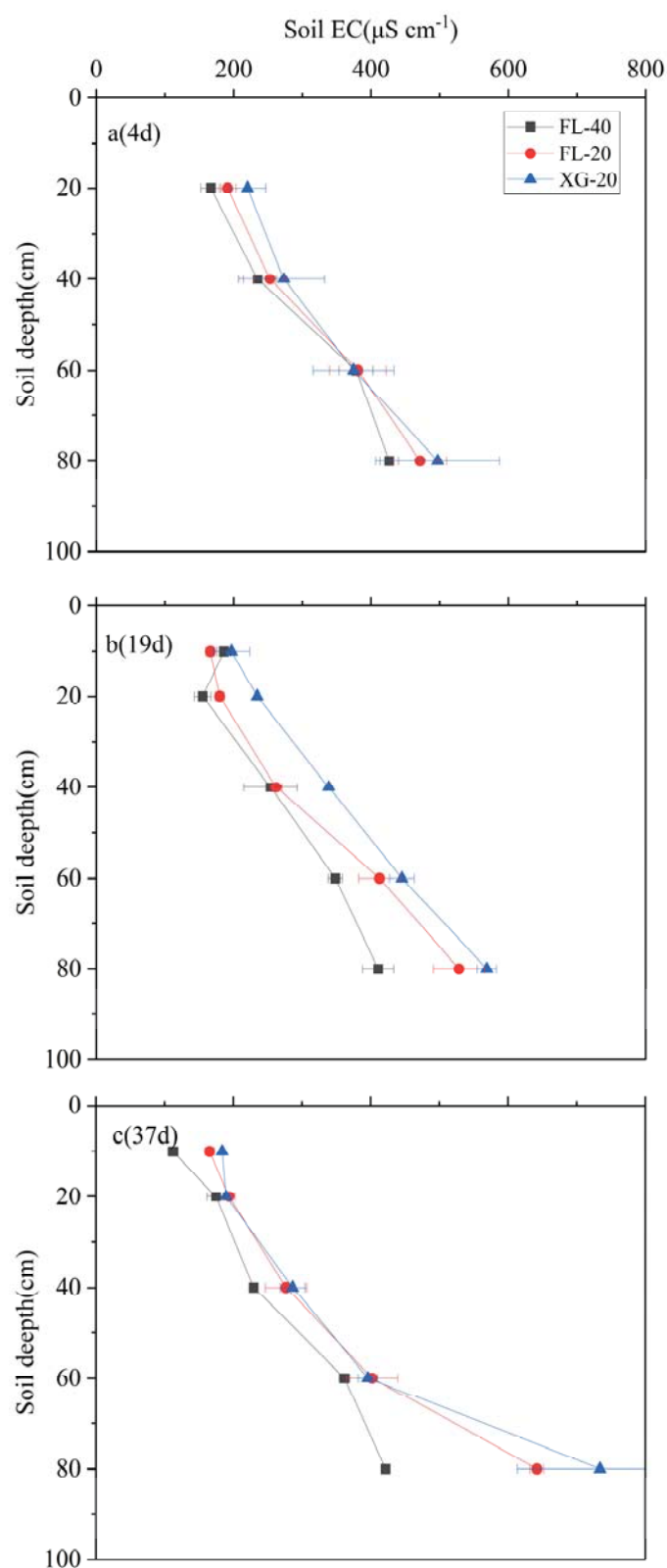


Figure 6. Dynamic distributions of EC in the soil profiles under different treatments.

The control of crop root zone salinity is the main purpose of saline soil improvements. This study showed that the deep vertical rotary tillage could reduce the salt content from 0–40 cm in the root zone. Compared with the traditional rotary tillage, the deep vertical rotary tillage treatment can effectively reduce the salt in the surface soil. The deeper the

deep vertical rotary tillage, the more the salt of the corresponding soil layer decreases. This study was consistent with the study of Cao et al. [40]. Water infiltration was hindered in saline soil, and salt was difficult to wash into the underlying soil. Deep vertical rotary tillage promoted soil water infiltration and increased the leaching efficiency of salt [32], which was the main reason for the reducing root zone salt. Other studies obtained the same results [18,40]. In addition, under the action of a strong capillary, salt was easily moved into the surface root zone soil with water. In this paper, it was concluded that deep vertical rotary tillage can reduce the evaporation of soil water and block the rise in capillary water. As a result, the upward movement of salt was reduced, and the desalting phenomenon of surface soil was effectively controlled. Other studies have shown that deep vertical rotary tillage can mix the topsoil into the subsoil, and effectively reduce salt in the topsoil [18]. This was another important reason to control salinity in the root zone. In terms of the cultivation depth of the deep vertical rotary tillage, the deeper the tillage depth, the better the salt reduction effect. This is closely related to the deep and loose tillage layer. Cao et al. concluded, through field experiments, that the salt reduction efficiency of deep vertical rotary was higher than that of traditional rotary tillage, and this was proportional to tillage depth. However, the shallower plough layer of traditional tillage reduced the efficiency of salt leaching because it hinders water infiltration. The soil block was large and unevenly distributed, with more macro-pores, and this preferential flow leads to insufficient salt leaching. The soil conductivity of FL-40 at 10 cm was significantly lower than that in the rotary tillage treatment. At the soil layer of 40 cm, the salinity of FL-20 and FL-40 cm in the 40 cm layer was higher than that in XG-20. The difference in salt content between XG-20 and FL-20 tillage layer may be due to the influence of the shallow water table. A large number of studies have shown that surface salt accumulation is significantly affected by groundwater when the groundwater level is relatively shallow and the salinity is high [41,42]. The deep vertical rotary tillage reduced the evaporation of surface soil water, weakening the capillary effect and reducing the upward movement of salt with water. As a result, soil salinities of 40 and 60 cm were lower than those of traditional rotary tillage. Under shallow water-level conditions, the deep vertical rotary tillage can reduce soil surface evaporation, reduce groundwater level and reduce the salt caused by rising capillary water.

4.4. Salt Reduction under the Different Tillage Methods

Reducing root zone salt is an important way of alleviating crop salt stress and improving saline soil [43,44]. In this study, FL-40 treatment had the lowest average salt content in 0–40 cm. The desalinization rate of FL-40 was significantly higher than that of the other two treatments in the 10 cm soil layer (Figure 7). However, the desalinization rate difference between the three treatments did not reach a significant level. The desalinization rate of FL-40 was still the maximum of the three treatments in 40 cm. The desalinization rate of each treatment became negative at 60 cm, indicating that salt began to accumulate in this layer. The difference between the three treatments reached a significant level, and the desalinization rate was FL-40 > FL-20 > XG-20. In general, the average desalinization rates of the three treatments in 0–60 cm soil layer were 13.15%, 13.31 and 29.47%, respectively. There was little difference in the average desalinization rates of FL-20 and XG-20 treatments. The average desalinization rates of FL-40 treatments were 13.99% and 16.32% higher than those of the first two treatments in the 0–60 cm soil layer. Therefore, it can be concluded that tillage depth was an important factor to improve the desalination rate. It may be that a higher tillage depth improved water infiltration capacity [14]. Thus, compared with 20 cm tillage treatment, FL-40 treatment could more easily promote the leaching of surface salt to deep soil.

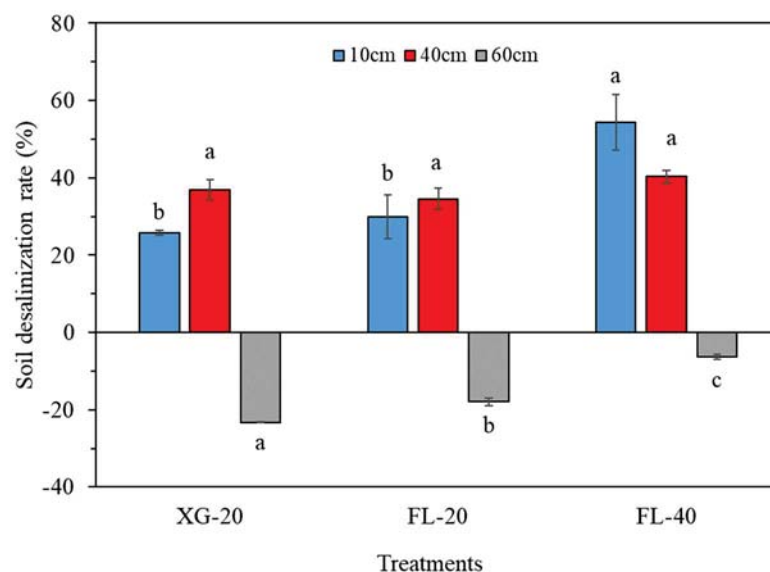


Figure 7. Desalinization rates of soils under different treatments.

The desalinization rate is an important index for evaluating the effect of soil salinity leaching. It was found that the desalinization rate of the deep vertical rotary tillage was significantly higher than that of traditional rotary tillage. The desalinization rate of FL-40 treatment in the 10 cm soil layer was significantly higher than that of the other two treatments. It can be seen that the desalinization rate of the surface layer increases with the increase in the depth of deep vertical rotary, which was consistent with the research of Cao et al. The desalinization rate of FL-40 was higher than that of traditional rotary tillage. With the deepening of tillage depth, there is more salt migration downward to plow deep soil layers [21]. As seen in Figure 7, salt accumulation began in the 60 cm soil layer in each treatment, and the deep vertical rotary tillage accumulation degree was lower than that of the other two treatments. The decrease in salt accumulation was caused by a combination of irrigation and reduced evaporation. The results of field experiments showed that after spring irrigation, with the deepening of the deep vertical rotary tillage, the salt pressure effect was better, and the leaching effect of salt in each soil layer was better than the traditional method.

4.5. Analysis of Different Tillage Methods and Their Application

Soil tillage is an important measure to regulate soil water, fertilizer, air and heat. Improving soil physical and chemical properties and increasing soil water use efficiency through improving tillage measures is also an important direction in water-saving agriculture research [13]. In this study, the dynamics of soil water and salinity were different between traditional rotary tillage and deep vertical rotary tillage. Deep vertical rotary tillage significantly increased soil water content and reduced soil water evaporation. The studies have shown that deep tillage improves the physical, biological and hydraulic properties of soil [4]. Compared with traditional rotary tillage, the soil water storage depth was further increased with the increase in tillage depth [40]. Traditional rotary tillage could not break through the 20–40 cm soil layer, which hindered rainwater infiltration and the leaching of salinity on the surface, so it is easy to accumulate salinity in the soil layer of 30–50 cm. Therefore, it is necessary to use deep tillage at a 30–50 cm depth to improve soil properties in the context of multi-year conservation agriculture. Deep vertical rotary tillage can cut off the soil capillary and weaken the evaporation of soil water, so as to effectively control soil salinization.

This experiment was carried out indoors without vegetation coverage, and the natural conditions, such as atmosphere and groundwater, were different from those in the field. The temporal–spatial dynamic distributions of soil water and salinity might be different

from those in the field. Therefore, the model requires the further validation of field data. As the coastal saline alkali land is affected by seawater intrusion, the underground water level is shallow, and the salinity is high. Deep vertical rotary tillage, combined with dark pipe drainage measures, may be better able to eliminate the saline barrier. On the other hand, the dark pipe plays a role in controlling the water table and preventing the accumulation of salt in the surface soil caused by the underground water level. This experiment only involved the effects of different tillage methods on soil water and salt movement through the laboratory soil column test. In the future, field experiments will be carried out to verify the experimental results and further study the dynamics of water and salt under different tillage methods and dark pipe combinations.

5. Conclusions

The spatial–temporal dynamic distributions of soil water and salt using different tillage methods were studied with the soil column experiment. The results showed that FL–40 effectively improved the soil water infiltration performance and changed soil water distribution. With the evaporation, although the surface soil water content decreased faster than traditional rotary tillage, it could still preserve the water content of the 40–60 cm soil layer. Fl–40 increased soil water content between 40 and 60 cm. Fl–40 effectively promoted the leaching of soil surface salt and increased the desalting rate. At the same time, this reduced soil evaporation and inhibited the accumulation of soil salt. The desalting rate of Fl–40 was significantly higher than other treatments in a 10 cm soil layer, and the salt accumulation was minimal at the 60 cm soil layer. Fl–40 provided a new means of providing the optimal control of water and salt in coastal saline soil.

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Article

Spatio–Temporal Variability Characteristics of Coastal Soil Salinization and Its Driving Factors Detection

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Abstract: The utilization efficiency of land resources in the coastal area of the Yellow River Delta has been deeply affected by salinization hazards. Key to improvement of the utilization efficiency of resources in this area is to grasp the spatio–temporal variability law of soil salinity and identify the driving factors of salinization. Wudi County in the coastal area of the Yellow River Delta is taken as the study area. Based on the data obtained from field measurements and laboratory analysis, the characteristics of soil salinity in spring and summer were analyzed by classical statistical methods; the spatial differentiation characteristics of salinization were analyzed from two–dimensional and three–dimensional perspectives using the geographic information system (GIS) and groundwater modeling system (GMS); the time variation characteristics of salinization were quantitatively analyzed by introducing the salinization severity index (S_i) and the dominant index of salinization degree change (C_i). The results show that: (1) In the study area, the soil salinity of the surface layer (0–15 cm) in summer is lower than that in spring, but the sub–surface layer (15–30 cm), the middle layer (30–45 cm) and the bottom layer (45–60 cm) are all larger than the corresponding layers in spring, and the correlation between the soil salinity of each layer in summer is generally lower than that in spring. (2) In two–dimensional space, the areas with a surface soil salinity greater than 0.4‰ in both seasons are mainly located in the northern part of the study area; in three–dimensional space, the soil is mainly moderately salinized in both seasons, and the complexity of the distribution of the salt profile is higher in summer than in spring; (3) Mashanzi Town was the area most seriously affected by salinization in both seasons (S_i values were greater than three); In the process of seasonal alternation, the dominant change type of salinized soil is from mild aggravation to moderate, with C_i value of 38.43%, followed by severe alleviation to moderate, with C_i value of 35.49%; (4) The driving factors of soil salinization in spring are mainly the soil salinity of the subsurface and middle layer, and soil water content; and in summer, mainly the soil salinity of subsurface layer, vegetation coverage and vegetation cover type. The interaction between any two factors has greater influence on the spatial variation of salinization than the corresponding single factor.

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1. Introduction

Soil salinization refers to the process whereby salt in groundwater moves up to the surface with water through soil capillaries under evaporation [1]. As one of the main causes of land degradation, salinization usually occurs in areas with an arid climate, high evaporation and low precipitation, high water table and high mineralization [2]. Both primary salinization (mainly influenced by natural factors) and secondary salinization (mainly influenced by human factors) have a serious negative impact on the sustainable

use of land resources and sustainable agricultural development [3]. More than 6% of the world's land is affected by salinization hazards, which are widely distributed in more than 100 countries and regions [4]. The total area of modern saline soils in China is as much as 36 million hm^2 [5]. It is of great significance to develop and utilize these saline soil resources reasonably for China, with its large population and small land [6]. The Yellow River Delta is the largest delta in China, with vast reserve land resources. However, due to its close proximity to the Bohai sea and high mineralization of the groundwater, the soil salinization in this region is a prominent problem, under the comprehensive influence of such factors as less precipitation, high evaporation, and significant seasonal alternation of wet and dry [7]. Timely grasp of the spatial distribution characteristics of soil salinization in this region, to find out their seasonal variations, and clarify the factors affecting salinization, will help to formulate targeted measures to effectively prevent, control and mitigate salinization hazards.

At present, many scholars have done a lot of research on the spatial distribution characteristics of soil salinization in a single season. Li et al. [8] analyzed the two-dimensional spatial distribution characteristics of soil salinization in summer in the Wei-Ku oasis by using the ordinary Kriging interpolation method, and pointed out that groundwater mineralization is the main factor causing soil salinization in this area. Su et al. [9] studied the two-dimensional spatial differentiation pattern of soil salinization in the Hetao irrigation area of Inner Mongolia in autumn, through the inverse distance weight interpolation method, and pointed out that the main influencing factors of soil salinization in this region include groundwater level, groundwater salinity, irrigation method and phreatic evaporation. As the research progressed, some scholars began to explore the spatial variation patterns of soil salinity in different seasons. Sun et al. [10] analyzed the two-dimensional spatio-temporal variation of soil salinity in a typical area of the Yellow River Delta by collecting conductivity data in spring, summer and autumn, and concluded that anthropogenic activities and rainfall had a significant effect on the salinity of the surface soil; Liu et al. [11] studied the spatio-temporal variation characteristics of soil salinity profiles in cotton fields in spring, summer and autumn based on conductivity data, and pointed out that soil texture and microtopography are the most direct factors influencing the distribution types of salt profiles. Most of the existing studies focus on the analysis of the two-dimensional spatial distribution of salinity in single or multiple seasons, but fail to intuitively reveal the three-dimensional spatial and temporal variation of soil salinity; and the individual studies involving the three-dimensional variation of salinity in different seasons are mostly focused on the inland field scale [12,13]. However, the research reports on the three-dimensional spatio-temporal variation of soil salinity in the coastal area of the Yellow River Delta are extremely rare. From a three-dimensional perspective, the visualization and analysis of soil salinity distribution in three-dimensional form can help to refine measurement and assessment of soil salinity, and lay a foundation for the development of zonal irrigation to achieve precise regulation of water and salt [13]. Studies on the driving factors of salinization mostly focused on the "fixed" factors such as topography, groundwater depth and groundwater mineralization [9–11], but neglected to analyze "variable" influence factors in different seasons; studies on seasonal variation law also failed to quantify the degree of differentiation.

In this paper, Wudi County in the coastal area of the Yellow River Delta is taken as the study area. Based on the data obtained from field measurement and laboratory analysis, we explored the multi-dimensional spatial distribution characteristics of soil salinity in spring and summer by using two-dimensional and three-dimensional inverse distance weight (IDW) methods, and introduced an index method to quantitatively reveal the spatio-temporal variation characteristics of soil salinization in the study area. The driving factors affecting the spatial distribution of salt in different seasons were explored by using geographic detection methods. The purpose of this paper is to provide a theoretical basis for the precise regulation of soil salinity in the coastal area.

2. Materials and Methods

2.1. Overview of the Study Area

Wudi County, with geographical coordinates of $37^{\circ}4' \sim 38^{\circ}16' \text{ N}$ and $117^{\circ}31' \sim 118^{\circ}04' \text{ E}$, is located in the northernmost part of Shandong Province, bordering the Bohai Bay in the northeast. It belongs to the overlapping area of many strategic plans such as the Shandong Peninsula Blue Economic Zone and the Yellow River Delta Efficient Ecological Economic Zone. The total area of the territory is 1998.12 km². It belongs to the continental climate of the East Asian monsoon region in the north temperate zone, windy and dry in spring, hot and humid and rainy in summer, with an average annual temperature of about 12.8 °C (the average temperature is 18.1 °C in spring and 26.5 °C in summer), an average annual precipitation of 570.1 mm (the average monthly precipitation in spring is 28.2 mm and 122.3 mm in summer), an average annual evaporation of 1285.5 mm (the average monthly evaporation in spring is 204.3 mm and 236.7 mm in summer), and an ratio of evaporation to precipitation of 2.3 (the monthly average ratio of evaporation to precipitation in spring is 7.3, and that in summer is 1.9) [14]. A total of 68.7% of the precipitation is concentrated in summer and 13.7% in spring. The topography is high in the southwest and low in the northeast, and the main types of landforms include river bank uplands, gently flat slopes and shallow flat depressions. Fresh water resources are scarce in the region, the areas with high underground water salinity are mainly distributed in the coastal area, and saline alkali lands are all over the territory. The northeast of the county is mainly tidal flats and salt fields, so this part of the area is not included in the study area of this paper (Figure 1).

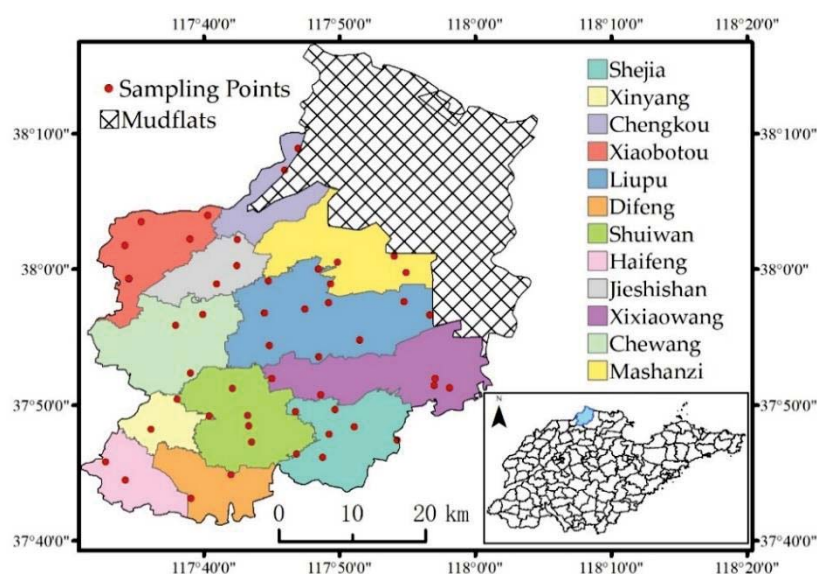


Figure 1. Overview of the study area.

2.2. Sample Collection and Data Sources

2.2.1. Sample Collection

The sampling points were arranged by grid method, covering the remote sensing image map of the study area with 5×5 km grids, with one sampling point arranged for each grid, avoiding the northern tidal flat area and the construction land in the area. During actual sampling, it was adjusted or selected according to the actual situation such as traffic accessibility, with 53 sample points actually collected (see Figure 1 for sample point distribution). The sampling was carried out from 26–28 April and 13–15 August 2015, respectively. The coordinates of the sample points were recorded using hand-held GPS, and the current land use type, vegetation coverage, crop growth, etc. were also recorded. Soil conductivity of the surface (0–15 cm), subsurface (15–30 cm), middle (30–45 cm) and bottom (45–60 cm) layers was measured using an EC110 portable conductivity meter (Spectrum Technologies, Inc., Aurora, IL, USA. Which range is 0.00–199.9 ms/cm, accuracy is $\pm 2\%$).

By referring to previous studies and using the empirical formula of our research team, the soil conductivity measured in the field was converted into salt content data, and the water content data measured in the field was corrected.

The equation for the relationship between the measured electrical conductivity (EC_0 , $\mu\text{S}/\text{cm}$) and the salt content (S_t , %) is [7]:

$$S_t = 0.000211 \times EC_0 + 0.0875R^2 = 0.9685 \quad (1)$$

The equation for the relationship between the laboratory soil water content (W_0 , %) and the field-measured water content (W_i , %) is [15]:

$$W_0 = 0.9112W_i + 0.2418R^2 = 0.9894 \quad (2)$$

According to the grade standard of salinization degree [16], soil salinization can be divided into five grades according to soil salinity (%): non-salinization (0, 0.1), mild salinization [0.1, 0.2), moderate salinization [0.2, 0.4), severe salinization [0.4, 0.6) and saline soil [0.6, $+\infty$). Since there is no non-salinization soil grade in the study area, only four grades are actually involved.

2.2.2. Data Source and Classification of Driving Factors

When analyzing the driving factors of salinization, previous scholars mostly considered “stable” factors such as topography and geomorphology, groundwater depth and groundwater mineralization, but lacked the research on “variable” factors between seasons. Among the driving factors selected in this paper (Table 1), the salt content of the subsurface, middle and bottom layers, together with the water content of the soil, form a water-salt transport system between soil layers at different depths [17], thus influencing the soil salt content of the surface layer; the vegetation coverage influences it through the evaporation of water; and the vegetation cover type influences the soil salt content through whether the vegetation is covered or not, and the degree of salinity tolerance of the vegetation itself. Among them, the data of soil salt content at different depths and soil water content are obtained through the inverse relation formula. Vegetation coverage data are first obtained from NDVI data through the Google Earth Engine (GEE) platform, and then obtained by pixel dichotomy in the ENVI 5.3 platform [18]; Vegetation cover type is obtained through field investigation.

Table 1. Classification of driving factors of soil salinization.

Level	Salinity of Soil Layers (%)			Soil Water Content (%)	Vegetation Coverage	Vegetation Cover Type
	Subsurface	Middle	Bottom			
1	0.2–0.4	0.2–0.4	0.2–0.4	>30	>0.8	Wheat–Maize
2	0.4–0.6	0.4–0.6	0.4–0.6	20–30	0.65–0.8	Cotton
3	>0.6	>0.6	>0.6	15–20	0.5–0.65	Winter jujube
4				12–15	0.4–0.5	Weeds
5				5–12	<0.4	Bare land

2.3. Research Methodology

2.3.1. Statistical Characteristics and Correlation Analysis of Soil Salinity

Statistical Product Service Solutions (SPSS) software (version: 23.0) [19] was used to statistically analyze the maximum, minimum, variance, mean, median, standard deviation, kurtosis, skewness and coefficient of variation of soil salinity in spring and summer, respectively. The coefficient of variation (CV) reflects the degree of dispersion and relative variation of random variables, and can be classified into three levels of variability: weak [0, 10%), medium [10%, 100%), and strong [100%, $+\infty$) [20]. The correlation between salt

contents of different soil layers was analyzed by using the Pearson–bilateral test correlation coefficient matrix.

2.3.2. Spatial and Temporal Distribution Characteristics of Soil Salinity

(1) Spatial distribution characteristics of soil salinity

Using ArcGIS (version: 10.7) [20], inverse distance weight interpolation was applied to soil salinity to analyze its two-dimensional spatial distribution characteristics. The inverse distance weight interpolation method was used to map the spatial distribution of soil salinity, which is more intuitive than Kriging in terms of regional and local trends [21].

Using GMS (version: 10.4.5) software [22], a three-dimensional grid was constructed with grid as the unit, and three-dimensional inverse distance weight interpolation (IDW) on soil salinity was carried out, so as to visualize and analyze the three-dimensional spatial and temporal variability of soil salinity. Three dimensional inverse distance weight interpolation is the application and expansion of two-dimensional inverse distance weight interpolation in three-dimensional space. Its basic principle is that the closer the distance between two points, the more similar the properties are. The distance between the sample point to be measured and the known sample point is used as the weight for weighted averaging, and the farther away the sample point to be measured, the smaller the weight given to the sample point [21]. The formula is as follows [23]:

$$V(x, y, z) = \sum_{i=1}^n w_i v_i(x_i, y_i, z_i) \quad (3)$$

$$h_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} \quad (4)$$

$$w_i = \left[\frac{R - h_i}{Rh_i} \right]^2 / \sum_{j=1}^n \left[\frac{R - h_j}{Rh_j} \right]^2 \quad (5)$$

In Equations (2)–(4), $V(x, y, z)$ is the value of the sample point to be measured, $v_i(x_i, y_i, z_i)$ is the value of the known sample point; h is the distance from the sample point to be measured to the known sample point; w_i is the weight; R is the maximum value of the distance from the n known sample points to the sample point to be measured participating in the calculation.

(2) Temporal variation characteristics of soil salinity

Based on the soil salinity data of two seasons, the change area and direction of different degrees of salinized soils in different seasons were analyzed by using a transfer matrix. The transfer matrix expression is [24]:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix} \quad (6)$$

where S_{ij} is the area transferred from saline soil type i to type j during the study period; i is the type of saline soil in spring, j is the type of saline soil in summer; n is the type of soil with different degrees of salinity. In this paper, $n = 4$.

The salinization severity index (S_i) is used to characterize the spatio-temporal distribution of regional soil salinity [25]:

$$S_i = \sum_{r=1}^4 \frac{A_r}{A} \times P_r \quad (7)$$

where S_i is the regional soil salinization severity index; A_r is the area of the r^{th} type of saline soil (For example A_1, A_2, A_3, A_4 represent the areas of mild, moderate, severe salinization

soil grades and saline soil); A is the area of different townships; P_r is the severity of different types of soil salinity, the weights of mild, moderate, severe salinization soil grades and saline soil are 1, 2, 3 and 4 respectively; the larger the value of S_i , the more serious the soil salinization in this area.

The dominant index of salinization degree change (C_i) is used to determine the main types of seasonal changes in soil salinization degree. The calculation formula is as follows [26]:

$$C_i = \frac{A_r}{\sum_{r=1}^4 A_r} \times 100\% \quad (8)$$

where C_i is the dominant index of the change area of the r th salinization soil type in the study area, with a value threshold of 0–100% (the larger the r th value, the more dominant the r th salinization soil change type is).

2.3.3. Detection and Analysis of Driving Factors of Salinization

The geo-detection method is a statistical method proposed by Wang et al. to analyze the spatial heterogeneity of geographical phenomena based on the theory of spatial variance [27]. This method can avoid the influence of human subjectivity, efficiently identify the relationship between multiple factors, and overcome the limitations that exist in traditional statistical analysis when dealing with categorical variables [28]. In this paper, two modules of the geo-detector: the factor detector and interaction detector, are used to quantitatively analyze the driving factors affecting soil salinity in the study area.

The factor detector module mainly detects the degree of influence of different driving factors on the spatial differentiation of soil salinity, and the higher the value of explanatory power q , the stronger the influence. The expression is [29]:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} = 1 - \frac{SSW}{SST} \quad (9)$$

$$SSW = \sum_{h=1}^L N_h \sigma_h^2 \quad (10)$$

where h is the classification of the salinization influencing factors; N_h and n are the number of units in layer h and the whole area, respectively; σ_h^2 and σ^2 are the variances of Y values in layer h and the whole area, respectively. SSW and SST are the sum of the variances within the layer and the total variance of the whole area, respectively; and the value range of q is [0, 1].

The interaction detection module is used to assess whether the interaction between two different driving factors, X_a and X_b , has an enhancing or weakening effect on the explanatory power of the dependent variable Y [30], which is judged on the basis shown in Table 2.

Table 2. Judgment basis of double factor interaction mode.

Criterion	Interaction
$q(X_a \cap X_b) < \min[q(X_a), q(X_b)]$	Non-linear weakening
$\min[q(X_a), q(X_b)] < q(X_a \cap X_b) < \max[q(X_a), q(X_b)]$	Single-factor nonlinear attenuation
$q(X_a \cap X_b) > \max[q(X_a), q(X_b)]$	Two-factor enhancement
$q(X_a \cap X_b) = q(X_a) + q(X_b)$	Independent Interaction
$q(X_a \cap X_b) > q(X_a) + q(X_b)$	Nonlinear independence

3. Results and Analysis

3.1. Statistical Characterisation of Soil Salinity

3.1.1. Descriptive Statistical Characteristics of Soil Salinity at Different Depths

The results of the descriptive statistical analysis of soil salinity are shown in Table 3. Both kurtosis and skewness of soil salinity in spring and summer were high, which did not conform to normal distribution. In spring, the average salinity values of the soil layers at 0–15 cm, 15–30 cm, 30–45 cm and 45–60 cm were 0.39%, 0.46%, 0.45% and 0.47%, respectively, with only the layer of 0–15 cm being at a moderate salinization level overall and all the layers of 15–60 cm being at the level of severe salinization. From top to bottom, the average values change trend of soil salinity is to increase first, then decrease, and then increase again. The largest variation range of the average soil salinity of the soil layers is found between 0–15 cm and 15–30 cm. The reason of this phenomenon may be that most of the sampling sites are located in farmland. In the natural state, long-term leaching resulted in the formation of a clay layer at about 30 cm, while the plough bottom layer was formed at about 15 cm under the action of mechanical tillage. At the same time, the lack of rainfall and irrigation in spring had hindered the migration of water and salt between soil layers. The coefficients of variation of soil salinity at the 0–15 cm and 30–45 cm layers were 117.49% and 105.41% respectively, which were a strong variation, while the 15–30 cm and 45–60 cm layers were of medium variability. In summer, the average values of soil salinity of 0–15 cm, 15–30 cm, 30–45 cm and 45–60 cm soil layers were 0.32%, 0.46%, 0.56% and 0.62%, respectively. The upper three layers were moderately salinized and the bottom layer was heavily salinized, with a gradual increase in salinity from top to bottom. Except that the soil salinity of 0–15 cm layer was of medium variation, the other soil layers were of strong variation. This is probably due to the uneven spatial distribution of rainfall. The average soil salinity of 0–15 cm layer in the study area is lower in summer than in spring, but the soil salinity of the 15–30 cm, 30–45 cm and 45–60 cm layers is correspondingly higher in summer than in spring, and the topsoil showed a clear characteristics of seasonal desalination. This may be related to the fact that in some areas, summer precipitation is too concentrated and acts as a bridge between highly mineralized groundwater in the soil, and salt is actively transported in the sub-surface layers resulting in higher salinity in each layer.

Table 3. Descriptive statistical characteristics of soil salinity in different seasons and depths.

Season	Soil Depth (cm)	Sample Size	Min (%)	Max (%)	Mean (%)	Variance	SD	Kurt	Skew	CV (%)
Spring	0–15	53	0.11	2.73	0.39	0.21	0.46	14.66	3.69	117.49
	15–30	53	0.21	2.76	0.46	0.19	0.43	15.95	3.71	93.88
	30–45	53	0.19	2.95	0.45	0.23	0.48	16.26	3.82	105.41
	45–60	53	0.21	2.39	0.47	0.15	0.39	12.01	3.24	84.12
Summer	0–15	53	0.14	1.72	0.32	0.087	0.29	18.95	4.30	90.61
	15–30	53	0.18	2.81	0.46	0.32	0.56	12.58	3.62	121.74
	30–45	53	0.22	3.25	0.56	0.41	0.64	12.32	3.56	114.29
	45–60	53	0.23	3.00	0.62	0.37	0.60	10.81	3.32	96.77

3.1.2. Correlation between Soil Salinity at Different Depths

The correlation coefficient matrix between soil salinity at different depth layers is shown in Table 4. It can be seen that the correlation coefficient of soil salinity in each layer is greater than 0.80 both in spring and in summer, showing a very significant positive correlation. In spring, the correlation coefficient between soil salinity of adjacent soil layers tended to increase gradually from top to bottom; 30–45 cm and 45–60 cm soil layers have the strongest correlation, with a correlation coefficient of 0.992; The correlation between 0–15 cm and 45–60 cm soil layers is the weakest, with a correlation coefficient of 0.968; The correlation between adjacent soil layers was greater than that between non-adjacent soil layers. In summer, the correlation between soil salinity of adjacent soil layers was also

greater than that between non-adjacent soil layers. The correlation between 15–30 cm and 30–45 cm soil layers is the strongest, and the correlation coefficient is 0.993. The correlation between 0–15 cm and 30–45 cm soil layers is the weakest, and the correlation coefficient is 0.849. In general, due to the uneven spatial distribution of rainfall in summer, the strong water salt movement among soil layers in regions with more rainfall, and the frequent changes in salt content of each soil layer, the correlation between soil salinity of each soil layer in summer was overall lower than that in spring.

Table 4. Correlation coefficient matrix of soil salinity.

Soil Depth (cm)	Spring				Summer			
	0–15	15–30	30–45	45–60	0–15	15–30	30–45	45–60
0–15	1				1			
15–30	0.985 **	1			0.864 **	1		
30–45	0.981 **	0.986 **	1		0.849 **	0.993 **	1	
45–60	0.968 **	0.975 **	0.992 **	1	0.854 **	0.972 **	0.983 **	1

Note: “**” indicates that the significance level is $p < 0.01$.

3.2. Spatial Distribution Characteristics of Soil Salinity

3.2.1. Two-Dimensional Spatial Characteristics of Seasonal Variation of Soil Salinity

The two-dimensional spatial distribution characteristics of surface soil salinity are shown in Figure 2 and Table 5. In spring, the area near the mudflats in the north is dominated by saline soils, with an area of 166.59 km², accounting for 12.07% of the total area of the study area. This area has been impregnated by seawater for a long time, with high groundwater mineralization and the most serious salinization. To the south, it is adjacent to the area of severe salinization grade soils, with an area of 201 km², accounting for 14.56%, distributed in strips. The area of moderate salinization grade soil is 816.74 km², accounting for 59.16%, which is mainly distributed in the western, central, southern and eastern parts of the study area. It is the main type of salinization soil in the study area. Mild salinization soil type is distributed in the southwestern part of the study area, with an area of 196.33 km², accounting for 14.22%. In summer, saline soil and severe salinization soil type are still mainly distributed in the northern part of the study area, with a total area of 159.06 km²; the moderate salinization soil type covers an area of 1184.25 km², accounting for 85.77%, which is distributed in a concentrated and continuous manner throughout the study area; mild salinization soil type is patchily distributed in the central part of the study area, accounting for only 2.71% of the area. The two-dimensional distribution map shows that the seasonal changes in surface salinization soils include both the desalination process (mainly in the severe salinization and saline soil areas in the north) and re-salinization process (mainly in the mild salinization areas in the southwest). This shows that the seasonal changes of soil salinization in the study area are more complex.

Table 5. Soil area with different degrees of salinization.

Degree	Saltiness (%)	Spring		Summer	
		Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)
Mild salinization	0.1–0.2	196.33	14.22	37.36	2.71
Moderate salinization	0.2–0.4	816.74	59.16	1184.25	85.77
Severe salinization	0.4–0.6	201.00	14.56	88.38	6.40
Saline soil	>0.6	166.59	12.07	70.68	5.12

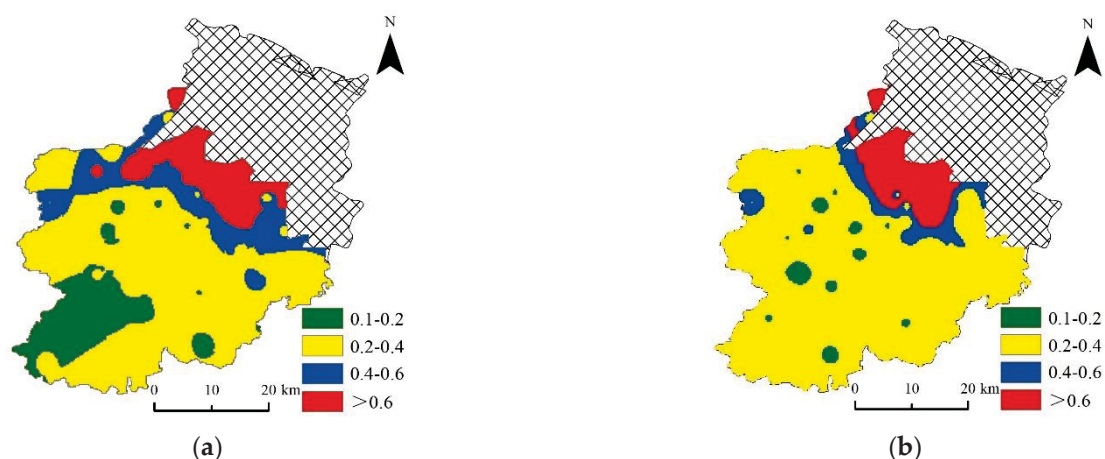


Figure 2. Spatial distribution of surface soil salinity: (a) spring; (b) summer.

3.2.2. Three-Dimensional Spatial Characteristics of Seasonal Variation of Soil Salinity

The three-dimensional spatial distribution of soil salinity in the study area is shown in Figure 3.

As can be seen from Figure 3a,b, in spring, the soils in the study area are mainly the moderate salinization type, and the profile distribution of soil salinization in most areas is through homogeneous type (similar salinity in all layers). In the northwest part of the study area, there is a local phenomenon of salt aggregation at the bottom (the salinity of the bottom layer is higher than that of the surface layer). This is related to the fact that the land use types of the sample sites are mainly arable land and that it is close to the Zhangwei New River, which has good irrigation conditions and helps the downward migration of salts with water. In the south-western part of the area, there is also localized salt accumulation at the bottom, but the overall salinity is low. This area is the highest terrain in the whole region, where salts do not accumulate easily and most of it tends to migrate out with water. As can be seen from Figure 3c,d, in summer, the soils in the study area are still predominantly the moderate salinization type, and the overall distribution of the soil salt profile is the homogeneous type. However, in the north-western part of the study area, the proportion of severe salinization soil type in the surface layer decreased significantly compared with that in spring, while the salinity degree at the bottom increased, showing a bottom aggregation distribution. This is clearly related to the different precipitation in spring and summer (Figure 4). The average monthly rainfall in summer of 2015 was 153.87 mm, while the average monthly rainfall in spring was only 39.2 mm. The summer rainfall reached its peak in early August, significantly enhancing the leaching of surface soil salt (Figure 3). Compared with spring, the soils in the southwest of the study area showed a slight re-salinization trend. This may be related to the fact that the concentration of rainfall was from July to early August, and the uneven spatial distribution. There was little rainfall in some areas, but the continuous high temperature and strong evaporation (the average monthly evaporation in summer is 236.7 mm) led to the enrichment of salts from lower layers to the surface layer under the action of capillaries.

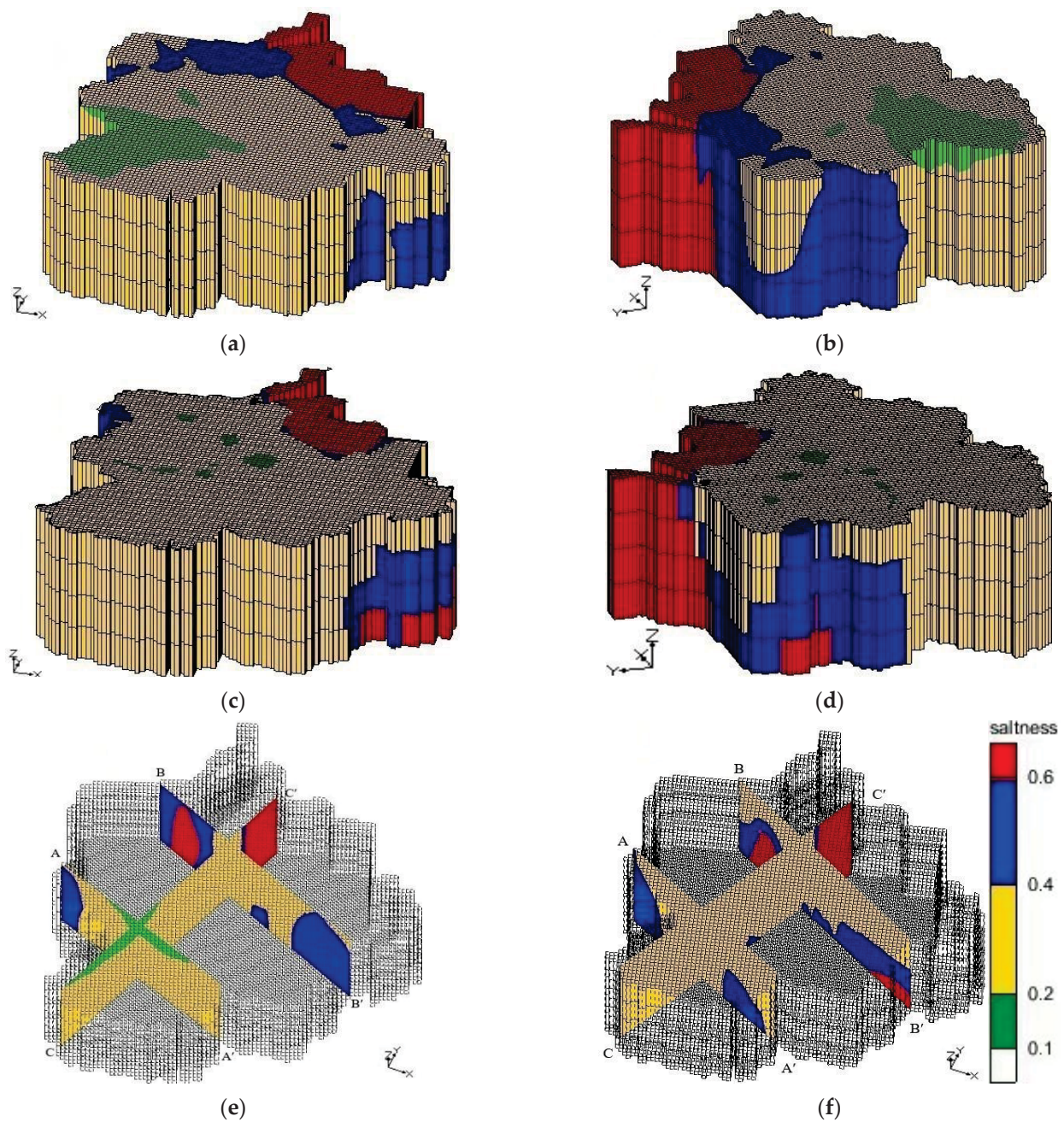


Figure 3. Three-dimensional spatial distribution of soil salinity: (a) Three-dimensional spatial distribution map of soil salinity in spring; (b) Three-dimensional spatial distribution map of soil salinity after 90° counterclockwise rotation of (a); (c) Three-dimensional spatial distribution map of soil salinity in summer; (d) Three-dimensional spatial distribution map of soil salinity after 90° counterclockwise rotation of (c); (e) Typical profile of three-dimensional soil salinity in spring; (f) Typical profile of three-dimensional soil salinity in summer.

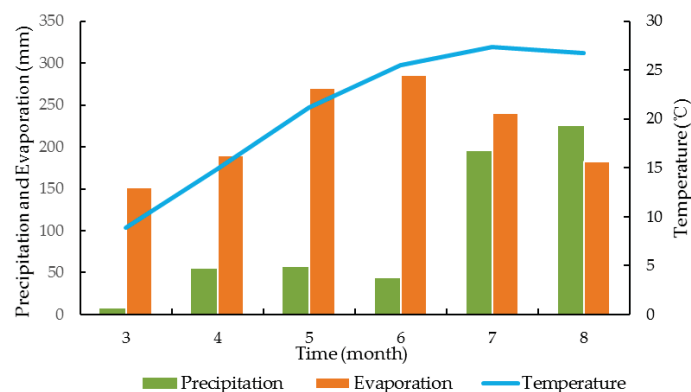


Figure 4. Statistics of monthly average precipitation, evaporation and temperature in the study area from March to August.

Based on the general characteristics of the spatial distribution of soil salinity in the study area in both seasons, and taking into account its topography, three typical cross-sections A–A', B–B' and C–C' (Figure 3e,f) were selected to analyze the distribution of salinity profiles in the study area. As shown in Figure 3, the A–A' cross-section runs from the south-west corner to the south-east corner of the study area. The soil profile is dominated by the moderate salinization soil type in both spring and summer, while the variation between seasons is more significant. The side at the A end (south-west corner of the study area) has a higher topography, a deeper water table (between 2–2.5 m) and a lower groundwater mineralization (2–5 g/L), which does not easily cause salt reversion even under strong evaporation in summer. The distribution of salinity in the profile changes from the homogeneous type in spring to the bottom accumulation type in summer. The central part of the section is gently sloping, with lower elevation, and although the mineralization of groundwater is also between 2–5 g/L, the burial depth of groundwater is mostly 1.5–2 m; This led to a slight trend of salinity reversion in the surface layer, and the salt distribution in the profile changed from the bottom accumulation type in spring to the homogeneous type in summer. Near A' (southeast of the study area), the bottom layer of the profile shows a salt accumulation trend, which changes from a homogeneous type in spring to a bottom accumulation type in summer. The difference in seasonal variation of the central part of the B–B' section is small, but the difference in seasonal variation between the two ends of the section is obvious. The seasonal desalination is obvious on the B side (northwestern part of the study area) and the B' side (eastern part of the study area), and the distribution of salinity in the section changes from the homogeneous type in spring to the bottom accumulation type in summer. According to the analysis of reasons, although both B and B' areas are shallow flat depressions with low terrain, they are mainly cultivated land with good irrigation conditions. The strong rainfall in summer has a significant effect on the leaching and salt pressing of surface salt. The C–C' section runs from the southwest corner to the northeast corner of the study area, and there is no significant difference between the seasonal changes in the rest of the area, except for a slight local re-salinization trend on the C side (southwest corner of the study area).

3.3. Temporal Variation Characteristics of Soil Salinity

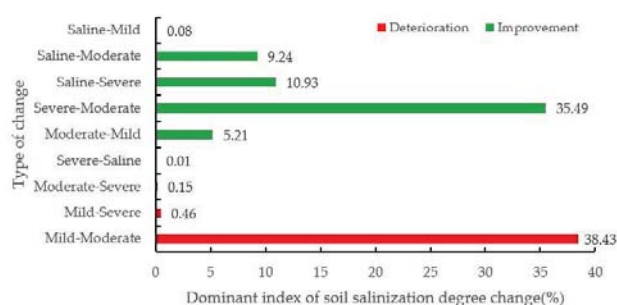
3.3.1. Characteristics of Soil Salinization Transfer

The surface soil salinization transfer area, dominant index of salinization degree change (C_i) and the salinization severity index (S_i) were used to characterize the temporal variation characteristics of soil salinity in the study area. As can be seen from Table 6, from spring to summer, the area of mild salinization soil type decreased significantly, from 196.44 km² to 37.58 km², reducing by 80.87%; the moderate salinization soil type increased from 817.44 km² to 1185.24 km², with an increase of 44.99%. Among them, the area of mild salinization soil type increased to moderate salinization soil type is 181.67 km², and the area

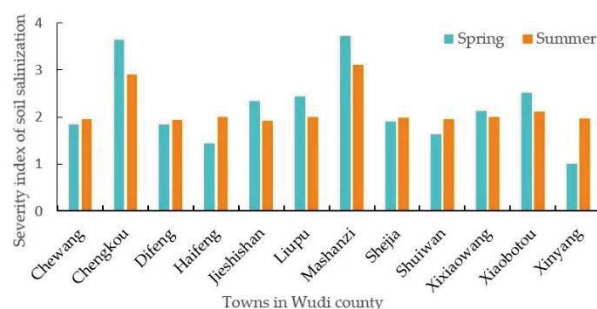
of severe salinization soil type decreased to moderate salinization soil type is 167.77 km². The area of severe salinization soil type decreased from 201.15 km² to 87.83 km², a decrease of 56.34%. The change range of the saline soil area is the smallest, decreasing by 95.16 km². Figure 5a shows the histogram of the change in area of different degrees of salinization soil in the study area. The seasonal change trend of salinization soil area of different salinization degrees is different. The area of mild, severe and saline soil decreased, while the area of moderate salinization soil type increased. Overall, the area with increased salinity from spring to summer is 184.61 km², and the area with reduced salinity is 288.09 km², with a difference of 103.48 km². In terms of area, the study area shows an overall desalination process from spring to summer.

Table 6. Transfer matrix of salinization soil of different degrees from spring to summer.

		Summer				
		Mild Salinization	Moderate Salinization	Severe Salinization	Saline Soil	Sum
Spring	Mild salinization	12.60	181.67	2.17	0.00	196.44
	Moderate salinization	24.64	792.10	0.70	0.00	817.44
	Severe salinization	0.00	167.77	33.31	0.07	201.15
	Saline soil	0.34	43.70	51.65	69.95	165.64
	Summation	37.58	1185.24	87.83	70.03	1380.67



(a)



(b)

Figure 5. Change degree of soil salinization: (a) Dominant index of soil salinization degree change; (b) Severity index of soil salinization.

The dominant index of soil salinization change (C_i) was calculated by Equation (9) to highlight the main types of seasonal changes in salinization soils (Figure 5a). From spring to summer, the change type of soil salinization degree is mainly from mild salinization to moderate salinization soil, with a dominance index of 38.43%. The second is the transition from severe salinization to moderate salinization soil, with a C_i value of 35.49%. The proportion of area change of four types of saline soil–mild salinization, severe salinization–saline soil, moderate salinization–severe salinization, and mild salinization–severe salinization is the smallest, with C_i values less than 1%. In the process of seasonal alternation, the significant degradation of mild salinization to moderate salinization soil type deserves attention. Necessary irrigation control measures should be taken to enhance the desalination effect in summer.

3.3.2. Severity of Soil Salinization in Different Towns

Based on the transfer matrix, the severity of soil salinization in different townships was quantified by Equation (7) (see Figure 5b). In spring, the salinization severity indexes of Mashanzi Town and Chengkou Town were 3.72 and 3.64, respectively, which were the two towns with the most serious salinization hazards in the study area, followed by Xiaobotou Town, Liupu Town, Jieshishan Town and Xixiaowang Town; Xinyang Town was the least

affected by salinity hazards, with a severity index of 1. In summer, only Mashanzi Town was located in the area where the salinization severity index was greater than 3. The towns with a salinization severity index between 2–3 were Chengkou, Xiaobotou, Liupu, Haifeng and Xixiaowang town in descending order; Jieshishan Town had the lowest salinization severity index at 1.94.

From spring to summer, Chewang Town, Difeng Street, Haifeng Street, Shejia Town and Shuiwan Town were the towns where the severity of soil salinization increased. Among them, the salinization severity of Haifeng Street was the most obvious, where the change rate of salinization severity index was 38.89%; The second was Shuiwan Town, with a change rate of 19.63%; The change rate of Difeng Street and Shejia Town was the lowest. The towns with a decreasing trend in the seasonal change of salinization severity were Chengkou Town, Jieshishan Town, Liupu Town, Mashanzi Town, Xixiaowang Town, Xiaobotou Town and Xinyang Town. Among them, Chengkou Town had the most obvious degree of salinization reduction, with a salinization severity index change rate of −20.06%, while Jieshishan town, Liupu town and Xiaobotou town had a similar degree of salinization reduction, with a change rate of about −17%.

3.4. Salinisation Driving Factors in Different Seasons

3.4.1. Driving Factors of Salinization Variation of Spring and Summer

The explanatory power of salinization driving factors in different seasons, obtained from factor detection of geographical detectors, is shown in Table 7. It can be seen that, from the perspective of horizontal factor contrast, the explanatory power of the different influencing factors on the spatial distribution of soil salinity in spring is in the order of large to small: subsurface soil salinity, middle soil salinity, soil water content, bottom soil salinity, vegetation cover type, and vegetation coverage. The influence values of subsurface soil salinity, middle soil salinity, soil water content, bottom soil salinity and vegetation cover type were all greater than 0.5, which were the dominant influencing factors of spatial distribution of soil salinization in the study area in spring; The influence value of vegetation coverage was 0.197 which was the weakest explanatory power. In summer, the explanatory power of influencing factors in descending order is: subsurface soil salinity, vegetation cover type, vegetation coverage, middle soil salinity, bottom soil salinity and soil water content. Among them, only the influence values of subsurface soil salinity and vegetation cover type are greater than 0.5, which are the dominant influencing factors of spatial distribution of soil salinity in summer in the study area; The vegetation coverage has strong explanatory power with an influence value of 0.425; The middle soil and bottom soil salinity have average explanatory power with q values between 0.3 and 0.4. Soil water content has the weakest explanatory power with a q value of 0.156.

Table 7. Explanatory power of salinization driving factors in different seasons.

	Spring		Summer	
	q	Rank	q	Rank
Subsurface soil salinity	0.666	1	0.555	1
Medium soil salinity	0.623	2	0.398	4
Bottom soil salinity	0.566	4	0.315	5
Soil water content	0.582	3	0.156	6
Vegetation coverage	0.197	6	0.425	3
Vegetation cover type	0.543	5	0.551	2

From the perspective of longitudinal seasonal change, the influence value of subsurface, middle and bottom soil salinity and soil water content on the spatial distribution of soil salinity in the study area showed a significant decreasing trend, that of vegetation coverage showed a significant increasing trend, and that of vegetation cover type showed a slightly increasing trend. Specifically, from spring to summer, the q -value of soil water content decreased from 0.582 to 0.156, with a significant decrease of 73.20% in explanatory power;

the q -value of soil salinity in the middle layer decreased from 0.623 to 0.398, with a decrease of 36.12% in explanatory power; the q -values of subsurface soil salinity and bottom soil salinity decreased by 0.111 and 0.251, respectively, and the reduction amplitude was 16.67% and 44.35%. The q value of vegetation coverage increased from 0.197 to 0.425, a significant increase of 115.74% in explanatory power; while the q value of vegetation cover type only increased by 0.008, an increase of 1.47%. In spring, the study area is dry and rainless, which causes the spatial distribution of soil salinity to be greatly influenced by the salinity of subsurface, middle and bottom soil; In summer, the rainfall increased significantly, relatively weakening the influence of soil water content on the spatial distribution of surface soil salinity; At the same time, with the increase of temperature and evaporation, the intensity of water-salt transport in the soil profile is intense, which led to the weakening influence of subsurface, middle and bottom soil salinity on their spatial distribution. August is the period of flourishing plant growth, when the degree of vegetation coverage is significantly increased compared with spring; this reduced the evaporation of surface soil water, so the influence value of vegetation coverage showed an increasing trend between seasons.

3.4.2. Interaction of Salinization Driving Factors

The interaction detection analysis module of the geographic detector can investigate whether the spatial distribution of soil salinity is driven by a single factor or by multiple factors [31]. On the one hand, the greater the q value of interactive detection interpretation force, the stronger the synergistic effect of driving factors than that of a single driving factor. On the other hand, it is also possible to explore whether the comprehensive effects of driving factors enhance, weaken, or are independent of each other for saline degradation [31]. From the interaction detection results (Figure 6), it is clear that the spatial distribution of soil salinity in the study area is not only influenced by a single driving factor, but also affected by the interaction of multiple factors.

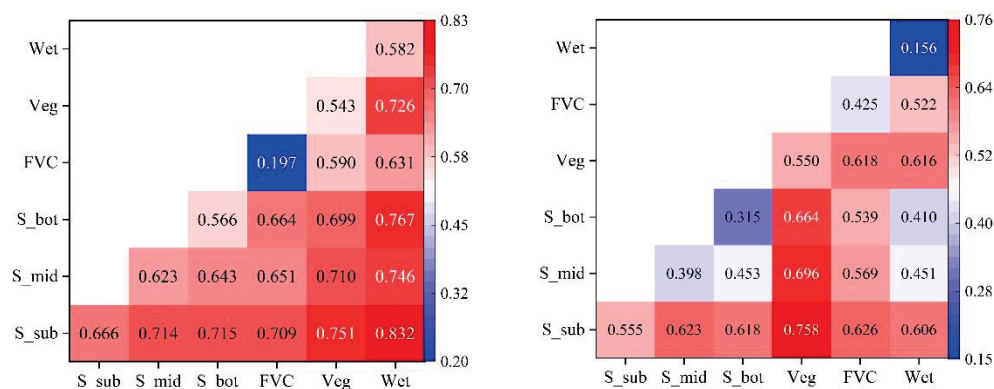


Figure 6. Interactive detection results in different seasons. S_sub, S_mid, S_bot, Wet, FVC, Veg represent subsurface soil salinity, middle soil salinity, bottom soil salinity, soil water content, vegetation coverage, and vegetation cover type, respectively.

In spring, soil water content $\cap$ subsurface soil salinity had the strongest explanatory power for the spatial distribution characteristics of soil salinity (0.832), followed by bottom soil salinity $\cap$ soil water content (0.767), subsurface soil salinity $\cap$ vegetation cover type (0.751), middle soil salinity $\cap$ soil water content (0.746), soil water content $\cap$ vegetation cover type (0.726), subsurface soil salinity $\cap$ bottom soil salinity (0.715), subsurface soil salinity $\cap$ middle soil salinity (0.714), middle soil salinity $\cap$ vegetation cover type (0.71), subsurface soil salinity $\cap$ vegetation coverage (0.709), all having an explanatory power greater than 0.7. In summer, subsurface soil salinity $\cap$ vegetation cover type had the strongest explanatory power, with a q -value of 0.758, followed by middle soil salinity $\cap$ vegetation cover type (0.696), and bottom soil salinity $\cap$ vegetation cover type (0.664), all of which had an explanatory power greater than 0.65. In spring and summer, the single factor with the strongest explanatory power of interaction in the study area included subsurface soil

salinity. This indicated that the coordination of subsurface soil salinity and other factors has an important impact on the spatial distribution of soil salinity in spring and summer in the study area.

4. Discussion and Conclusions

4.1. Discussion

When previous scholars studied the spatial and temporal variation characteristics of regional soil salinization, they mostly based their studies on two-dimensional spatial distribution characteristics. Some of the studies involving three-dimensional spatial distribution characteristics of salinity were located in the Yili Valley [12], the Production and Construction Corps of Xinjiang [13], etc. The three-dimensional spatial and temporal analysis of soil salinization in coastal regions is relatively lacking. The climate in the study area is windy and dry in spring, with less rainfall and large evaporation, and hot and rainy in summer, with concentrated precipitation, leading to significant variability in the seasonal variation of soil salinization. However, the exploration of seasonal variation of salinization in this region is still not in-depth. This paper analyzed the spatial and temporal variability of soil salinity in spring and summer of Wudi County in the coastal Yellow River Delta from two-dimensional and three-dimensional perspectives, and made a tentative exploration of the three-dimensional visual analysis of the spatial characteristics of soil salinization and the excavation of the temporal and spatial variation mechanism of salinization. The results of this paper show that the basic characteristics of the soil salinization process in the study area from spring to summer is desalination, which is generally consistent with the findings of Zhang et al. [32]. However, there is a more complex situation of salinization variation in different locations in the study area. The average soil salt content in the study area in spring changes from top to bottom with the trend of first increasing, then decreasing, and then increasing, which is different from the research results of Lv et al. [33]. This is probably due to the fact that there are more cultivated lands in the sampling sites. The clay deposit layer and plough bottom layer were formed at 30 cm and 15 cm, respectively, under long-term natural leaching and mechanical tillage. To a certain extent, they hindered the vertical water-salt transport between soil layers, and the lateral movement was highlighted. However, research on the role of these two “isolation layers” is still not in-depth. Jiang et al. [34] believed that compaction of subsurface soil would lead to a reduction of soil capillary pores, the reduction of soil aeration and permeability, and increase soil infertility. Schneider et al. [35] believed that on a global scale, breaking the bottom of the plough would help improve crop yield. But can it be the same in salinized areas? In the future, these “isolation layers” could be considered to be included in the research on the mechanism of water and salt transport between soil layers as an important aspect of the transfer from the macro to the micro perspective. In this paper, the severity index of soil salinization was introduced to quantify the severity of salinization in different towns. Among them, the soil salinization in Mashanzi Town is the most serious in spring and summer. This is closely related to its proximity to tidal flat, high groundwater mineralization, shallow groundwater burial depth, etc., and therefore Mashanzi Town should be a key area for monitoring and preventing salinization damage in the study area.

Unlike most previous studies that focused on the analysis of “stable” influencing factors [36–38], the influencing factors selected in this paper were mostly “variable” between seasons. The dominant driving factors affecting the spatial distribution of soil salinity in spring and summer were preliminarily identified. However, considering the availability of data, only six types of factors were selected for analysis in this paper. In the follow-up study, more factors can be considered to further clarify the factors influencing the variability of salinity in different seasons.

4.2. Conclusions

- (1) The results of mathematical statistics and correlation analysis showed that the soil salinity of the surface soil in the study area was lower in summer than in spring, but

the soil salinity of the subsurface, middle and bottom soil layers was correspondingly higher than that in spring; the surface soil showed obvious characteristics of summer desalination. The variation of soil salinity was obvious, and the variation coefficients of soil salinity at different depths in the two seasons were all greater than 90%. The correlation between the soil salinity of adjacent soil layers was greater than that between non-adjacent layers in both seasons; The correlation between the salinity of each soil layer in summer was lower than that in spring.

- (2) In two-dimensional space, the areas where the surface soil salinity was greater than 0.4‰ in both seasons were mainly located in the northern part of the study area. In three-dimensional space, the soils were mainly of the moderate salinization type in both seasons, and the distribution of the salt profile was mainly the homogeneous type in spring, while more areas had a bottom aggregation distribution in summer in addition to the homogeneous type. Overall, the distribution of soil salt profile is more complex in summer than in spring.
- (3) In terms of temporal variability, Mashanzi Town was the most severely affected area by salinization in both seasons, with the salinization severity index S_i greater than 3. At the change of seasons, the area of mild and severe salinization soil and saline soil tended to decrease, while the area of moderate salinization soil tended to increase. Among them, mild aggravated to moderate salinization soil were the dominant change type, with the dominant index of salinization change value (C_i) of 38.43%, followed by severe mitigated to moderate salinization soil types with C_i value of 35.49%.
- (4) The single-factor detection results show that sub-surface soil salinity, middle soil salinity and soil water content are the main factors influencing the spatial distribution of salinity in the study area in spring; sub-surface soil salinity, vegetation cover type and vegetation coverage are the main factors influencing the spatial distribution of salinity in the study area in summer. The influence value of vegetation coverage tends to increase significantly when the seasons change. The results of the interaction detection show that the influence of the interaction between any two factors on the spatial distribution of salinity is greater than that of the corresponding single factor, and that the subsurface soil salinity and other factors act in concert to have an important influence on the spatial distribution of soil salinity in the study area in spring and summer.

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Article

Coastal Soil Salinity Amelioration and Crop Yield Improvement by Biomaterial Addition in East China

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Abstract: A field experiment was conducted to investigate the effects of biochar (BC), fulvic acid (FA) and *Bacillus subtilis* (BS) on soil properties and crop growth in the coastal salt-affected soil. Four levels of BC (0, 7.5, 15, 30 t ha^{−1}), two levels of FA (0, 1.5 t ha^{−1}) and BS suspension (0, 108 CFU mL^{−1}) were designed during the maize cultivation. The results showed that 30 t ha^{−1} BC treatment was the most beneficial for improving the soil qualities. The grain yields in treatments containing FA and BS were lower than that in the BC treatments, and they were lower than that in the CK treatment. The treatment of 15 t ha^{−1} BC + BS obtained the highest grain yield, which was 1.75 times more than CK. An antagonism effect of the combination of FA and BS induced a grain yield decrease, and a higher content application of BC alleviated the negative effects.

Keywords: biomaterial; maize; soil organic carbon; soil salinity; yield

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1. Introduction

Soil salinity is the main obstacle factor in developing farmland in a coastal tidal flat reclamation region. The way to address this challenge will be a long-term mission. Efforts have been made to control soil salinity by various technological means, including physical, hydrological, chemical, biological techniques and combined remediation techniques. Soil conditioner is a mixture of various substances, which has great potential in salt removal [1], promotion of crop growth [2], improvement of crop quality and amelioration of soil culture [3]. The present study pertains to the soil conditioner and provides more information about it for further research.

Biochar (BC) is a classic type of charcoal, which is produced by heating wood, crop waste or other biomass in a tightly closed container with little or no available air at relatively low temperatures (<700 °C) [4]. As an agricultural amendment, the use of biochar has attracted much attention for the coastal amelioration of saline-alkali soil. Biochar is commonly alkaline; it can be used to increase the pH in acidic soils [5]. Although the properties of biochar effects are limited by the reaction vessel, the original organic material, the heating rate, the highest temperature and the holding time of pyrolysis, porosity and a stable structure are its common properties. In addition, carbonates are the major alkaline components in biochar, its metal cations being generated from the different feedstock [6]. Therefore, we can take advantage of its porosity and stability properties for saline-alkali soil conditions improvement after reducing its carbonate content.

Fulvic acid (FA) is a water-soluble humic material, which is well known as a kind of plant biostimulant for enhancing nutrient uptake and growth by the plant, controlling soil-borne diseases and improving soil condition. *Bacillus subtilis* (BS) is beneficial for plants by promoting growth and inducing disease suppression [7–9]. The strain has the ability to adapt to the soil environment by exchanging linked blocks of genes and maintaining gene diversification [10]. The isolation of halotolerant *Bacillus subtilis* was conducted in many

research works, and it has been proven that it exerts positive effects on the physiology characterization of plants under salinity stress [11].

Each year, China produces approximately 800 million tons of agricultural straw, but almost 40 percent is burned in the fields as waste [12]. The biochar produced from these agricultural residues could be applied to agricultural land for an efficient use of resources, which could also help reach the goals of carbon reduction and sequestration. Maize is one of the most important cereal crops in the world as a salt-sensitive crop [13]. The promising material ‘biochar’ and fulvic acid could be added into soil with maize plantations, and then, the influence of different treatments on soil properties and the physiological character of the plants could be compared. Maize planting experiments would be an effective approach to improve the soil habitat and develop coastal area agriculture.

Therefore, our objective for the study was to investigate the effects of biochar, fulvic acid and *Bacillus subtilis* on soil properties and maize agronomic characteristics. We hypothesized that biomaterial additions would improve plant performance in the coastal tidal flat region and provide assistance for saline agricultural development by using the optimal result of the research.

2. Materials and Methods

2.1. Experimental Site and Soil

The field experiment was conducted in Huanghaiyuan Farm (32°38′42.01″ N, 120°54′8.04″ E), which is located in Jianggang village of Dongtai city, Jiangsu province, China. The experimental field was reclaimed in 2005, and it is approximately 2 km away from the coastline of the China Yellow Sea. The climate of the study area is subtropical, and it is influenced by the transition, oceanity and monsoon, with large seasonal fluctuations in temperature and rainfall as well. The mean annual precipitation in the study area is 1042 mm, occurring mostly during the rainy season from June to September, which is about 70% of the annual precipitation. The mean annual evaporation is 1417 mm, and the average annual temperature, wind velocity and relative humidity are 14.6 °C, 3.3 m s^{−1} and 81%, respectively.

In the study area, marine deposits are the main soil parent materials, and soil salinity is known as the main barrier factor. The soil in the study area is typical coastal saline soil in east China. Silty loam is the predominant soil type in the study area because it has a poor soil environment, such as low porosity (42%), high infiltration and soil impedance (cone index 4.86 Mpa), as well as low organic matter content (3.2 g kg^{−1}).

2.2. Characterization of Biochar, Fulvic Acid and *Bacillus Subtilis*

Biochar was derived from wheat straw residue by temperature treatment at 350–550 °C and a furnace residence time of 8 h in a biogas energy pyrolysis system (Sanli New Energy. Ltd., Xinxiang City, China). It contained 467 g kg^{−1} organic carbon, 0.6 g cm^{−3} bulk density with a surface area of 8.92 m² g^{−1} and a cation exchange capacity of 21.7 cmol kg^{−1}. The pH and EC values of biochar were 10.41 and 1.01 ds m^{−1}, determined at 1:20 biochar to deionized water extraction (GB/T 12496.7 1999), respectively.

FA was produced by Hongtudi Humic Acid Company in JiangXi Province. The FA was produced using straws—first by cutting the wheat straw to average 0.5 cm fragments, then combining the straw with microbial fermentation and adjusting the pH of the combination to 7.5. After 2 weeks of cultivation, the liquid was extracted, and a 0.1 mol L^{−1} NaOH solution was added to obtain the sediments, which were then left to set for 1 h. The FA powder was produced by passing the sediments through 100 meshes. The pH value of FA measured in the extraction deionized water was 5.65; the water was 1:5 FA. Otherwise, the *Bacillus subtilis* was purchased from Kelvfeng Biochemistry Science and Technology Company in Baoding city. It was produced starting from the test tube strain. The culture was increased by step expansion, and finally, *Bacillus subtilis* was fermented by a mechanical stirring tank. The cultivation media consisted of wheat straw, sugar, protein, water and salt solutions. The *Bacillus subtilis* agent had approximately one billion live bacteria per gram.

2.3. Experimental Design

A field experiment design was established in June 2015 using a completely randomized factorial design to investigate the effects of applying different proportions of BC and/or FA and/or BS on the properties of soil and on the growth and productivity of maize. Some measures were implemented to reduce the salinity of biochar. Firstly, we ground the biochar to pass it through a sieve of 2 mm and soaked the biochar in deionized water for 24 h and stirred it for some time before filtrating the water. Then, we wetted the biochar to 25% (w/w) to prevent the ashes from floating away. The FA were sprayed on a BC surface with the treatment design containing BC and FA. *Bacillus subtilis* was used for the treatment of maize seeds, and the seeds were soaked in the bacterial suspension incubated at 27 °C for 2 h [14]. The seeds were air-dried after BS incubation for sowing in the soil.

Four levels of biochar were designed in the study: 0 t ha⁻¹, 7.5 t ha⁻¹, 15 t ha⁻¹ and 30 t ha⁻¹. The amount of FA was 0, 1.5 t ha⁻¹, and the concentration of the BS suspension was 108 CFU ml⁻¹. A summary of the treatments is provided in Table 1. Each treatment was designed in triplicate, and each plot was arranged in a completely randomized block design. Each plot of 4 × 4 m in the area was separated with a drainage ditch 30 cm in width and 20 cm in depth. The treated biochar was spread on the soil surface, and then, we mixed it into the uppermost 15 cm of the soil within a plow. The FA was used in the soil following the same treatment procedure as BC treatments, which contained the FA without BC. The treatment group underwent the same tillage treatment as the plots with biochar. A week after amending the biochar in the soil, the maize cultivar Changjiangv-9 was directly sown in each plot after treatment with the bacterial suspension. The sowing depth was 5–6 cm. The crop management was normal, and no irrigation was applied during the cultivation. Inorganic fertilizers were used in the experiment; total N, P fertilizers were applied at the rates of 240 kg N ha⁻¹ and 135 kg P₂O₅ ha⁻¹ in the forms of urea and monoammonium phosphate (MAP). A graphical representation of the experiment design is shown in Figure 1.

Table 1. The experimental treatments and their coding.

Medium	Treatments		
	Biochar (t ha ⁻¹)	Fulvic Acid (1.5 t ha ⁻¹)	BS Suspension Soak Seed
CK	0	N	N
T1	0	N	Y
T2	0	Y	N
T3	0	Y	Y
T4	7.5	N	N
T5	7.5	N	Y
T6	7.5	Y	N
T7	7.5	Y	Y
T8	15	N	N
T9	15	N	Y
T10	15	Y	N
T11	15	Y	Y
T12	30	N	N
T13	30	N	Y
T14	30	Y	N
T15	30	Y	Y

Note: The 'Y' represents the design implemented in this treatment; 'N' represents the design not implemented in this treatment. BS: *Bacillus subtilis*.



Figure 1. The experimental design of biomaterials obtained from straws for saline soil amelioration.

2.4. Sampling, Measurements and Analyses

Soil samples (0–20 cm) were collected by using a soil auger in each plot before applying the BC and FA, then air-dried and ground to pass through a 0.25 mm sieve for the soil organic C (SOC) analysis. The undisturbed soils (0–10 cm) were sampled with a ring knife to measure the bulk density (BD). The average values of soil water content (WC), soil saturated water content (SWC), capillary water holding capacity (CHC), soil total porosity (STP), capillary porosity (CP) and noncapillary porosity (NP) were measured by the ring knife test method. After planting maize, we took soil samples (0–20 cm) four times during the growth period to measure soil electrical conductivity (EC) and acidity (pH). The sampling periods were the seedling period (10 June), the elongating period (2 July), the tasseling period (28 July) and the rippling period (15 September), respectively. Subsequently, the samples were air-dried and passed through a 1 mm mesh sieve. During the rippling period, soil samples were obtained by a soil auger and a ring knife for the SOC and BD measurements. The saturated water content and field water capacity were measured with the ring knife. For measuring the maize growth characters, the heights of ten plants in each plot were recorded, and their grains were collected.

The parameters of SOC, BD, WC, TP and CP were determined as follows. The SOC was measured with the $K_2Cr_2O_7$ - H_2SO_4 oxidation testing method [15]. The EC and pH were measured at a solid/water ratio of 1:5 by a pH meter (pH 211 microprocessor pH meter, HANNA, Woonsocket, RI, USA) and an EC meter (EC 215 conductivity meter, HANNA, Sarmeda di Rubano, Italy). The soil bulk density (BD) and soil water holding capacity (SWC and CHC) were measured with the ring-cutting method (diameter and height of the ring knife were 5 and 5 cm, respectively) [15]. Total porosity (TP) was calculated from the bulk density and particle density (assumed to be 2.65 g cm^{-3}), calculating the capillary porosity (CP) and noncapillary porosity (NP) as well. For maize yield measurement, the grains in each plot were collected and weighed after drying at 65°C .

2.5. Statistical Analyses

All data were analyzed using SPSS (Statistical Product and Service Solutions) 19.0 (IBM company, New York, NY, USA) for Windows software. Significant differences for all data were tested with one-way ANOVA analysis followed by least significant differences (LSD) at $p < 0.05$.

3. Results

3.1. Soil Properties

3.1.1. Soil Bulk Density

More biochar addition had stronger interactive effects on the soil bulk density. In all treatments, only T12, T13, T14, T15, which were treated with 30 t ha⁻¹ biochar, decreased the BD by 4.47%, 4.62%, 0.02% and 3.59%, respectively. No significant differences ($p > 0.05$) were found between T5 (BC 7.5 t ha⁻¹ + BS), T9 (BC15 t ha⁻¹ + BS) and T12 to T15. Biochar addition was the major factor, which reduced the BD of soil. Treatments with 15 t ha⁻¹ biochar (T8, T9, T10, T11) increased the BD by 7.59%, 6.29%, 5.33% and 8.41%, separately. T2 (1.5 t ha⁻¹ Fulvic acid) resulted in the highest improvement rate of 8.49% of BD, which increased from 1.30 g cm⁻³ to 1.41 g cm⁻³. The average growth rate of BD compared with the initial value of different biochar dosages of 0, 7.5, 15 and 30 t ha⁻¹ was 5.39%, 4.17%, 6.91% and -3.17%, respectively (Figure 2).

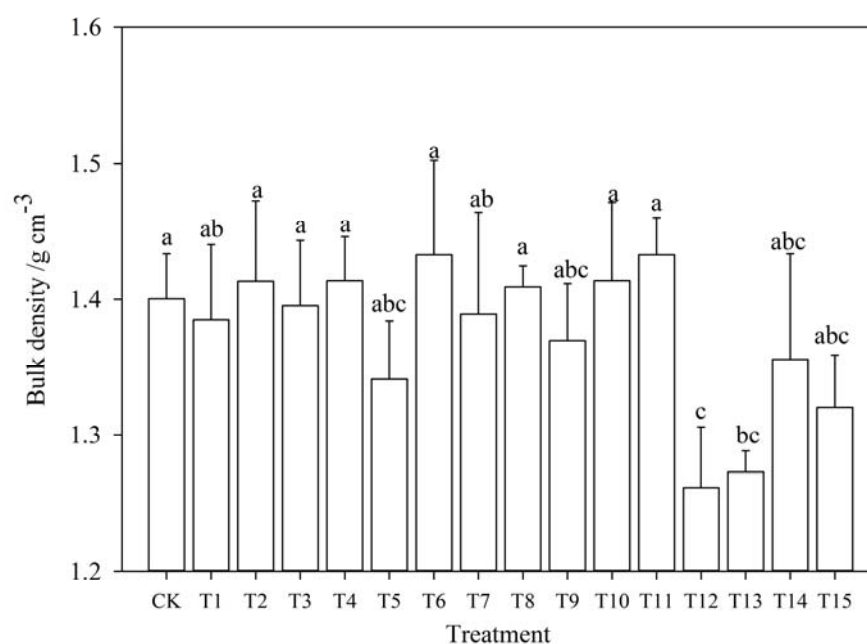


Figure 2. Soil bulk density (BD) of different treatments after maize planting. The error bar is standard deviation, and the different letters indicate significant difference under different treatments during maize ripping at $p < 5\%$.

3.1.2. Soil Water Content, Saturated Water Content, Capillary Water Holding Capacity, Soil Porosity

During the maize ripping period, treatments with 30 t ha⁻¹ biochar had larger values in WC, SWC, CHC, STP, CP and NP than other treatments. Biochar addition improved the soil water holding capability and soil porosity. Compared with the initial value, the WC and CP were lower among all treatments, and the NP was larger than the other parameters. Experimental incubation improved the soil properties through restricting salt accumulation in soil surface layer along the capillary. Lower biochar level (0, 7.5 and 15 t ha⁻¹) could not increase SWC, CHC and STP, but all values were larger than CK, and T12, T13, T14, T15 with 30 t ha⁻¹ biochar addition showed the most appealing effects. T12 (30 t ha⁻¹ BC) had the highest WC, SWC, CHC, STP and CP of 26.47%, 38.31%, 35.03%, 54.32% and 42.4%. The NP of all treatments was 1.75 to 3.85 times larger than the initial value, T10 (biochar 15 t ha⁻¹ + fulvic acid 1.5 t ha⁻¹), with the highest NP of 17.85%. The WC of T6 (biochar 7.5 t ha⁻¹ + fulvic acid 1.5 t ha⁻¹) reached a saturation situation and accounted for 92.18% per cent of SWC, and the WC of T12 (biochar 30 t ha⁻¹) resulted in a minimum rate of 69.08% (Table 2).

Table 2. The average value of soil water content (WC), soil saturated water content (SWC), capillary water holding capacity (CHC), soil total porosity (STP), capillary porosity (CP) and noncapillary porosity (NP) measured in different treatment plots compared with the initial values of soil properties.

Treatment	WC (%)	SWC (%)	CHC (%)	STP (%)	CP (%)	NP (%)
CK	15.69	18.41	17.65	42.36	26.96	15.40
T1	21.62	25.49	24.06	45.41	34.81	10.60
T2	18.99	24.23	22.66	43.25	34.07	9.18
T3	20.57	24.90	23.25	45.26	33.72	11.54
T4	16.69	22.04	20.88	46.52	29.59	16.93
T5	24.01	30.46	28.52	49.20	38.39	10.81
T6	20.11	21.82	20.95	42.91	31.70	11.21
T7	23.50	26.68	24.58	45.38	35.57	9.81
T8	25.19	29.45	28.04	46.98	39.39	7.59
T9	23.60	26.58	24.80	46.94	34.87	12.07
T10	25.85	30.40	23.05	49.00	31.15	17.85
T11	23.20	26.28	25.24	44.74	36.96	7.78
T12	26.47	38.31	35.03	54.32	42.40	11.92
T13	22.16	30.11	26.79	50.39	35.22	15.17
T14	22.69	26.07	24.57	45.53	35.47	10.06
T15	25.32	33.36	28.96	51.85	36.95	14.90
Initial Value	28.12	33.29	32.36	48.31	44.30	4.00

3.1.3. EC, pH

The EC in different maize growth periods expressed the variation trends of the soil salt content. Soil alkalinity was determined by the soil pH. Although the initial soil salt content was uneven, there were three fluctuations in soil salinity as the time went on. Firstly, the EC value decreased from 10 June to 2 July and then increased until 15 September in CK, T1, T4, T5, T8, T9, T11, T12, T13 and T15. Secondly, the EC of T2, T3 and T11 consistently grew from 10 June to 15 September. Thirdly, the EC reduced from 10 June to 2 July, then increased until 28 July and finally dropped by 15 September in T6, T7, T10 and T14. The third growth period was the best time for soil salt rejection (Figure 3). The EC of T6 (biochar 7.5 t ha⁻¹ + fulvic acid 1.5 t ha⁻¹) on 15 September was less than that on 10 June, and it was the most effective treatment for salt removal among all plots.

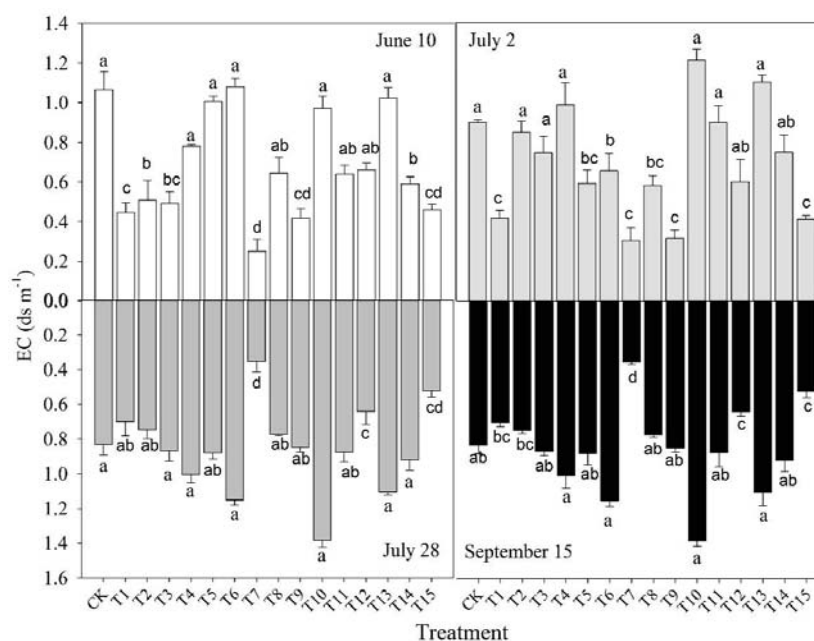


Figure 3. The average value of electrical conductivity (EC) during different maize growth periods of every third treatment plot. The EC was measured in a soil–water (1:5 *w/w*) solution, using an EC meter (EC 215 conductivity meter, HANNA, Italy). Different letters indicate significant differences between treatments at the $p < 0.05$ level.

Contrary to the various variations of the EC, the pH decreased gradually, and the values of all treatments were larger than 8.5. Moreover, in all treatments, T7 (7.5 t ha⁻¹ BC + 1.5 t ha⁻¹ FA + BS) had a minimal difference during the growth period (Figure 4). Biochar addition slightly increased the pH; therefore, soil salinization and alkalinity were the primary agricultural nature barriers in the study area, as per usual.

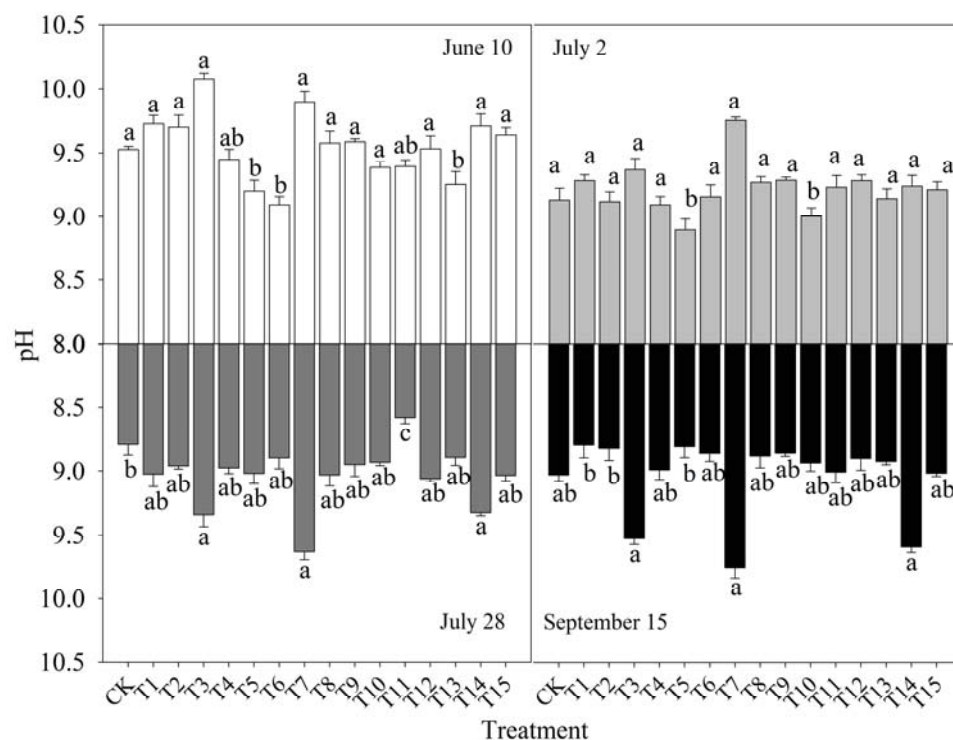


Figure 4. The average value of pH during different maize growth periods of every third treatment plot. The pH was measured at a solid/water ratio of 1:5 by pH meter (pH 211 microprocessor pH meter, HANNA, Italy). Different letters indicate significant differences between treatments at the $p < 0.05$ level.

3.2. SOC

Biochar addition had little effect on increasing SOC in T6 (BC 7.5 t ha⁻¹ + FA), T7 (BC 7.5 t ha⁻¹ + FA + BS) and CK (Table 3) treatments. Biochar addition rates significantly influenced the SOC content; the order of the mean of SOC_{2nd} classified with different BC dosage was 30 t ha⁻¹ (T11, T12, T13, T14) 5.79 g kg⁻¹ > 15 t ha⁻¹ (T7, T8, T9, T10) 5.09 g kg⁻¹ > 0 t ha⁻¹ (CK, T1, T2, T3) 4.38 g kg⁻¹ > 7.5 t ha⁻¹ (T4, T5, T6, T7) 4.33 g kg⁻¹. The order of the mean of SOC_{2nd} minus SOC_{1st} classified with different biochar dosage was the same as the mean of SOC_{2nd}, with values 2.21 g kg⁻¹ > 1.69 g kg⁻¹ > 0.52 g kg⁻¹ > 0.24 g kg⁻¹. There were no significant differences ($p > 0.05$) found between different BC usage plots in the SOC_{2nd}. Significant differences ($p > 0.05$) were found between T1 and T7, T3 and T12, T7 and T12. BC combined with FA or BS had an extremely significant effect on SOC improvement in treatments with 7.5 t ha⁻¹ BC, but the increase extent was lower than that in the BC treatments.

Table 3. Soil organic carbon (SOC) measured in the no-seedling period (SOC_{1st}) and the ripping period (SOC_{2nd}). Different letters in the same column indicate significant difference at $p \leq 5\%$.

Treatment	SOC _{1st} (g kg ⁻¹)		SOC _{2nd} (g kg ⁻¹)		SOC _{2nd} –SOC _{1st} (g kg ⁻¹)
	Mean	Standard Deviation	Mean	Standard Deviation	
CK	5.20 ^a	0.43	4.67 ^{abc}	0.07	−0.53
T1	3.63 ^{cde}	0.74	4.33 ^{ab}	0.67	0.70
T2	3.42 ^{cde}	1.22	4.72 ^{abc}	0.28	1.30
T3	3.43 ^{cde}	1.38	4.09 ^{bc}	0.64	0.66
T4	4.09 ^{abcd}	0.27	4.66 ^{abc}	0.30	0.57
T5	3.71 ^{cde}	0.76	4.98 ^{abc}	0.85	1.27
T6	5.09 ^{ab}	0.14	4.38 ^{abc}	1.12	−0.71
T7	3.48 ^{cde}	0.52	3.30 ^c	0.89	−0.18
T8	4.13 ^{abcd}	0.61	5.86 ^{ab}	1.28	1.73
T9	3.26 ^{cde}	0.27	4.86 ^{abc}	0.89	1.60
T10	3.32 ^{cde}	1.09	4.41 ^{abc}	1.26	1.09
T11	2.86 ^{de}	0.76	5.21 ^{ab}	1.12	2.35
T12	3.60 ^{cde}	0.22	6.20 ^a	0.87	2.60
T13	4.24 ^{abc}	0.73	5.96 ^{ab}	1.79	1.72
T14	2.66 ^e	1.20	5.55 ^{ab}	2.46	2.89
T15	3.86 ^{bcde}	0.58	5.46 ^{ab}	1.40	1.61
F probability		*		ns	
LSD (0.05)		1.29		-	

Note: * Significant difference at $p \leq 0.05$ level; ns, not significant; - indicates that the LSD was not calculated due to non-significant results. Different letters in the same column indicate significant differences ($p < 0.05$) between the treatments.

3.3. Plant Height and Grain Yield

The maize grain yields in BC, BC + BS, FA or BS treated plots were higher than with other treatments. T9 (BC 15 t ha⁻¹ + BS) produced the highest grain yield, 7.98 kg, and a significant difference between T9 and CK was observed ($p < 0.05$). T3, T7, T11, T14 had no significant differences in grain yield, and they had the lowest production with different BC dosages compared with other treatments (Figure 5). The more BC that was added, the higher the standard variation of the grain yield was observed. The maize height of T3, T7, T11 and T14 showed the same properties of the grain yield, and they were the minimum values among the four treatments with the same BC content. The BC + FA + BS combination treatment had slight effects on improving the maize grain yield and maize height. The maize grain yield reduced with the amount of BC added in BC + FA treatments. The grain yield was uneven in FA with BC dosage 0, 7.5 and 15 t ha⁻¹ treated plots. The appropriate BC application rate and the right combination resulted in a considerable crop production, in treatments T6 and T9, which were 67.69 and 75.39% higher than the treatment with CK.

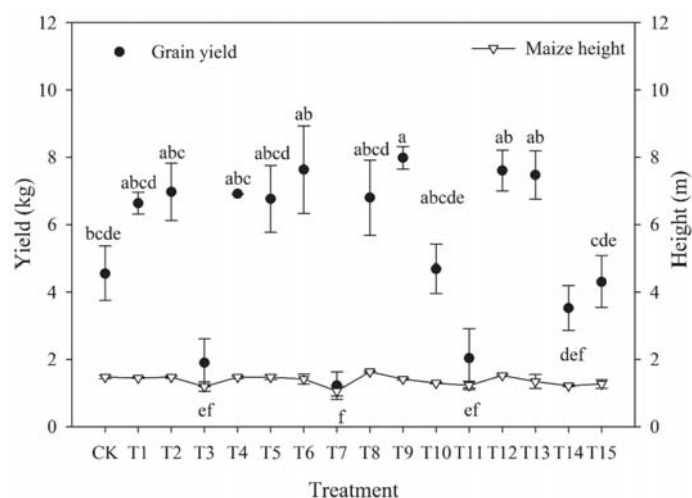


Figure 5. Effects of BC, FA and BS treatment on yield and height of maize. BC = biochar, FA = fulvic acid, BS = *Bacillus subtilis*. Different letters indicate significant differences between treatments at the $p < 0.05$ level.

4. Discussion

The soil parameters measured in this paper included the bulk density (BD), soil saturated water content (SWC), capillary water holding capacity (CHC), soil total porosity (STP), capillary porosity (CP) and noncapillary porosity (NP), electrical conductivity (EC), pH and soil organic carbon (SOC). Biochar addition resulting in reduced BD has been reported in many studies. For example, the application of 5, 10, 20 t ha⁻¹ BC in this study brought about an average reduction of 2.86% compared with the control in paddy soil [16], with 5 t ha⁻¹ BC reducing the BD from 1.41 to 1.36 g cm⁻³ in rainfed Alfisol [17], with woodchip biochar inducing greater decreases in BD in the coarse-textured Planosol [18], with the 22.5 Mg/ha BC decreasing the bulk density of the alkaline cambosols by 10.3% compared with the control [19], and the same decreasing effect was reported in a salt-stressed cropland [20]. Although biochar possessed a larger porosity [21] and a lower density [22] than soil [23], it was difficult to decrease the soil bulk density when the rain induced soil hardening in this study. We found that the treatments containing 30 t ha⁻¹ biochar decreased the BD by more than its initial value and CK as well. On the contrary, treatments containing 0, 7.5 and 15 t ha⁻¹ biochar addition had little effect on reducing the bulk density (Figure 2). The water content, SWC, CHC, STP and CP in all treatments were larger than those of CK [24–27], which increased with the biochar addition dosage and showed no correlation with the fulvic acid addition and BS treatment (Table 2). The pH decreased during the four-time soil sampling (Figure 4), and the result was contrary to many pot and field experiments [28–30]. Lynne et al. [31] demonstrated that soil pH and EC were all increased in the pot experiment with alkaline Calcisol under the application of biochar. In the present study, increases in EC accompanied by pH reduction were found in all treatments. Soil EC and pH under field trials were mainly affected by groundwater, wind, sunshine, rainfall and saltwater intrusion in the study area. Soil alkalinity was mainly influenced by the sodium carbonate content; therefore, the decreases in pH may have been caused by the reduction in alkaline salt. Hence, the tillage method or natural factors decreased the reduction effect of BC on soil bulk density. Firstly, the initial value was measured before biochar addition, with no soil plowed. The soil was disturbed through plowing and rain washing before the second soil sampling time. Secondly, the integrated effect of the natural and human action disturbed the soil balance in the field. However, the more biochar-amended soil had higher water holding ability and total porosity, and lower bulk density, than the unamended control soil [32]. The SOC content can greatly affect soil quality by maintaining and determining the important soil physical conditions, properties and soil functions [33]. In this study, biochar amendment improved soil physical properties. The more biochar addition, the higher the SOC content in soil. The SOC content of treatments including biochar and fulvic acid (FA) was lower than biochar-only treatments, which contained the same dosage. Treatments with biochar 15 t ha⁻¹ and fulvic acid even resulted in lower SOC than the initial value. The stimulation of FA activated the microbial activities [34] and accelerated the decomposition of biochar. The effect and the change of microbial activity under the BC and FA treatment were reported by Rutigliano [35]. The study shows that after approximately four months in one maize growing season, microbial activity increased immediately in a short time. Biochar and humic acid amendments could improve the microbial biomass C of the growth media, and it accelerated soil carbon consumption [36].

The crop growth response to treatments mainly depends on the properties of the biochar [37], *Bacillus subtilis* [8] and fulvic acid [38], climatic conditions [39], soil conditions [40], underground water, irrigation and drainage system [41], cultivation method [42], crop type and crop variety [43]. In this study, the maize height and grain weight were merely affected by the amount of biochar with or without FA and BS combination. The FA + BS and BC + FA + BS treatments obtained a lower grain yield than other treatments within the same biochar addition. Seeds were sown a week after biochar was plowed into the soil, and this indicated that FA and BC + FA treatments inhibited the growth of maize seedling after BS pretreatment. Bakry [44] reported that humic acid + mycorrhiza + biochar

treatment had a significantly superior effect on many agronomic characteristics than other combinations. Sun [45] found that all biochars were able to support *Bacillus mucilaginosus* to peat at densities analogous to the population. The adsorption of FA onto BS was strongly pH dependent, and it would separate with the soil pH improvement. The lower absorption of FA when compared with humic acid may be affected by its lower hydrophobicity [46]; therefore, this indicated the antagonism effect between FA and BS, which inhibited crop nutrition adsorption, and biochar addition ameliorated the unhealthy soil situation and increased the grain yield (Figure 5).

5. Conclusions

The field experiment showed that the three biomaterial—biochar, fulvic acid and *Bacillus subtilis*—application affected the soil properties and the characteristics of maize. The bulk density increased in the control group and lower biochar addition plots, and total porosity decreased by more than the initial value in control plots. This phenomenon indicated the soil degradation tendency during the plant cultivation period in the study area. Soil organic carbon increased with more biochar addition. Soil salinity and alkalinity were mainly affected by the natural environment, and the pH decreased with the EC increasing. Biochar and other measures improved the quality of the soil and provided benefits for maize growth. The antagonism effects in FA and BS combination treatments resulted in a lower grain yield and plant height, but BC addition improved the soil physical properties and soil aeration, thus increasing soil production. To extend our work in investigating the biological factors related to plant growth, the underlying mechanisms of aged biochar and other biomaterials affecting the soil microbial composition in plant rhizosphere need to be researched.

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Article

Biochar Effects Coastal Saline Soil and Improves Crop Yields in a Maize-Barley Rotation System in the Tidal Flat Reclamation Zone, China

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Abstract: The summer maize-winter barley (or wheat) rotation system is a conventional farming method in coastal areas of east China. However, researchers have paid little attention to the increasing soil degradation after successive crop rotation in coastal saline agriculture. In the current study, a two-year field experiment was conducted to investigate the changes in soil physio-chemical properties and crop grain yields under the maize-barley rotation system. Wheat straw derived biochar (BC) was applied to topsoil (0–20 cm) at four different rates (0, 7.5, 15 and 30 Mg ha^{−1}) before summer maize cultivation, and no biochar was added in the cultivation of the winter barley. Bulk density (BD), water holding capacity (WHC), water stable aggregate (WSA), soil electrical conductivity (EC), pH (1:5 water *w/v*) and soil organic carbon (SOC), at the harvesting time of maize and barley, were analyzed. The application of biochar increased WHC and macro-aggregate (>2 mm) content after barley harvest. Soil EC was mainly affected by the rain during maize cultivation and increased only slightly under BC treatments. However, no difference in EC was found among all treatments after barley harvest. The application of BC at 30 Mg ha^{−1} increased the maize yield by 66% but produced no difference in the barley yield. We concluded that biochar could be an effective option to mitigate soil degradation and improve crop productivity in coastal saline agriculture.

Keywords: crop rotation; crop yield; saline soil; soil salinity; biochar

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1. Introduction

Land reclamation from the sea provides more lands to satisfy global demands for resources and it has been practiced since ancient times [1]. Nevertheless, soil salinization, saline intrusion, high sodium adsorption ratio, and a shortage of fresh water are serious issues restricting the production potential of coastal saline soils [2]. Among the stresses on plant agriculture in coastal reclamation regions, soil salinization is considered the major limiting factor for crop productivity [3]. Salt stress inhibits the growth and development of plants and even causes damage under plant conditions [4]. Many approaches have been established to maintain and develop sustainable saline agriculture in coastal areas, such as using saltwater drip irrigation [5], brackish ice for salt leaching [6], halophytes to absorb and remove soil salts [7], microorganisms for mediating plant salt tolerance [8], transgenic technologies to improve crop yield [9], crop rotation [10].

Crop rotation refers to the continuous cultivation of different crops on the same land, and it is a simple and effective technique used in organic agriculture. This kind of agronomic practice is beneficial to crop production, ameliorates the ecosystem of the cropland, and promotes the combination of soil use and nourishment [11]. However, long-term crop rotation by itself induces soil degradation (e.g., increased soil compaction, reduced water holding capacity and soil salinization). Due to increased runoff from fertilizers increased

and poor farming methods [12–15]. Therefore, it is still very important to improve the soil quality in coastal reclamation regions after consecutive years of cultivation, in order to develop sustainable saline agriculture. Meanwhile, more attention needs to be paid to solve the problems caused by soil degradation in order to ameliorate soil physical characteristics, enhance soil fertility and mitigate soil salt levels in the plow layer.

Biochar (BC) is an organic carbon-rich porous material produced by biomass pyrolysis reaction, which is used as a soil modifier to improve soil productivity and properties [16]. Biochar can alleviate the effects of salt stress on plants through salt adsorption [17], enhance soil water holding capacity [18], and improve soil physical and hydraulic properties [19]. Compared with other modifiers, such as gypsum [20], humic acid [21], and manure and green waste [22], the longevity of biochar in soil provides obvious advantages for bioremediation [23].

In light of the above mentioned factors, we conducted a two-year field trial with the addition of biochar to a conventional farming system: a long-term crop rotation process conducted by native farmers in the coastal tidal flats reclamation region of Jiangsu Province, China. We hypothesized that biochar application would ameliorate the soil characteristics, and improve the crop yield and, therefore, promote the development of sustainable saline agriculture. We aimed to determine the effects of biochar application on soil amelioration and crop yield in a maize-barley rotation system. As far as we know, the potential of biochar as a soil modifier to mitigate salt stress and improve soil quality has received little attention in this field.

2. Materials and Methods

2.1. Experimental Site

The field experiment site was located in Huanghai Raw Seed Farm (32°38′42.01″ N, 120°54′8.04″ E), Jiangsu Province, China (Figure 1). The study area was reclaimed in 2005 lying approximately 2 km from the coastline of the China Yellow Sea. The main soil type was classified as solonchak based on the World Reference Base for Soil Resources (IUSS Working Group WRB, 2007). The soil texture was mainly silty loam, characterized by low porosity and infiltration (Table 1). The area was governed by a subtropical oceanic monsoon climate with large seasonal fluctuations in precipitation. Approximately 70 percent of the local rainfall occurred from June to September every year, and there was a regular annual variation in the salt content of the soil. The average annual precipitation, evaporation, temperature, and relative humidity were 1061 mm, 1414 mm, 14.6 °C, and 81%, respectively.

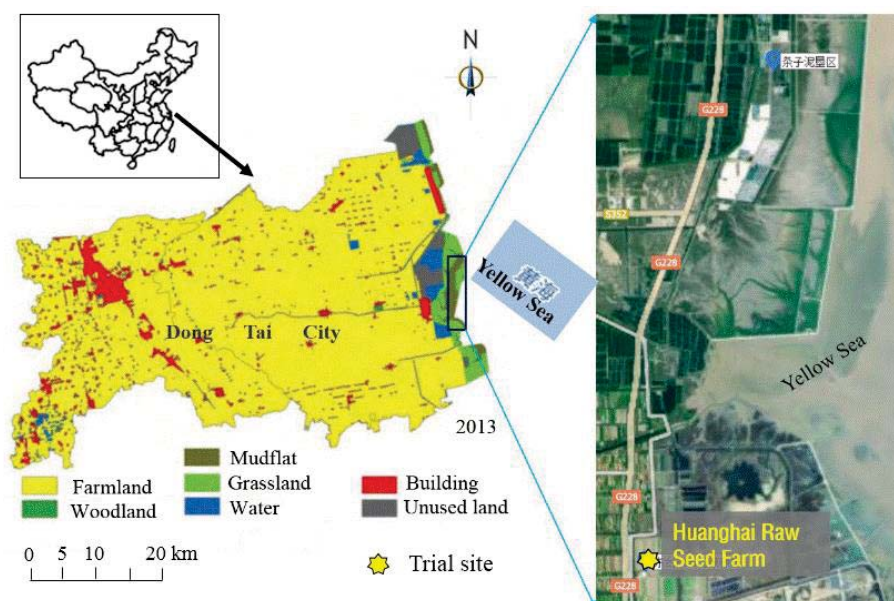


Figure 1. Location of study area.

Table 1. Basic properties of the original topsoil (0–20 cm) and biochar used for the experiment.

Sample	pH _{H2O}	CEC	BD	SOC	TOC	Total N	Salt	Sand	Clay	Silt
		cmol kg ^{−1}	g cm ^{−3}	g kg ^{−1}	g kg ^{−1}	g kg ^{−1}	g kg ^{−1}			
Topsoil	9.2	2.4	1.41	2.4		0.3	2.3	191	124	685
Biochar	10.4	21.8	0.65		467	5.9	42.0	ND	ND	ND

Note(s): EC, cation exchange capacity; BD, bulk density; TOC, total organic carbon; ND, not detected.

2.2. Biochar

The biochar used for the field experiment was derived from wheat straw by pyrolysis at a temperature of 350–550 °C in a vertical kiln made of refractory bricks in Sanli New Energy Company, Nanyang city, China. With the technology developed by the company, was expected 35% of the wheat straw dry matter mass to be converted to biochar [24]. Biochar material was ground to pass through a 2 mm sieve and homogenized thoroughly for the experiment. The basic properties of biochar are presented in Table 1, and more detailed properties have been reported previously [25,26].

2.3. Experimental Design

A two-year field trial was conducted during the maize-barley rotation. A single factor randomized complete block design was adopted, involving four treatments with three replicate plots, for a total of 12 plots. Each treatment plot was 10 × 4 m in the area and separated by a 1 m wide buffer zone with no crops sowed. The biochar was applied at rates of 7.5, 15 and 30 Mg ha^{−1}. The control plots were treated with no biochar. Before summer maize sowing, urea and monoammonium phosphate were applied at 144 kg ha^{−1} N and 135 kg ha^{−1} P₂O₅, respectively. Fertilizers were broadcast and incorporated into the soil, with no potassium fertilizer application because the soil K content was already sufficient for plant growth [27]. An additional 96 kg ha^{−1} N of urea was top-dressed at the jointing stage. For maize growth, the row spacing and spacing within the rows were 50 cm and 20 cm. The density was approximately six plants per m^{−2}. Winter barley was sown by machine after summer maize harvest. The row spacing was 25 cm and the seeding rate was 375 kg ha^{−1}. Chemical fertilizers containing 168 kg N ha^{−1} and 90 kg P ha^{−1} were broadcast and incorporated into the soil. At the jointing-booting stage, 72 kg N ha^{−1} urea was additionally top-dressed as a supplementary fertilizer. During the crop cultivation, rain was the major water supply, as no irrigation system was used.

Before sowing the seeds, biochar and base fertilizers were sprinkled onto the soil surface and immediately mixed into the tilling layer (0–20 cm). Maize (Suyu 21) was seeded on 12 June 2015, and harvested on 28 September 2015. Barley (Supi 4) was also seeded on 30 October 2015, with the continued application of fertilizer but no further addition of biochar, and it was harvested on 22 April 2016. The crop growth management was consistent across the plots.

2.4. Soil Sampling and Analysis

To measure soil salinity, a composite sample at a depth of 0–20 cm was obtained from five subsamples collected using a soil auger from each treatment plot on June 10 (seeding stage), July 2 (seedling stage), July 28 (elongation stage), and September 30 (mature stage) in 2015, and April 25 (harvest stage) in 2016. Each date represented, respectively, the seedling stage, jointing stage, filling stage, and ripening stage of the maize, and the ripening stage of the barley. Samples were air-dried and ground to pass through a 2 mm sieve, and a portion was then ground to pass through a 0.15 mm sieve for soil fertility measurement. At the ripening stage of the maize and barley, undisturbed soil cores ($d = 5$ cm, $l = 5$ cm; $v = 100$ cm³) were taken from topsoil to measure bulk density (BD) and soil water holding capacity (WHC). For water stable aggregate content measurement, soils (0–20 cm) were sampled on 25 April 2016.

Soil electrical conductivity (EC) and acidity (pH) were determined by a HANNA EC215 conductivity meter and a HANNA pH 211 microprocessor pH meter using 1:5 (*w/v*) soil: water suspensions. The electrical conductivity from 1:5 samples was converted to total soil salt content using the equation proposed by [28]:

$$TS = 2.47 EC_{1:5} + 0.26 \quad (1)$$

where, $EC_{1:5}$ is the electrical conductivity of the soil water extract ($dS\ m^{-1}$) and TS is the total salt content ($g\ kg^{-1}$).

The soil organic carbon (SOC) was obtained by the Walkley-Black dichromate oxidation method [29]. The sizes of water stable aggregates included four fractions: (1) large macro-aggregates ($>2\ mm$); (2) small macro-aggregates ($0.25\text{--}2\ mm$); (3) micro-aggregates ($0.25\text{--}0.053\ mm$) and (4) silt + clay ($<0.053\ mm$).

2.5. Statistical Analysis

Statistical analysis was performed using SPSS, version 19 (IBM SPSS Statistics, New York, NY, USA, 2010). All analytical data are presented as a mean plus/minus one standard deviation. Any significant differences among treatments were determined by one-way analysis of variance (ANOVA). The post-hoc test was carried out using Dunnett's method at the level of significance of $p < 0.05$.

3. Results

3.1. Soil Physical Properties

3.1.1. Soil Bulk Density

There was no significant reduction in soil bulk density (BD) under biochar application treatment compared to the control after the maize harvest in 2015 (Figure 2). Meanwhile, BD increased by 3.3% and 3.7% under the 7.5 and 15 $Mg\ ha^{-1}$ biochar treatments compared to the control. However, the 15 and 30 $Mg\ ha^{-1}$ biochar treatments resulted in significant decreases in BD (5.9% and 6.2%, respectively) compared to the untreated plots after the barley harvest in 2016. Furthermore, there were no difference for the 7.5 $Mg\ ha^{-1}$ biochar treatment across the maize—barley rotation system, but a small reduction (2.4%) compared to CK was found in 2016.

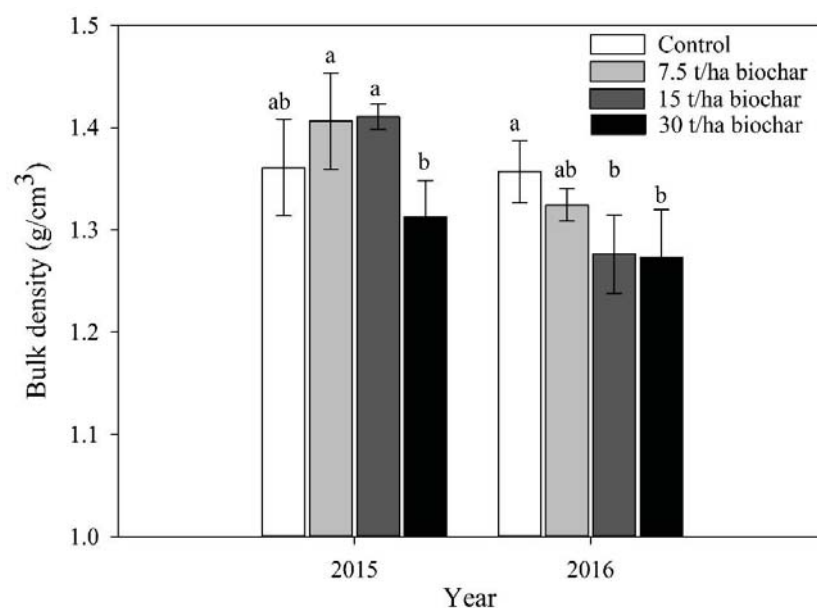


Figure 2. Bulk density (BD) as affected by biochar (BC) treatment. Error bars represent one standard deviation from the mean. Different letters indicate significant difference ($p < 0.05$) between control and treatments in different years.

3.1.2. Soil Water Holding Capacity

Increases were found in WC and FC in 30 Mg ha⁻¹ BC treated plot compared to the control plot, after maize harvest (Table 2). Compared to CK, the 30 Mg ha⁻¹ BC treatment increased the WC from 29.1% to 31.0% and the FC from 32.4% to 37.5% in the maize-planting experiment in 2015. In the subsequent barley cultivation period, the WC was increased compared to CK from 21.1% to 24.7% and FC from 23.7% to 26.7% in the 30 Mg ha⁻¹ BC treatment plot. Moreover, no differences were observed in the WC, SWC, and FC under the 7.5 and 15 Mg ha⁻¹ treatments across the maize-barley rotation compared to CK.

Table 2. Parameters of soil water content (WC), saturated water capacity (SWC) and field capacity (FC) measured in October 2015 and March 2016 by ring-cutting method after maize and barley harvest.

Biochar Rate Mg ha ⁻¹	Maize			Barley		
	WC	SWC	FC	WC	SWC	FC
	g 100 g ⁻¹	g 100 g ⁻¹	g 100 g ⁻¹	g 100 g ⁻¹	g 100 g ⁻¹	g 100 g ⁻¹
0	29.1 ± 1.3 b	33.7 ± 1.8 a	32.4 ± 1.3 b	21.1 ± 0.7 b	25.2 ± 0.4 a	23.7 ± 0.6 b
7.5	29.6 ± 1.4 ab	35.5 ± 1.1 a	33.7 ± 0.5 b	22.4 ± 2.4 ab	26.9 ± 3.5 a	25.1 ± 3.2 ab
15	29.3 ± 1.1 ab	37.0 ± 3.8 a	34.6 ± 2.6 ab	23.2 ± 0.5 ab	26.7 ± 0.2 a	25.1 ± 0.5 ab
30	31.0 ± 1.3 a	37.5 ± 5.9 a	36.4 ± 2.1 a	24.7 ± 0.7 a	29.1 ± 1.5 a	26.7 ± 0.2 a

Note(s): Different letters in the same column indicate significant differences ($p < 0.05$) between the treatments.

3.2. Water Stable Aggregate Content

Figure 3 shows the effects of the BC treatments on the distribution of the different aggregate size fraction in the topsoil (0–20 cm) after the winter barley harvest in 2016. The silt + clay fraction dominated the size distribution (65%), followed by micro-aggregates (29%), then small macro-aggregates (3%). The large macro-aggregates were the least represented fraction (2.8%). Remarkably, significant increases were observed in large macro-aggregates (>2 mm) (103% and 104%, respectively) for the 15 and 30 Mg ha⁻¹ biochar treated-plots compared to the control. Biochar addition had no significant effect on silt + clay, micro-aggregates, and small micro-aggregates proportion. The 7.5 and 15 Mg ha⁻¹ biochar treatments were themselves not significantly different. There were decreases in Micro-aggregates by 9%, 7% and 17% under the 7.5, 15 and 30 Mg ha⁻¹ biochar treatments compared to CK, respectively.

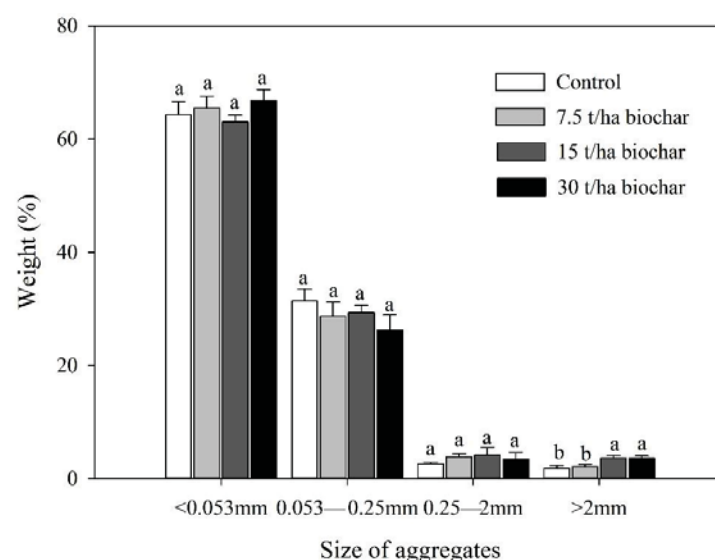


Figure 3. Changes in water stable aggregate percentages of soil as affected by biochar (BC) treatment. Error bars represent one standard deviation from the mean. Different letters indicate significant difference ($p < 0.05$) between control and treatments in different years.

3.3. Soil Salinity

Although no significant difference was observed during the crop cultivation, a higher EC value was found for the BC treatments compared to the untreated plot (Table 3). Meanwhile, similar trends of EC and pH changes were found at the depth of 0~20 cm from the beginning to the end of the maize-barley rotation period under all treatments. The EC and pH were also inversely related. Moreover, the EC of all treatment plots was significantly reduced (by 43%, 42%, 37% and 25%) at a depth of 0~20 cm on 25 April 2016 compared to June 2015 under the 0, 7.5, 15, and 30 Mg ha⁻¹ biochar treatments, respectively. Reductions in the EC at the moderate depth of 20~40 cm by 25%, 36%, 23%, and 35% were seen after barley harvest compared to the maize rippling period, under CK, 7.5, 15 and 30 Mg ha⁻¹ BC treated plots. The effects of biochar addition on salt-affected soil amelioration were better in deep soil than in topsoil. However, the decrease in pH at 0~20 cm was higher than the decrease in pH in depth at 20~40 cm. The largest reduction in pH was seen under the 15 Mg ha⁻¹ BC treatment (from 9.70 to 9.12 in the surface soil layer (the top 20 cm), and from 9.20 to 9.16 in the soil layer of 20~40 cm).

3.4. SOC and Crop Yield

Biochar addition improved soil organic carbon (Figure 4). With an initial average value of 2.32 g kg⁻¹, SOC was greatly increased by 5%, 13% and 25% in 2015 and 8%, 14% and 34% in 2016 compared to the control, in 7.5, 15 and 30 Mg ha⁻¹ BC treated plots, respectively. The higher the biochar addition, the greater the improvement in SOC. In addition, there were increases in SOC by 7%, 11%, 9%, and 15% under 0, 7.5, 15 and 30 Mg ha⁻¹ biochar treatments, respectively, in 2016 compared to 2015.

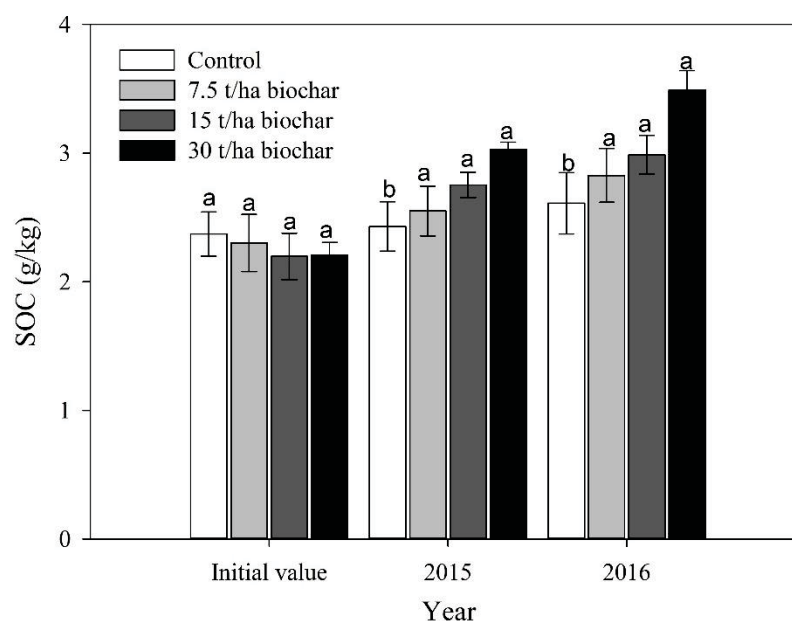


Figure 4. Soil organic carbon (SOC) as affected by biochar (BC) treatment. Values are means $\pm$ SD ($n = 3$). Bars with different letters in each year are significantly different according to LSD at $p < 0.05$.

The maize grain yield varied from 2.79 Mg ha⁻¹ in the control to 4.62 Mg ha⁻¹ in 30 Mg ha⁻¹ BC plot, and the barley yield varied from 2.65 Mg ha⁻¹ in CK to 3.13 Mg ha⁻¹ in 7.5 Mg ha⁻¹ BC treated plot (Figure 5). There were increases in the maize yield by 1.54 per hectare and 1.84 per hectare under 15 and 30 Mg ha⁻¹ biochar treatments compared to the control. The highest maize yield was found under the highest biochar-dose.

Table 3. Values of electrical conductivity (EC) and pH values of soils sampled at different points during crop cultivation. EC and pH were measured in 1: 5 w/v ratio soil suspensions.

Property	Biochar Rate Mg ha ⁻¹	10 June 2015 Seeding Stage			2 July 2015 Seedling Stage			28 July 2015 Elongation Stage			30 September 2015 Mature Stage			25 April 2016 Harvest Stage		
		0~20 cm	20~40 cm	0.30 ± 0.11 a	0.30 ± 0.11 a	0.30 ± 0.11 a	0.30 ± 0.11 a	0.49 ± 0.19 a	0.49 ± 0.19 a	0.49 ± 0.19 a	0.68 ± 0.27 a	0.52 ± 0.32 c	0.25 ± 0.06 a	0.48 ± 0.26 a	0.51 ± 0.22 a	0.60 ± 0.11 a
EC dS m ⁻¹	0	0.43 ± 0.18 a	0.64 ± 0.27 a	0.30 ± 0.11 a	0.55 ± 0.28 a	0.48 ± 0.17 a	0.47 ± 0.21 a	0.56 ± 0.25 a	0.68 ± 0.27 a	0.79 ± 0.30 a	0.66 ± 0.34 a	0.30 ± 0.14 a	0.30 ± 0.14 a	0.51 ± 0.22 a	0.60 ± 0.11 a	0.60 ± 0.11 a
	7.5	0.51 ± 0.34 a	0.79 ± 0.29 a	0.36 ± 0.12 a	0.48 ± 0.17 a	0.49 ± 0.15 a	0.51 ± 0.34 a	0.37 ± 0.13 a	0.73 ± 0.30 a	0.75 ± 0.20 a	0.62 ± 0.20 a	0.33 ± 0.03 a	0.33 ± 0.03 a	0.54 ± 0.11 a	0.60 ± 0.11 a	0.60 ± 0.11 a
	15	0.50 ± 0.54 a	0.78 ± 0.20 a	0.34 ± 0.18 a	0.49 ± 0.15 a	0.53 ± 0.23 a	0.58 ± 0.25 a	0.50 ± 0.08 a	0.82 ± 0.24 a	0.82 ± 0.24 a	0.62 ± 0.20 a	0.33 ± 0.03 a	0.33 ± 0.03 a	0.54 ± 0.11 a	0.60 ± 0.11 a	0.60 ± 0.11 a
pH	0	0.47 ± 0.14 a	0.83 ± 0.19 a	0.39 ± 0.25 a	0.53 ± 0.23 a	0.53 ± 0.23 a	0.58 ± 0.25 a	0.50 ± 0.08 a	0.82 ± 0.24 a	0.82 ± 0.24 a	0.62 ± 0.20 a	0.33 ± 0.03 a	0.33 ± 0.03 a	0.54 ± 0.11 a	0.60 ± 0.11 a	0.60 ± 0.11 a
	7.5	9.8 ± 0.3 a	9.3 ± 0.1 a	9.3 ± 0.1 a	9.2 ± 0.2 a	9.2 ± 0.2 a	9.1 ± 0.3 a	9.0 ± 0.1 b	8.9 ± 0.1 a	8.9 ± 0.1 a	9.1 ± 0.1 a	9.2 ± 0.1 a	9.2 ± 0.1 a	9.3 ± 0.1 a	9.4 ± 0.3 a	9.4 ± 0.3 a
	15	9.5 ± 0.7 a	9.5 ± 0.5 a	9.1 ± 0.3 a	9.4 ± 0.4 a	9.4 ± 0.4 a	9.2 ± 0.2 a	9.3 ± 0.4 ab	9.1 ± 0.6 a	9.1 ± 0.6 a	9.4 ± 0.5 a	9.2 ± 0.1 a	9.2 ± 0.1 a	9.4 ± 0.3 a	9.4 ± 0.3 a	9.4 ± 0.3 a
	30	9.7 ± 0.4 a	9.2 ± 0.3 a	9.2 ± 0.2 a	9.2 ± 0.1 a	9.2 ± 0.1 a	9.1 ± 0.1 a	9.0 ± 0.0 ab	8.9 ± 0.1 a	8.9 ± 0.1 a	9.2 ± 0.1 a	9.2 ± 0.1 a	9.0 ± 0.1 a	9.2 ± 0.1 a	9.2 ± 0.1 a	9.2 ± 0.1 a
	30	9.7 ± 0.5 a	9.4 ± 0.6 a	9.5 ± 0.4 a	9.4 ± 0.2 a	9.4 ± 0.2 a	9.3 ± 0.3 a	9.4 ± 0.4 a	9.4 ± 0.4 a	9.4 ± 0.4 a	9.4 ± 0.4 a	9.4 ± 0.4 a	9.1 ± 0.3 a	9.4 ± 0.3 a	9.4 ± 0.3 a	9.4 ± 0.3 a

Note(s): Data are means ± standard deviation. Lowercase letters indicate significant differences at $p < 0.05$ in EC or pH for different biochar application rates.

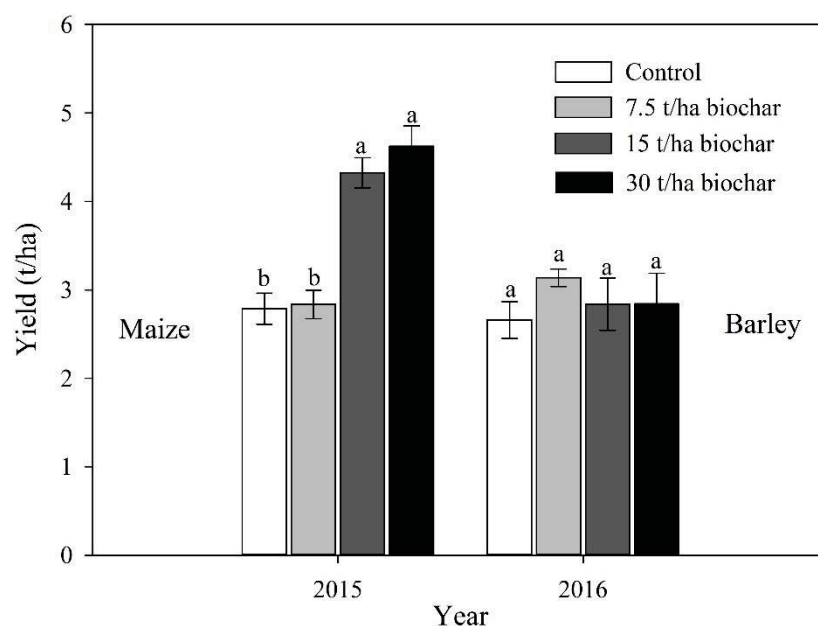


Figure 5. Crop yields of maize and barley as affected by biochar (BC) treatment. Values are means $\pm$ SD ($n = 3$). Bars with different letters in each year are significantly different according to LSD at $p < 0.05$.

4. Discussion

4.1. Effects of Biochar on Improvement of Soil Physical Properties

Soil physical properties are important indicators of soil quality, which can be defined as the ability of soil to support crop growth without causing soil degradation [30]. Soil degradation in coastal areas induced by crop rotation was investigated in the study, and biochar was considered a suitable material for mitigating or improving soil limiting factors [31,32]. Physical changes in soil bulk density, water holding capacity, and water stable aggregates were investigated in this field experiment.

Bulk density not only affects the availability of soil nutrients and moisture but also indirectly reflects productivity [33]. As a porous abundant material, biochar performs well in improving soil physical properties [34] and can alleviate the negative physical effects induced by soil-compaction [35]. However, in the maize-barley rotation system, the bulk density only decreased in the 30 Mg ha⁻¹ biochar treated plots, when compared to the control, after summer maize cultivation in 2015. At the same time, lower biochar rates of 7.5 and 15 Mg ha⁻¹ increased the BD by 0.04 and 0.05 g cm⁻³, respectively. However, after the winter barley harvest the following year, significant decreases were observed under all biochar treatments compared to CK (Figure 2). The bulk density of soil depends greatly on the soil particle size, mineralogy, organic matter content, and management. During the ripping period of the maize, salt accumulated in the topsoil (0–20 cm), and a higher salt content existed in the biochar-treated plots than in the control plots (Table 3). Additionally, the rain was thought to be a key factor, as the rainy season fell during the summer maize cultivation. As the climate conditions and planting management were consistent, we hold the opinion that rainfall leaching caused the soil-compaction and thus made the soil heavier in 2015. During the subsequent barley cultivation, very little rain fell, and the soil salt decreased under the biochar treatments compared to CK. Thus, a higher reduction in BD after the barley harvest was observed with the highest biochar addition rate.

The results showed that the addition of biochar increased the soil water content (WC), saturated water capacity (SWC), and field capacity (FC), relative to the no-biochar controls (Table 2). Biochar addition improved soil water-holding capacity due to its highly porous structure, in another experiment [36]. However, significant differences were only observed in plots treated with 30 Mg ha⁻¹ biochar treated plots compared to CK in the maize-barley

rotation system. The soil water holding capacity in 2016 was lower than that in 2015, indicating soil degradation. Biochar application mediated the soil degradation. The higher the biochar rate, the higher the water holding capacity of the soil, and the total porosity of the soil increased with the decrease in bulk density [37] over the experimental period. During barley cultivation, the topsoil was disturbed by plowing and sowing. However, there was a low level of rainfall from October to April in this study area, which limited the formation of soil capillaries. Therefore, the lower soil water content after the barley harvest may have been caused by a reduction in the capillary porosity.

After one maize—barley rotation, the 15 and 30 Mg ha^{−1} biochar treatments substantially increased the soil large macro-aggregates (>2 mm) content compared to the 7.5 Mg ha^{−1} and no-biochar treatments (Figure 3). No significant differences were found in the small macro-aggregates (0.25–2 mm), micro-aggregates (0.25–0.053 mm) and silt + clay (<0.053 mm) contents, across all treatments compared with CK. Our results were in line with those of other studies [38,39], which reported no effect of biochar on micro-aggregation improvement. However, some studies have reported different effects of biochar on water stable aggregates. For example, (Dong et al.) [40] reported increased aggregation under the selected biochar supplementation rates, and the soil organic carbon extracted from the biochar was considered to be an important factor to improve the stability of aggregates. A previous study [41] indicated that SOC initially induces the formation of micro-aggregates (<250 µm) by connecting polyvalent cations and clay particles, and the subsequent formation of macro-aggregates (>250 µm) comes as a result of the combination of micro-aggregates. Liu et al. [42] observed incremental aggregation under 40 Mg ha^{−1} BC treatment, but no effect under 20 Mg ha^{−1} treatment, which is similar to our results. We postulated that the differences in the effect of biochar addition might have been due to the application rate [42], application time [43,44], incubation method [45], climate [46], soil properties [47,48] and the texture of the biochar used [49]. Additionally, appropriate biochar application rates are a feasible method for accelerating water stable aggregate formation [50].

4.2. Effects of Biochar on Soil Salinity

Our results indicated that the addition of biochar to soils had a poor effect on mitigating the soil salt content during maize cultivation. The more biochar was added, the higher the EC in soil. However, the EC measured after the barley harvest showed no differences between all biochar treatments (Table 3). At the same time, the pH decreased in all biochar treated plots compared to CK. A large proportion of rainfall occurred during maize cultivation, and the soil salt content changed significantly over time as shown in Table 3. The soil salt content was higher at a depth of 20~40 cm than at 0~20 cm on 30 September 2015. Nevertheless, an inverse relationship between the EC values of the two soil depths was shown in 2016. The soil pH in saline soil is closely related to carbonate and bicarbonate [51], so the soil pH decrease in 2016 may have been caused by the corresponding salt transfer from topsoil to the deeper soil. Biochar showed a delayed effect on soil salinity elimination in our study, demonstrating no benefit in the short-time experiments. Unlike the controlled incubation conditions in laboratory studies [31,52,53], some natural field factors such as rain and groundwater changed continually during the crop cultivation period in our study area. The soil salinity was mainly determined by the meteorological conditions during the maize-barley rotation system. Therefore, long-term experiments should be carried out to study the continuous effects of biochar on soil salinity mediation. Additionally, due to its stability, large specific surface area, and porosity [54], the biochar added to the soil is primarily used for nutrient storage [55], microbial activity improvement [56], root growth [57] and soil physical culture modification [58], thus accelerating nitrogen uptake by crops [59,60] and blocking salt upward movement through capillary water.

4.3. Effects of Biochar on Carbon Sequestration and Yield

In good agreement with [54,61], which showed that biochar added to soil significantly increased the SOC, the SOC in our study area increased continuously during the crop rotation cultivation period (Figure 3). Applying biochar to agricultural soils could retard the soil C cycle and the non-CO₂ greenhouse gas (GHG) emissions [62]. Some reports have shown that biochar application decreased soil GHGs, including CH₄, N₂O, and NO fluxes [60,63]. Global warming caused by GHGs could lead to sea level rises, and seawater intrusion would bring more serious problems in coastal saline soil agriculture. Furthermore, recent estimates suggested that by 2100, the global average sea level may have risen by more than 2 m [64], which will result in serious harm to coastal ecology, agriculture, fishing, and human life. Therefore, we suggest that biochar could play a role in slowing down climate change by ensuring the sustainable development of coastal agriculture.

It is well documented that biochar modifies soil to improve crop productivity [65–67]. Biochar supplementation at rates of 7.5, 15, and 30 Mg ha^{−1} exerted a significant positive effect on improving maize grain yield by 1.70%, 55.14%, and 65.59%, respectively, but only small increases in barley yield were achieved in the subsequent cultivation period following no further biochar amendment (Figure 4). Humified materials (humic-acid-like material and fulvic-acid-like materials) in biochar could improve crop growth [68], and Wang, et al. [69] also reported that biochar amendment promoted humic acid synthesis. However, low temperatures could limit biochar performance, as has been reported by Nelissen et al. [70].

5. Conclusions

Soil degradation was observed in the maize-barley rotation system in our study area, and this phenomenon was especially obvious in terms of soil water holding capacity changes. We showed that biochar is a potentially suitable soil amendment for coastal saline agriculture, because it improved the physical properties of the soil in this study. Moreover, biochar is an effective treatment for coastal saline soil agriculture because it increased the large macro-aggregate content and SOC in the soil, which resulted in an improvement in the water stable aggregates. Furthermore, the grain yield of the maize and barley cultivated in biochar-treated soil was improved.

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Article

Ecosystem Service Value Response to Different Irrigation and Drainage Practices in a Land Development Project in the Yellow River Delta

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Abstract: The potential for development of saline land is enormous; the concept has recently attracted great scientific attention regarding its use and development. It is especially crucial to consider the issue of ecological balance when carrying out large-scale land remediation in the Yellow River Delta region since the saline land there is rich in resources and is also typically an ecologically delicate area. In order to quantitatively estimate the value of ecosystem services under various irrigation and drainage modes, this paper uses an undeveloped land development project in the Yellow River Delta as an example, simulates five different irrigation and drainage modes, and combines the market value method and the calculation method of factor equivalents. A quantitative estimation of the ecosystem service value under different irrigation and drainage modes is carried out, exploring the impact of different irrigation and drainage modes on the ecosystem from the perspective of ecosystem service value. The findings revealed that while the “Pipeline irrigation + concealed pipe” irrigation and drainage model increased the area of cultivated land by 4.04 km², the overall ecological value increased by only Renminbi (RMB) 6.707×10^6 . It is clear that only an increase in the area of cultivated land will not increase the ecological value as a whole. Through comparison, it is found that the ecological value of ‘Pipeline irrigation + open ditch’ irrigation and drainage pattern increases the most, which is RMB 28.405×10^6 . It can increase the area of cultivated land and protect the ecological benefits to a greater extent, which can better meet the requirements of the current comprehensive development. The study’s findings can serve as a foundation for the sustainable development of the area and the scientific selection of development in ecologically vulnerable coastal areas.

Keywords: different drainage methods; value of ecosystem services; Yellow River Delta; ecological balance; sustainable development

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1. Introduction

The development of saline land management and its comprehensive use is of considerable relevance to safeguarding the security of China’s arable land and food production since coastal saline land is a valuable land reserve resource [1,2]. To protect China’s arable land and food production, saline and alkaline land management and comprehensive usage are of utmost importance. The Yellow River Delta region, one of China’s most significant land reserve resource areas, has more than 600,000 hectares of salinized arable land and more than 100,000 hectares of undeveloped saline land that can be converted into agricultural land.

Significant contributors to soil salinization in this area include the shallow subsurface depth, highly salinized groundwater, and intense evaporation [3,4]. The salinization of land can be prevented and improved via drainage and irrigation [5]. The success or failure of managing saline soil is directly impacted by inadequate drainage, which causes salt to accumulate [6].

Salinized farmland treatment mainly includes drainage, soil backfilling, chemical improvement, biological improvement, and other measures. The use of farmland drainage

technology is still an important way to handle soil salinization. At present, the drainage methods adopted in the process of saline–alkali land improvement and treatment in China mainly include open-ditch drainage, subsurface pipe drainage, and shaft drainage [7]. Domestic and foreign scholars have done much research on drainage salt reduction [8–10]. The groundwater in the Yellow River Delta is high in salt content and shallow in depth, and the soil salinization is profound. At the same time, this area is located in a temperate continental climate zone, the precipitation is relatively concentrated, the soil in the rainy season is mostly salinized, and the land use efficiency is extremely low. It represents a typical soil salinization area. The Yellow River Delta area's drainage and salt discharge projects are still primarily based on open ditch drainage, but because concealed pipe drainage technology has a good handle on groundwater levels and land-saving benefits, it is quickly gaining in popularity and has grown to be the largest area of concealed pipe promotion and application in China [11]. Currently, there are different drainage combinations, such as “open ditch drainage” [7], “concealed pipe + open ditch drainage” [12], and “concealed pipe drainage” [13], on the field scale of various development projects in the area. The drainage standard can be improved using concealed pipe drainage technology, which is based on open ditch drainage and is the fastest-growing technology in this field [5]. In the process of treating saline–alkali soil, canal water conveyance and canal-lining technology are still widely used for irrigation, and pipeline irrigation has also advanced quickly due to the region's growing water constraints from the Yellow River.

Land remediation has had a variety of effects on the spatial patterns of natural ecosystems and ecosystem services while promoting regional economic and social advantages [14,15]. Land remediation has significantly altered land use patterns and the accompanying ecosystem services in China [16], making it one of the largest coordinated human operations to alter land use patterns and impact terrestrial ecosystems [17]. Ecological land remediation has entered a crucial phase of theoretical innovation and practical application, as a result of the ongoing promotion of ecological civilization construction and the transformation of multifunctional land management [18].

An urgent scientific issue is how to utilize and apply the theoretical framework of ecosystem service functions to scientifically and impartially assess the changes in ecosystem service values that are brought about by land remediation activities [19], but there are still no methods that have been proven to be effective in the real world for identifying and evaluating agro-ecosystem service functions [20]. Many studies have been conducted in China [15,21–23], based on changes in ecosystem service function gains and losses in land remediation projects or administrative areas before and after remediation; however, comparative studies on ecosystem service function responses under various remediation technology measures are lacking. This makes it difficult to evaluate and choose ecologically based remediation technologies. One of the crucial types of land rehabilitation is the development and management of saline land. The land use structure of the project area after management, as well as the area occupied by the field road system, will be directly impacted by the development and management of saline land if different irrigation and drainage design schemes are adopted. This, in turn, will inevitably affect the spatial distribution pattern and service function of the ecosystem after management, and result in corresponding ecological and environmental effects [24].

The overuse and irrational usage of coastal-zone land have been a significant issue and are a threat to China's ecological security [25]. In order to increase the overall value of ecosystem services in coastal areas, it is crucial to carry out land development and remediation in the environmentally vulnerable coastal area of the Yellow River Delta and to choose ecologically oriented development and management strategies. This article selects the Yellow River Delta region and the Dongying City Hekou District Beili land development project as the object. It simulates five different irrigation and drainage designs, including “Irrigation channel + open ditch”, “Pipeline irrigation + open ditch”, “Irrigation channel + open ditch + concealed pipe”, “Irrigation channel + concealed pipe” and “Pipeline

irrigation + concealed pipe”, and then examines how the land use structure changes under each design scheme.

2. Materials and Methods

2.1. Overview of the Study Area

The project area ($37^{\circ}59'28''$ – $38^{\circ}00'20''$ N, $118^{\circ}17'48''$ – $118^{\circ}20'28''$ E), which encompasses five administrative villages and covers an area of 4.63 km^2 , is situated in the Hekou District of Dongying City. These villages are Shuanghe, Xingxing, Beili, Dongfeng, and Xinli of Xindu Town. The project area has a broad, flat topography, located in the Yellow River’s present alluvial plain, and has a northern temperate semi-humid continental climate. The deep soil has a significant salt content (4‰) as a result of the soil formation process of seawater impregnation. Land-use types are typically broken down into four groups, based on the present state of land use in the project area: arable land, forest land, other agricultural land, and unused land. Arable land includes both dry and wet ground, while other agricultural land also contains hardened channels, open drainage ditches, hardened roads, and vegetative roads. Saline land makes up the remaining area. The use of different land use types is shown in Table 1.

Table 1. Use of different land use types in the project area.

Land Use Type	Usage
Dry land	Fields growing xerophytic crops from natural precipitation without irrigation
Watered land	Fields with water guarantee and irrigation facilities are used to plant economic crops such as cotton.
Harding channels	Field irrigation and drainage channels using concrete as a base
Guttering	Diversion of low-lying catchment water to soil ditches outside crop fields and roadbeds
Hardened Road	Used for cargo transportation, vehicle traffic, etc.
Packway	Mostly distributed in the field, more for daily farming and so on

2.2. Data Sources

The basic data in this paper are from the current land-use map of the project area (Figure 1), local survey data, and statistical data, such as the statistical yearbook of Dongying City. Other data, such as crop prices and planting areas, are from the official website of EPS data (accesses on 15 April 2022), the Statistical Yearbook of China (2020), and the compilation of national agricultural product cost-benefit data.

2.3. Design Simulations for Different Irrigation and Drainage Modes

This paper establishes five irrigation and drainage modes: “Irrigation channel + open ditch”, “Pipeline irrigation + open ditch”, “Irrigation channel + open ditch + concealed pipe”, “Irrigation channel + concealed pipe”, and “Pipeline irrigation + concealed pipe”, by the land-use change characteristics of the project area and prior planning experience. The specific scheme is shown in Table 2. Figure 2 is the simulation distribution diagram of five modes.

2.4. Calculation of Ecosystem Services Value

The system of ecosystem service value proposed by Costanza is currently primarily used in the evaluation of ecological values [26]. Xie Gaodi et al. [27] improved Costanza’s system, which was based on a questionnaire survey and study, to increase the accuracy of the computation of ecosystem service value. The ecosystem service functions in the project area were divided into production, ecological, and life aspects for assessment in this paper, based on the types of terrestrial ecosystem service values in China that have been proposed by Xie Heights, combined with the functional characteristics of farmland ecosystems. The ecological function includes six aspects of biodiversity maintenance value, gas regulation

value, climate regulation value, hydrological regulation value, environmental purification value, and maintaining soil value. The production function only takes into account the production of agricultural products. The life function is chosen as characterized by landscape aesthetics (Table 3).

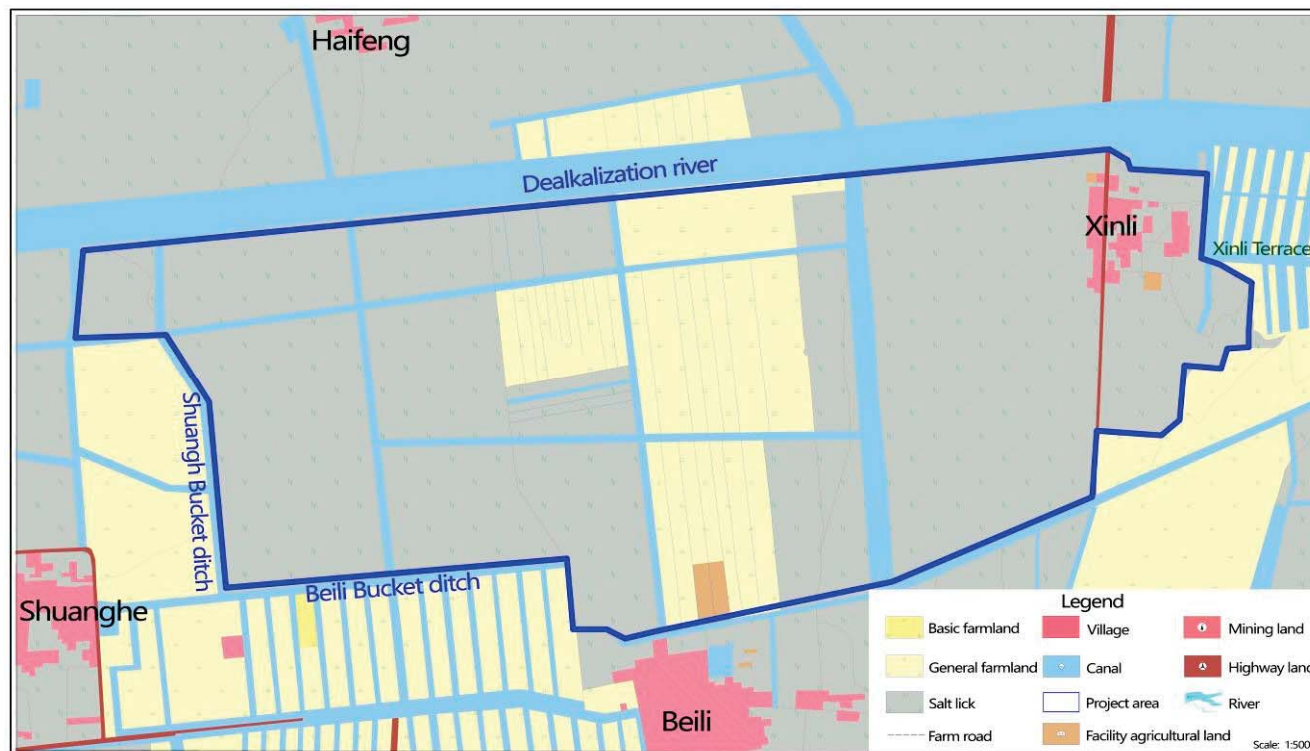


Figure 1. Current land-use map of the project area.

Table 2. Design options for different irrigation and drainage modes.

Irrigation and Drainage Patterns	Water Conveyance System	Design Solutions Drainage System	Comprehensive Width of Field
Irrigation channel + open ditch	Hardened branch canal, bucket canal, agricultural canal	Branch ditches, bucket drains, farm drains	50 m
Pipeline irrigation + open ditch	Branch pipe, bucket pipe, agricultural pipe	Branch ditches, bucket drains, farm drains	50 m
Irrigation channel + open ditch + concealed pipe	Hardened branch canal, bucket canal, agricultural canal	Concealed pipe, farm drains	100 m
Irrigation channel + concealed pipe	Hardened branch canal, bucket canal, agricultural canal	Concealed pipe	100 m
Pipeline irrigation + concealed pipe	Branch pipe, bucket pipe, agricultural pipe	Concealed pipe	100 m

Table 3. Classification of ecosystem functions in the project area.

Category	Ecosystem Service Value	Evaluation Methodology
Production	Production function value	Market Value Method
Ecology	Biodiversity maintenance value, gas regulation value, climate regulation value, hydrological regulation value, environmental purification value, maintaining soil value	Equivalent factor method
Life	Landscape aesthetic value	Equivalent factor method

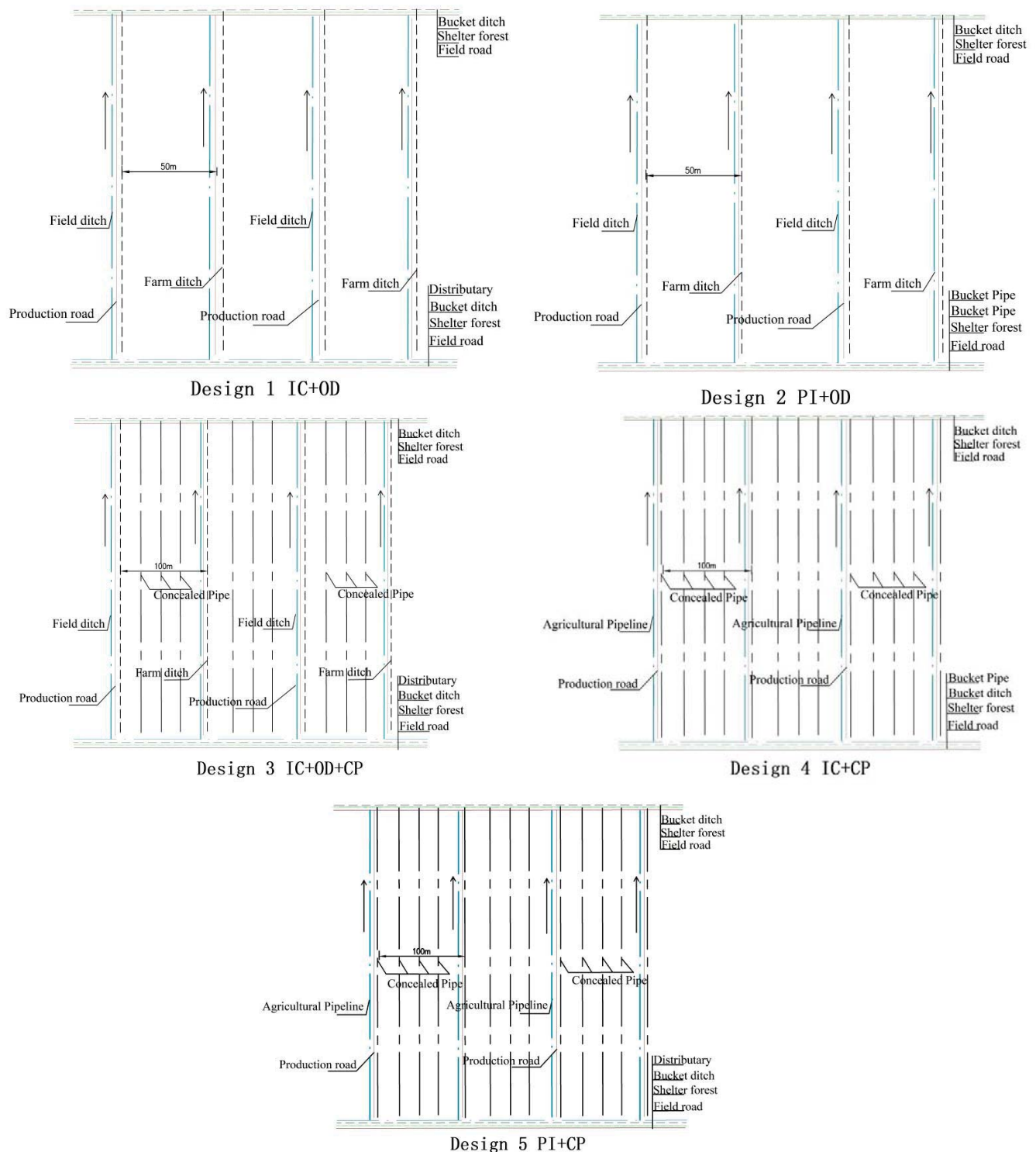


Figure 2. Design schematics for various irrigation and drainage techniques.

2.4.1. Calculation of Production Value

The total value of agricultural production function under various irrigation and drainage modes in the project area was calculated using the following formula, based on the calculation method of the agricultural food production service function presented by Xie Gaodi et al. [28]:

$$E_p = S \times \sum_{i=1}^n \frac{m_i p_i q_i}{M} \quad (1)$$

where E_p is the total economic value of the production service function of farmland in the project area (RMB/km²); S is the cultivated area of the project area under different irrigation and drainage patterns (km²); i is the type of crops grown; m_i is the planted area of i crops (km²); p_i is the national average price of i crops (RMB/kg); q_i is the yield per unit area of i crops (kg/km²); M is the total planted area of crops.

Cotton, corn, and wheat are the primary crops today and will remain so after the proposed development in the project area. The production value of the project area under various irrigation and drainage modes is determined using the aforementioned method, with reference to the national agricultural market prices in 2020.

2.4.2. Calculation of Ecological and Life Values

The value equivalent factor approach was employed to determine the ecological value of the project area by calculating the ecological function value of various types of land, in conjunction with the actual land use in the project area. The equivalent value of watered land in the project area was calculated using the benchmark of ecosystem service value equivalents per unit area, as proposed by Xie Gaudi. The hardened channels had water periods of only 15 to 30 days per year, and the rest were bare concrete surfaces, in accordance with the equivalent value assigned to the construction land by An Sven et al. [29]. The value of the ecosystem services offered by hardened channels was calculated based on actual conditions. Open drainage ditches in the project area are always used for water storage; their ecological value is measured based on the water surface. Unused land is salty and can be compared to the equivalent desert and bare land. The majority of the vegetation in the project area is mixed coniferous; the increase in forest land following remediation is based on the coniferous equivalent of the second-class classification in a first-class forest. The ecosystem service value of the vegetation road surface is calculated using bare land, while the ecological value of the hardened road surface is determined using construction land. The aesthetic value of the landscape was chosen as an indicator to evaluate the living value of the project area because the natural landscape created by the plant community can be physically and mentally enjoyable, can provide an aesthetic landscape, and may also potentially be used for recreation and gain cultural and artistic value. The equivalent factor approach is also used to determine the aesthetic value of the landscape in the project area. The final unit area ecosystem services value equivalent factor results are shown in Table 4.

Table 4. Equivalent factor of ecosystem service value per unit area.

Land Use Type	Biodiversity Maintaining	Gas Conditioning	The Equivalent Weight Factor of ESV				Landscape Aesthetic
			Climate Control	Hydrological Regulation	Clean-Up Operation	Soil Conservation	
Watered land	0.17	0.89	0.465	1.495	0.135	0.52	0.075
Dry land	0.13	0.67	0.36	0.27	0.10	1.03	0.06
Hardened channels	0.01	0.06	0.01	0.02	0.01	0.01	0.01
Guttering	2.55	0.77	2.29	102.24	5.55	0.93	1.89
Hardened Road	−0.01	0.04	0.01	0.02	0.01	0.01	0.02
Packway	0.02	0.02	0	0.03	0.10	0.02	0.01
Woodland	2.60	2.35	7.03	3.51	1.99	2.86	1.14
Saline-alkali land	0.07	0.065	0.05	0.12	0.205	0.075	0.03

The ecological service value of a unit farmland ecosystem in Dongying City in 2020 was calculated using 1/7 of the market value of the grain yield of cotton, corn, and wheat, the main crops in the city, as the standard for farmland ecological service value. The correction coefficient [30] was then used to correct the equivalent value of the ecosystem services of different land types.

2.5. Ecological Value Sensitivity

The ecological value sensitivity (C_s) is a measure of the dependence of the total value of ecosystem services on the value coefficient. When $C_s > 1$, this means that the value of ecosystem services is elastic, while when $C_s < 1$, this means that the value of ecosystem services is inelastic. The specific formula is:

$$C_s = \left| \frac{(V_g - V_f) / V_f}{(C_{v,g} - C_{v,f}) / C_{v,f}} \right| \quad (2)$$

where C_s is the sensitivity of ecological value, C_v is the ecological service value coefficient, V is the total value of ecosystem services, and f and g are the value of ecosystem services before and after the adjustment of value coefficients.

2.6. Statistical Methods of Various Land-Use Types

According to the design scheme of each irrigation and drainage mode in Figure 2, the ArcGIS software is used to draw the design diagram of the different mode project areas, and the mask extraction tool in the software is used to identify different land use types in the project area. According to the extraction results, the geometric area of each land-use type layer is calculated. In the drawing process, the width of the hardened channel is the width of the channel base, while the width of the drainage ditch is selected as the width of the upper mouth of the drainage ditch, which can more accurately calculate the final occupied area of the hardened channel and the drainage ditch.

3. Results and Analysis

3.1. Analysis of Land Use Changes in Different Irrigation and Drainage Modes

The land-use structure of the project area was created and simulated in accordance with the various irrigation and drainage modes, and the land use in each mode is depicted below (Table 5).

Table 5. Land use of different irrigation and drainage patterns. Unit: km².

Type of Irrigation and Drainage	Land Use Type							Unused Land Saline Land	Total
	Watered Land	Arable Land Dry Land	Hardening Channels	Other Agricultural Land Guttering	Hardened Road	Packway	Woodland Arbor Land		
Raw data	0	1.17	0	0.37	0	0.13	0.002	2.96	4.63
Design 1	3.06	0	0.30	0.90	0.10	0.18	0.09	0	4.63
Design 2	3.35	0	0	0.90	0.10	0.18	0.09	0	4.63
Design 3	3.56	0	0.17	0.63	0.10	0.09	0.09	0	4.63
Design 4	3.87	0	0.17	0.31	0.10	0.09	0.09	0	4.63
Design 5	4.04	0	0	0.31	0.10	0.09	0.09	0	4.63

Under the five irrigation and drainage patterns, the forest land and unused land underwent the largest overall changes in terms of land-use type. The area of forest land increased from 0.002 km² before becoming 0.09 km² after development, and the area of unused land decreased from 2.96 km² to 0 after remediation, when all unused land was converted into usable land. The “Design 5” mode is the most effective model for increasing arable land when compared to other irrigation and drainage methods because it reduces the need for hardened channels and so results in a significant increase in the amount of arable land. The traditional “Design 1” mode needs to occupy more topsoil area than other modes, so the cultivated land area is the least among the five irrigation and drainage modes, at only 3.06 km², while the hardened channel, drainage ditch, and other agricultural land types are the opposite, accounting for the highest proportion. This is because the traditional “Design 1” mode requires more topsoil area for open ditches than other modes. The “Design 2” model significantly increases the size of open drainage ditches and dirt

roads, while significantly decreasing the area occupied by hardened channels, compared to the “Design 3” and “Design 4” modes. The farmed land only covers 3.35 km².

3.2. Value Changes for Ecosystem Services under Various Irrigation and Drainage Methods

The final calculation results are displayed in Table 6. The ecosystem service values of the “Design 2” and “Design 1” modes, at RMB 46.585×10^6 and RMB 45.798×10^6 , respectively, are much greater than those of the other three modes. The “Design 4” drainage type has the lowest ecosystem service value, at only RMB 24.429×10^6 . The most significant element of the overall ecosystem service value, from the perspective of various functional values, is the ecological value. The largest amount of arable land is provided by “Design 5”, which also has the highest production value. “Design 2” has the highest ecological value, which is RMB 40.585×10^6 . The “Design 1” irrigation and drainage model expands the area of woodland on the original land type while maintaining the original number of ecological open ditches, increasing the production value and ecological value.

Table 6. Value of ecosystem services under different irrigation and drainage patterns. Unit: RMB10⁶.

Type of Irrigation and Drainage	Ecosystem Service Value			Total	Value Added
	Production Value	Ecological Value	Life Value		
Raw data	1.796	16.09	0.295	18.18	
Design 1	4.841	40.249	0.707	45.798	27.618
Design 2	5.256	40.615	0.714	46.585	28.405
Design 3	5.635	29.931	0.539	36.104	17.924
Design 4	6.132	17.945	0.342	24.419	6.239
Design 5	6.393	18.148	0.346	24.887	6.707

The pattern of change in ecosystem service value of arable land is not consistent with the trend of changes in arable land area, according to the change in the ecosystem service value of each land-use type under various irrigation and drainage systems. Most arable land area was expanded by the “Design 5” irrigation and drainage method; however, the overall ecosystem value was low, and the ecosystem service value only increased by RMB 6.707×10^6 . Even though the “Design 1” irrigation and drainage model improved the least amount of arable land, it had a far higher gain in ecosystem service value than “Design 5”, coming in at RMB 27.617×10^6 . The “Design 2” irrigation and drainage model offers the biggest gain in ecosystem service value, which is RMB 28.405×10^6 . The original ecological open agricultural ditch is kept for its ecological value. The three irrigation and drainage techniques of “Design 3”, “Design 4”, and “Design 5” have increased the area of arable land, but they are insufficient to balance the growth of hardened channels and the decline of vegetation roads. Therefore, despite a growth in the amount of cultivated land, the value of ecosystem services, as a whole, did not improve.

3.3. Sensitivity Analysis

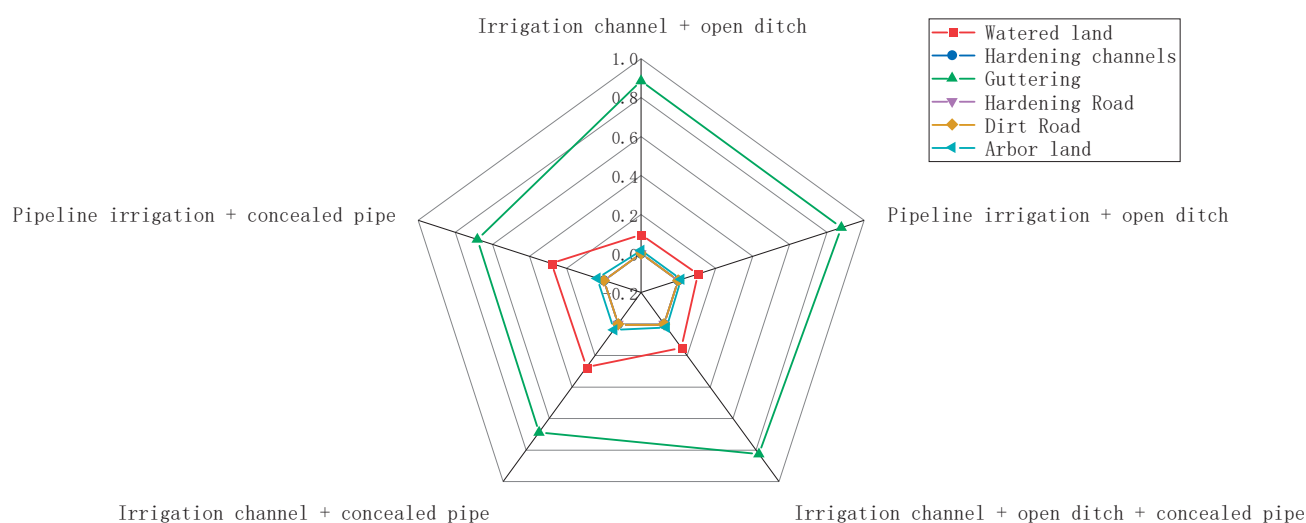
In order to calculate the sensitivity index of the ecosystem service value of the project area under five irrigation and drainage modes, the ecological value coefficients of cropland, forest land and other agricultural land were adjusted up- and downward by 50%. After that, the overall ecosystem service value change caused by the change in the ecosystem service value of the land type was calculated (Table 7).

Table 7. Changes in the project area’s sensitivity indices (CS) of ecosystem service values under five different forms of irrigation and drainage.

Irrigation and Drainage Patterns	Land-Use Type					
	Watered Land	Hardened Channels	Guttering	Hardened Road	Dirt Road	Arbor Land
Design 1	0.097	0.000	0.886	0.000	0.000	0.016
Design 2	0.105	0.000	0.878	0.000	0.000	0.016
Design 3	0.151	0.000	0.826	0.000	0.000	0.022
Design 4	0.274	0.000	0.688	0.000	0.000	0.037
Design 5	0.283	0.000	0.681	0.000	0.000	0.036

According to the results in the table, the sensitivity index (CS) for each type of land use under the five irrigation and drainage modes ranged from 0.000 to 0.886, with a total value of less than 1. This shows that the ecosystem service value in the project area is inelastic to the corrected ecosystem service value equivalent coefficient; that is, the corrected ecosystem service value equivalent coefficient is consistent with the actual situation in the project area, and the calculation results have a high degree of confidence. The calculated results have strong confidence; the adjusted Ecosystem Service Value Equivalent Coefficient is compatible with the project area’s current state. The ecosystem service value (ESV) of hardened channel, hardened road, and plain road is around zero, suggesting that the ecological service value equivalency coefficient (VC) of these three land use types has little influence on the ecosystem service value. Conversely, the CS of the open drainage ditch is the greatest among all land types, demonstrating that the accuracy of VC is the most essential factor for the calculation of ESV.

The overall distribution trend is the same, from small to large, followed by hardened roads, plain soil roads, arboreal forest land, irrigated land, and open drainage ditches. However, the impact degree of various land use types will vary, as seen from the perspective of the order change in sensitivity indexes of different land use types in each irrigation and drainage mode (Figure 3). The three modes of “Design 1,” “Design 2,” and “Design 3” each have a higher sensitivity index for open drainage ditches, with the mode of “Design 1” having the highest index at 0.886. This means that the entire ecosystem service value coefficient of the project area will grow or decrease by 88.6 percent for every 1 percent change in the corresponding coefficient of ecosystem service value of an open drainage ditch.

**Figure 3.** Comparison of sensitivity indices for each land-use type under different irrigation and drainage patterns.

4. Discussion

In the current process of improving saline–alkali land, the improvement methods adopted are different according to the actual conditions of each project area [31–33]; however, the project implementation and research focus mainly on the improvement effect of different modes on the drainage and salt discharge of saline–alkali land [34,35]. There is a lack of comparative research on the impact of the different irrigation and drainage modes used in the improvement process regarding ecological value. The five irrigation and drainage modes designed in this paper are some of the more common ways to improve saline–alkali land through drainage and irrigation. The comparative analysis of the ecological value of different modes fills the gap in research to a certain extent and provides a basis for the selection of irrigation and drainage in the process of saline–alkali land improvement in the future. The patterns provide a reference.

The ongoing discussion concerning land use and ecosystem service value is mostly conducted for a finished project or the entire region [36,37]. This article chooses five distinct irrigation and drainage modes for simulation, based on an underdeveloped project area, and computes the ecosystem service value for each option. The findings demonstrate that merely pursuing an increase in the cultivated land area throughout the process of developing underused land would not raise the ecosystem service value in a manner that is commensurate. The influence of various land types on the value of ecosystem services should be taken into account when making a thorough selection since this serves as a guide for selecting design schemes that are appropriate. The project area's land ecosystem service value was previously estimated by roughly dividing the different land types; here, the ultimate overall value evaluation will be different. For instance, the ecological service value of agricultural hardened open ditches is not explicitly provided, but the ecosystem service value of field roads is directly categorized under other land categories [38,39]. Field roads in this paper are split into plain soil roads and hardened roads for assessing the value of ecosystem services. According to the real situation and the equivalent of building land, the fields' open hardened ditches are assigned.

A single parameter's increase in the area of cultivated land cannot cause its corresponding ecological value to increase synchronously, which is something that needs to be taken into account as part of the goal of increasing cultivated land and meeting the demand for land for social and economic development. This paper makes use of the comparable table of ecosystem service value per unit area proposed by Xie Gaodi for the terrestrial environment in China. Although it has been updated to reflect Shandong Province's current circumstances, the value of each ecosystem service has not been further clarified. The issue of spatial disparities has not been included in research on the shift in ecosystem service value; this is an area that needs to be expanded upon in future studies.

5. Conclusions

The paper simulates five different irrigation and drainage modes, based on an undeveloped land development project in the Yellow River Delta. The modes are “Design 1 (Irrigation channel + open ditch)”, “Design 2 (Pipeline irrigation + open ditch)”, “Design 3 (Irrigation channel + open ditch + concealed pipe)”, “Design 4 (Irrigation channel + concealed pipe)”, and “Design 5 (Pipeline irrigation + concealed pipe)”. The paper also uses the market value method and the unit area equivalent method to determine the respective ecosystem service values, based on various land use conditions.

- (1) The corresponding land-use structures are developed from the five simulated irrigation and drainage modes. The conventional “Design 1” irrigation and drainage style takes up the most surface space, while other agricultural land makes up the majority of this area. Among them, the “Design 5” model occupies less surface area and can provide the most cultivated area. After development, there is no more undeveloped terrain.
- (2) The ecosystem service value under the five irrigation and drainage modes of “Design 1”, “Design 2”, “Design 3”, “Design 4”, and “Design 5” in the study area is calculated us-

ing the market value method and equivalent factor method. The results show that the overall value has increased and is, respectively, RMB 45.798×10^6 , RMB 46.585×10^6 , RMB 36.104×10^6 , RMB 24.419×10^6 and RMB 24.887×10^6 . Comparative analysis reveals that the “Design 2” option has the highest ecosystem service value. This model combines a classic open agricultural ditch with underground pipeline irrigation to optimize the ecological value, while maintaining the cultivable land area. The most significant increase in the cultivated land area cannot considerably raise the total ecological value because “Design 5” only has a small impact on the rise of ecosystem service value.

- (3) The open drainage ditch and irrigated land have relatively high ecological value sensitivity indices that significantly affect the value coefficient of ecosystem services. The ranking of the ecological value sensitivity index for each land type is unaffected significantly by the various irrigation and drainage methods. The ecological value sensitivity index of irrigated land has grown in comparison in “Design 5” and “Design 4”, whereas the ecological value sensitivity index of the open drainage ditch has somewhat dropped.

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Article

Manure plus Plastic Film Mulch Reduces Soil Salinity and Improves Barley-Maize Growth and Yield in Newly Reclaimed Coastal Land, Eastern China

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Abstract: In newly reclaimed coastal soil, saline conditions and nutrient deficiency are the restraining factors for crop yield. Manure and plastic film mulch are proved to play a vital role in reducing soil salt, increasing soil water, and improving soil nutrients and plant growth. A field experiment was carried out with plastic film mulch, manure, and their combinations in the Tiaozini reclamation area; four treatments were set up as (1) control treatment (CK), (2) plastic film mulch (PM), (3) farmyard manure (FM), and (4) combined application of plastic film mulch and farmyard manure (PM+FM). The main results showed that, compared with CK treatment, the average soil water content under the FM+PM treatment was increased by 5.8% and 3.6%, and the average soil salt content was reduced by 20.2% and 10.0% at 0–20 cm and 20–40 cm soil layers, respectively. This was because of the decrease in soil bulk density and increase in saturated hydraulic conductivity and saturated water content. Meanwhile, soil organic matter, total nitrogen, available nitrogen, and available phosphorus were significantly increased under the PM+FM treatment, except that for AN, which was significantly decreased at the 0–10 cm soil layer owing to plant uptake. Based on the decrease in soil salt, there was an improvement in soil hydraulic properties and soil nutrients, which resulted in summer maize biomass and yield being increased by 106% and 137%, respectively, and barley biomass and yield were increased by 133% and 106%, respectively, under FM+PM treatment. Consequently, combined manure and plastic film mulch application was better at reducing soil salt; increasing soil water content; and improving soil nutrients, plant growth, and yield production in newly reclaimed salt-affected soils.

Keywords: organic fertilizer; mulch; soil water content; soil property; crop yield

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1. Introduction

The global area of saline-alkali soil is about 900 million ha [1]. In China, the area of saline-alkali soil is about 3.67 million ha and accounts for 4.88% of the total available land [2]. Saline-alkali soil is characterized by high salinity and sodicity and pH value [3], poor soil quality and structure [4], scarcity of organic matter [5], low hydraulic conductivity [6], and low resource utilization efficiency [7,8]. Reclamation of coastal saline soil in recent decades has greatly alleviated the shortage of cultivated land in coastal regions [9]. However, the newly reclaimed coastal saline soil has characteristics of high evaporation, seasonal precipitation, high groundwater table, and poor soil nutrients, which are not conducive to soil desalination and agricultural development. Thus, it is necessary to choose a suitable method to develop agriculture in salt-affected soil.

It has been reported that the use of organic fertilizer is beneficial in remediating salt-affected soil [10]. It can improve the physical properties of the soil [6], such as reducing soil bulk density, increasing soil porosity and saturated hydraulic conductivity, reducing soil salinity, improving soil quality and carbon sequestration [11], and increasing grain yield. Chen et al. (2021) reported that organic matter played a key role in soil quality, phosphorus

availability, and plant growth [8]. Han et al. (2021) conducted a pot experiment with maize crop in newly cultivated land, indicating that soil fertility and microbial structure were rapidly improved with the organic fertilizer application [12]. Cao et al. (2021) suggested that straw return could be a promising management practice to reduce mineral phosphorus fertilization without a significant reduction in seed cotton yield on coastal saline lands [13].

Mulching is considered to be one of the positive ways to increase crop yield and is widely used around the world [14–17]. It can reduce evaporation from the soil because of the formation of mulch [15,18], inhibit soil salt ascending [19], reserve soil moisture [20], and improve water use efficiency and nitrogen use efficiency [21]. Based on plot and field experiments, Bu et al. (2013) showed that plastic film mulching can effectively increase maize yield and water use efficiency in Loess Plateau in China [14]. Li et al. (2018) reported that plastic film, gravel-sand, and straw surface mulch can decrease soil water evaporation during early crop growth stage and increase crop yield and water use efficiency, but the plastic film mulch works best [22]. Ding et al. (2019) indicated that the plastic film mulch significantly improve crop production and increase resource use efficiency in a winter wheat–summer maize rotation system [23]. Ramadhan (2021) reported that application of wheat straw mulch could be the most effective soil management practice for improving corn production in an arid subtropical climate region [16].

There are also reports about the combination of film mulch and organic fertilizer. Zhang et al. (2014) reported that farmyard manure and mulch increased water holding capacity, saturated water content, and saturated hydraulic conductivity and decreased soil bulk density [6]. Duan et al. (2022) indicated that ridge–furrow planting with mulching and organic amendment improved soil physical properties and increased soil organic and total nitrogen, which could be a sustainable and efficient cultivation practice for alleviating drought stress, improving soil properties, and increasing the economic benefit on the Tibetan Plateau [24]. However, the combined effects of mulch and manure on soil water and salt dynamics, soil properties, and crop yield of maize and barley in newly reclaimed coastal land remain unclear. Therefore, the objectives of this study were to (1) investigate the effects of manure and film mulch application on soil water and salt dynamics, soil properties, plant growth, and yield production; (2) clarify the effect of salt reduction and soil properties improvement on plant growth and yield production; and (3) determine an optimized practice for improving soil properties and crop yield in newly reclaimed salt-affected soil.

2. Materials and Methods

2.1. Study Site

Field experiments were conducted at Tiaozini reclamation area (32° 50′ N, 120° 56′ E, mean altitude 1.86 m), which is located in Dongtai, Jiangsu province of eastern China. The soils in this area are mainly halosols according to Chinese Soil classification system [25], which developed from the marine deposits [26]. The texture was silty loam and contained 6.3% of sand, 80.1% of silt, and 13.6% of clay. Initially, at the experiment site, the average soil properties of 0–20 cm soil layer were as follows: soil bulk density (BD) was 1.44 g/cm³; salt content, organic matter (OM), and total nitrogen (TN) were 1.8, 6.06, and 0.54 g/kg, respectively; pH was 9.20; and available nitrogen (AN) and available phosphorus (AP) were 63.11 and 17.2 mg/kg, respectively.

The climate at the experiment site is monsoon with a mean annual temperature of 14.6 °C and a mean annual precipitation of 1100 mm [27]. Approximately 70% of the rainfall occurs from June to September. The groundwater table at this site was around 1.2 m, with a salt concentration of about 12 g/L.

2.2. Experimental Design and Field Management

The experiments were conducted from June 2016 to October 2017. The experiment was set up to include four treatments: (1) control treatment (CK), (2) plastic film mulch (PM), (3) farmyard manure (FM), and (4) combinations of plastic film mulch and farmyard

manure (PM+FM). PM was the transparent plastic film (0.01 mm thickness), which was removed after harvesting and was mulched immediately at planting. FM was the chicken manure (TN 16.53 g/kg, OM 309.4 g/kg, and salt content 1.32 g/kg) applied at a rate of 1.5 t/ha, which was spread manually and mixed into 15 cm depth by means of rotary harrowing. The treatments were arranged as a randomized complete group design with three replications. Each plot was 3 m wide and 4 m long, isolated by drainage ditch with a width of 20 cm and depth of about 30 cm.

The amount of fertilizer applied is based on the local traditional application rate. The nitrogen fertilizer dosage of maize and barley in the whole growth period is 225 kg/ha N, and the phosphorus fertilizer dosage is 90 kg/ha P. The specific application is shown in Table 1. In 2016, maize was sown on 22 June and harvested on 5 October. In 2017, maize was sown on 22 June and harvested on 15 October. Barley was planted on 15 November and harvested on 21 May of the following year. Maize is sown directly after barley is harvested, but barley is sown after rotary tillage when maize is harvested. The daily precipitation and temperature during the three growing seasons are shown in Figure 1. Total precipitation during the maize growth stage in 2016 and 2017 was 723 mm and 663 mm, respectively. While the total precipitation during the barley growth stage was 334 mm. The 2016 maize growing season was a little wetter than the 2017 maize growing season, and more rainfall occurred in the later stages of maize growth compared with 2017.

Table 1. Specific fertilization information (kg/ha).

	Barley			Maize			
	Basel Fertilizer	Reviving	Heading	Basel Fertilizer	Seeding	Jointing	Tasseling
Monoammonium phosphate (11% N, 44% P)	204			204			
Urea (46% N)	146	146	146	146	97	97	97

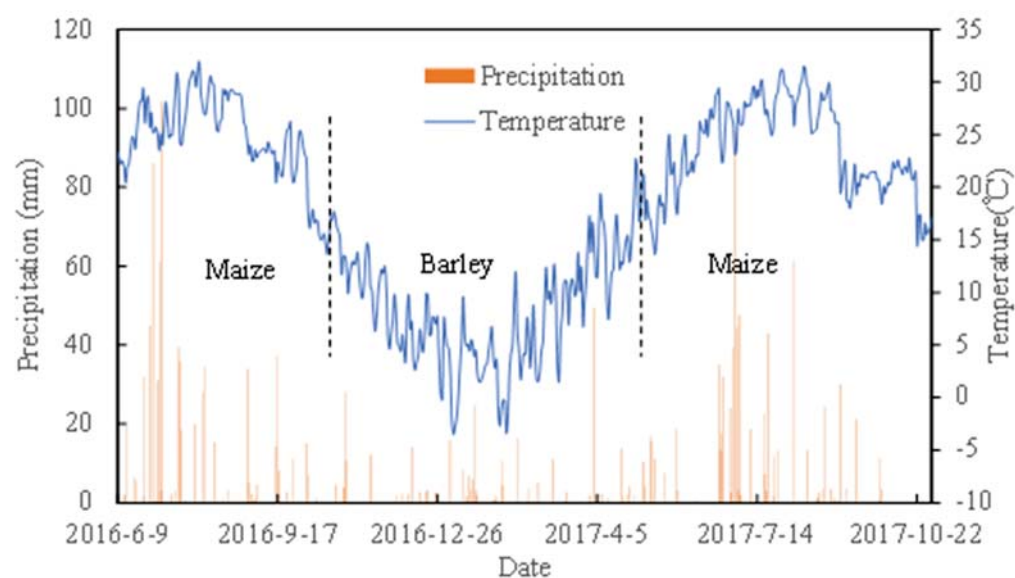


Figure 1. Daily precipitation and temperature during the experimental period.

In the 2016 maize growing season, the mean air temperature ranged from 15 °C to 31.9 °C, averaging 25.2 °C. In the 2017 maize growing season, it was 18–31.5 °C, averaging 25.3 °C, and in the barley growing season, it was −3.5–24.9 °C, averaging 9.30 °C. The average and highest temperature of two maize growing seasons were largely the same, but

the lowest temperature of the first growing season was 3 °C lower than that of the second maize growing season.

2.3. Sampling and Measurement Methods

During the crop growing season, the soil water content was measured gravimetrically at the depth of 0–20 cm and 20–40 cm with about a 30-day intervals (except for the barley overwintering stage). Soil sampling points were chosen between two rows of crops and as close to the center of the plot as possible. Samples were air-dried and ground to pass through a mesh of 2 mm size and were used for soil salt measurement. Soil salinity was measured by an extraction ration of 1:5 ($EC_{1:5}$) using an electrical conductivity meter (LE438, Mettler Toledo, Shanghai, China). Then, the $EC_{1:5}$ values were converted to the salt content in percent (total salt, TS) based on the formula of $TS = 2.47EC_{1:5} + 0.26$ ($R^2 = 0.96$, $p < 0.001$). This formula is based on our measured data in the coastal area.

In addition, physical indexes such as soil bulk density (BD), saturated water conductivity (K_s), and saturated water content (SWC), as well as nutrient indexes such as soil organic matter (OM), total nitrogen (TN), available nitrogen (AN), and available phosphorus (AP), were measured in 0–10 cm and 10–20 cm soil depth. BD was determined by the cutting ring method [28] and K_s was measured by the constant head test [29]. OM was determined by oxidization by the potassium dichromate-external heating method, TN was measured by Kjeldahl distillation, AN was determined by alkaline hydrolysis diffusion method, and AP was analyzed by sodium bicarbonate extraction-molybdenum antimony anti colorimetry [28].

2.4. Plant Growth Measurements

At maturity, nine plants were randomly chosen in each plot to measure plant height. At harvest, all aboveground crop parts were harvested manually from each plot and grain yields were obtained. Six samples were collected from each plot and separated manually to straw and grain, and then oven drying was carried out to obtain the dry matter yield. The ratio between the straw and grain was determined. The straw biomass in each plot was calculated by multiplying the oven-dried yield and the ratio between the straw and the grain.

2.5. Statistical Analysis

Excel 2016 software was used for basic data processing, including calculation of the mean value of each processing, standard deviation, and so on. SPSS program was used for one-way analysis of variance. Mean comparisons were performed using the Fisher's LSD (the last significant difference) test at $p < 0.05$.

3. Results

3.1. Soil Water Content

Soil water content dynamics within 0–20 cm and 20–40 cm are shown in Figure 2. In the top 0–20 cm soil layer, the initial soil water content among treatments was basically consistent. With the development of maize growth, the difference in soil water content among treatments first increased and then decreased. The soil water content on 15 August 2016 was 1.6%, 2.0%, and 5.6% higher under the FM+PM than that of PM, FM, and CK, respectively. During the barley growing season, the soil water contents under FM+PM and PM were higher than those of FM and CK. The largest difference occurred on 28 March 2017, when the soil water content under FM+PM was about 2.7% and 4.1% higher than that under FM and CK, respectively. In the 2017 maize season, the variation in soil water content in all treatments was similar to that of 2016, but there were significant differences among treatments, especially between the mulched and uncovered treatments. On 2 August 2017, the soil water contents under FM+PM were 14.8% and 20.0%, significantly higher than those under FM and CK.

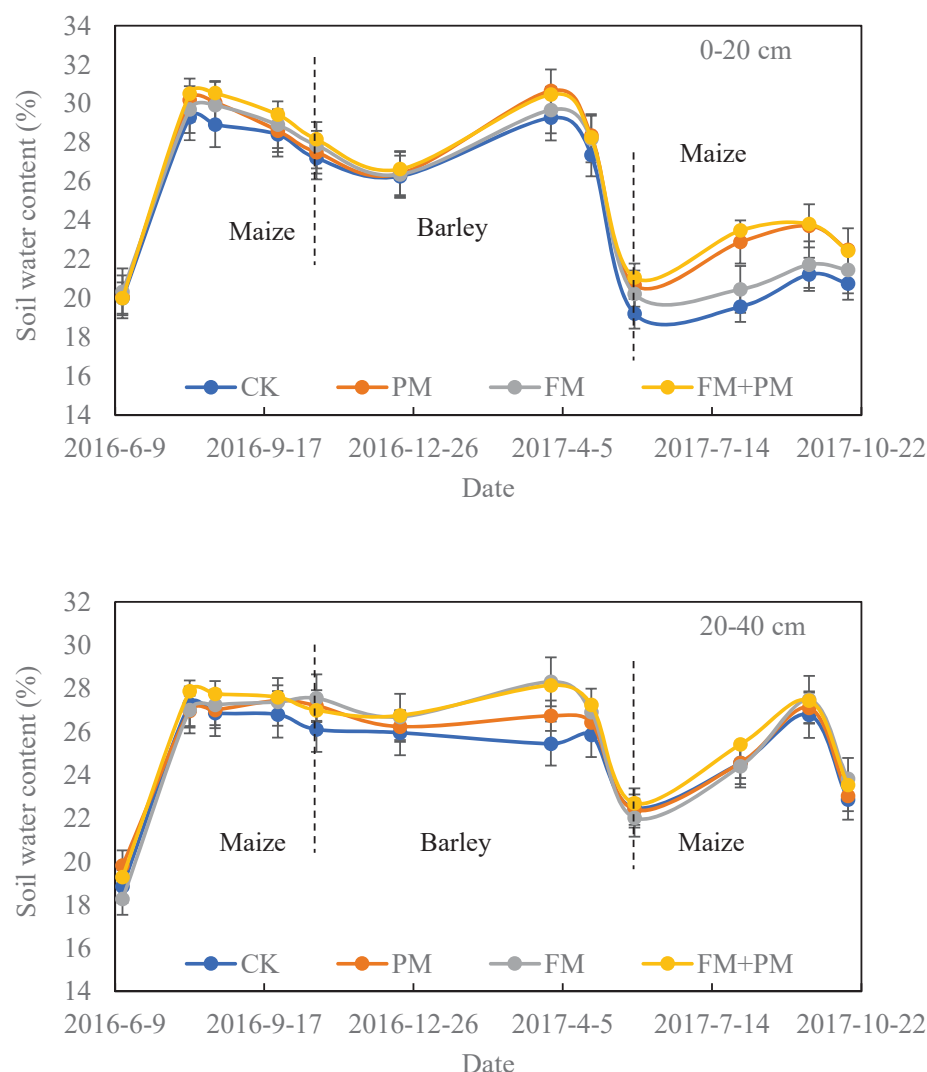


Figure 2. Soil water content in the 0–20 cm and 20–40 cm soil layers under CK, PM, FM, and PM+FM treatments during the experimental period. CK: control treatment, PM: plastic film mulch, FM: farmyard manure, PM+FM: plastic film mulch combined with farmyard manure. The vertical bars represent the standard deviations of the data.

Different from 0–20 cm, the patterns of soil water content among treatments under 20–40 cm were more complicated, especially for the 2016 maize growing season. At the beginning of planting, the soil water content under PM treatment was higher than that under FM+PM, CK, and FM treatments, with the values of 2.8%, 5.2%, and 8.4%, respectively. Then, the soil water content under FM+PM began to be higher than that of other treatments until 26 September 2017. At harvest time, the soil water content of FM treatment was 1.3%, 2.0%, and 5.5% higher than that of FM+PM, PM, and CK, respectively. For the barley growing season, the soil water content under FM+PM and FM treatments was basically the same, and it was significantly higher than that under PM and CK treatments until 24 April 2017. The biggest difference occurred on 28 March in 2017, and the soil water content of FM treatment was 5.9% and 11.2% higher than that of PM and CK treatment, respectively. In the maize growing season of 2017, it was found that there was little difference among all treatments, especially for CK, PM, and FM treatments.

3.2. Salt Content

Changes in salt content at 0–20 cm and 20–40 cm depth among treatments during the three growing seasons are shown in Figure 3. At the 0–20 cm soil layer, the salt contents

under PM and FM+PM were significantly lower than that under FM and CK during the whole experimental period. In the 2016 maize growing season, before 26 September, the soil salinity in all treatments fluctuated very little, and then the soil salinity began to increase rapidly, especially in the uncovered treatment. The average salt content under PM was 16.5%, 28.3%, and 25.5% lower than under FM+PM, FM, and CK, respectively. During the barley growing season, salt content in all treatments was on a downward trend until 28 March 2017, when soil salt content began to increase. Similarly, the average salt content under PM was 21.0%, 34.4%, and 31.1% lower than under FM+PM, FM, and CK, respectively. In the maize growing season of 2017, salt content under mulched treatment increased first and then decreased during the whole growth period, while salt content under non-mulched treatment showed an increasing trend and remained stable. The difference between mulched and non-mulched treatments was significant. The average salt content under PM was 20.2%, 55.4%, and 51.6% lower than under FM+PM, FM, and CK, respectively.

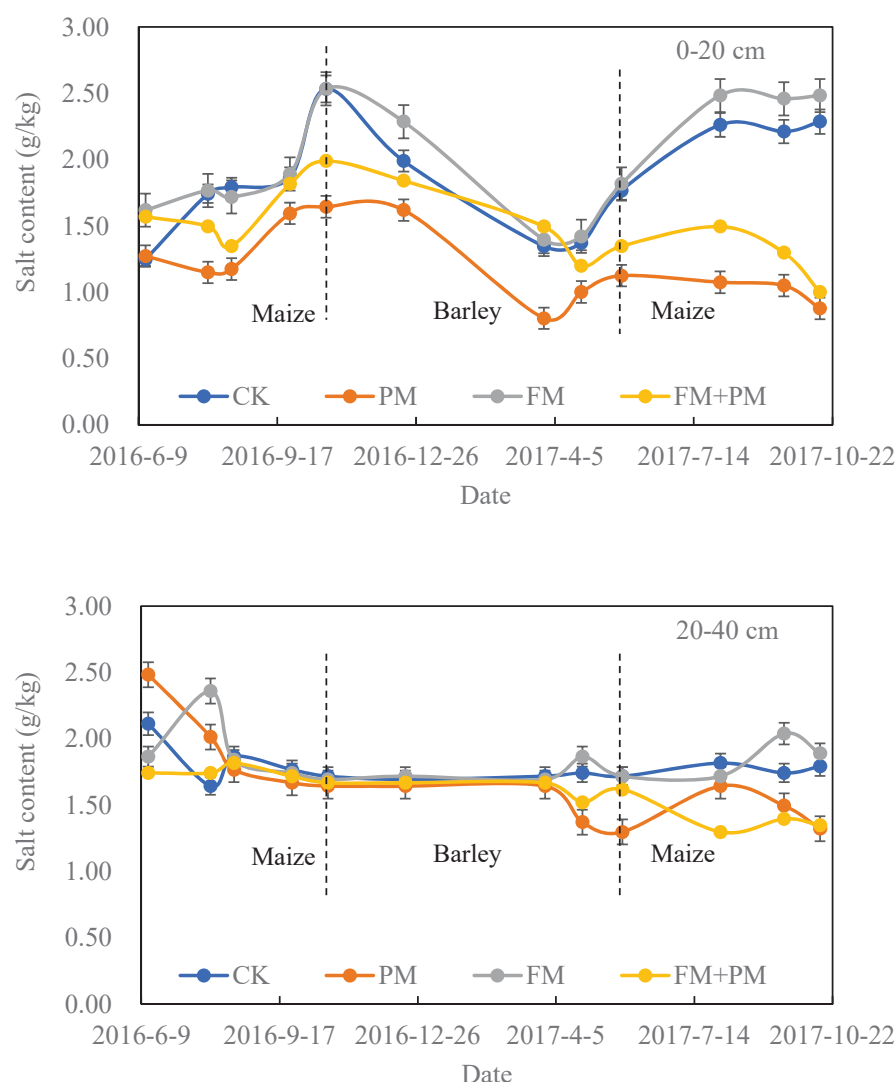


Figure 3. Soil salt content in the 0–20 cm and 20–40 cm soil layers under CK, PM, FM, and PM+FM treatments during the experimental period. CK: control treatment, PM: plastic film mulch, FM: farmyard manure, PM+FM: plastic film mulch combined with farmyard manure. The vertical bars represent the standard deviations of the data.

At the 20–40 cm soil depth, less variation was observed, especially for the barley growing season. As for the maize growing season in 2016, there was no obvious pattern

of changes in the salt content of all treatments until August 15, but they all showed a downward trend with the growth period, except for FM treatment. In the barley growing season, the salt content of all treatments was basically the same until March 28. Then, the soil salt content of FM treatment showed a trend of first increasing and then decreasing, while that of PM treatment showed a trend of decreasing, and that of FM+PM treatment showed a trend of first decreasing and then increasing. In the subsequent growing season of maize, the salt content under FM+PM and PM treatments maintained a consistent downward trend, while the salt content under CK treatment basically remained stable, and salt content under FM treatment first increased and then decreased. The average salt content under PM was 11.0%, 29.9%, and 27.1% lower than under FM+PM, FM, and CK, respectively.

3.3. Soil Physical Properties

Soil bulk density was reduced by applying plastic film mulch and organic fertilizer, and the effect of both was better than that of single treatment (Table 2). In the 0–10 cm soil layer, the BD under PM, FM, and FM+PM treatments decreased by 2.1%, 4.2%, and 5.6%, respectively, compared with that in CK, while that in the 10–20 cm soil layer under PM, FM, and FM+PM decreased by 2.1%, 4.9%, and 5.6%, respectively. The effects of mulching and organic fertilizer application on K_s and SWC were opposite to that of BD; especially, organic fertilizer application significantly improved soil water conductivity and water content. In the 0–10 cm soil layer, K_s under PM, FM, and FM+PM treatments increased by 9.4%, 18.0%, and 24.4%, respectively, compared with that under control treatments, and SWC increased by 1.3%, 2.5%, and 3.4%, respectively. In the 10–20 cm soil layer, the increase in K_s and SWC was less than that in the 0–10 cm soil layer. The K_s and SWC under PM, FM, and FM+PM treatments increased by 6.9% and 0.9%, 17.4% and 1.9%, and 19.6% and 2.5%, respectively, compared with that of CK.

Table 2. Soil physical properties under different treatments.

Soil Depth (cm)	Treatment	BD (g/cm ³)	K_s (cm/d)	SWC (%)
0–10	CK	1.42 ± 0.01 a	10.98 ± 0.45 a	37.91 ± 0.33 a
	PM	1.39 ± 0.03 ab	12.01 ± 0.48 a	38.40 ± 0.33 ab
	FM	1.36 ± 0.02 b	12.95 ± 0.37 b	38.86 ± 0.38 b
	FM+PM	1.34 ± 0.03 b	13.65 ± 0.24 b	39.20 ± 0.40 b
10–20	CK	1.43 ± 0.02 a	10.06 ± 0.37 a	37.46 ± 0.15 a
	PM	1.40 ± 0.04 a	10.75 ± 0.24 a	37.80 ± 0.60 ab
	FM	1.36 ± 0.05 a	11.81 ± 0.38 b	38.18 ± 0.50 b
	FM+PM	1.35 ± 0.03 b	12.02 ± 0.49 b	38.41 ± 0.70 b

Values are the means ± standard deviations; values within a column followed by the same letter are not significantly different (LSD, $p < 0.05$); CK: control treatment, PM: plastic film mulch, FM: farmyard manure, PM+FM: plastic film mulch combined with farmyard manure, BD: soil bulk density, K_s : saturated water conductivity, SWC: saturated water content.

3.4. Soil Nutrients

Film mulching and application of organic fertilizer significantly increased soil organic matter content (Table 3). The content of OM in the 0–10 cm and 10–20 cm soil layers under PM, FM, and PM+FM treatments increased by 19.3%, 57.5%, and 51.5%, respectively, and 22.6%, 58.9%, and 33.8%, respectively, compared with that under CK treatment. Similarly, film mulching and organic fertilizer application also increased TN and AP, especially for the organic fertilizer application treatment. In terms of TN in the 0–10 cm and 10–20 cm soil layers, PM, FM, and PM+FM treatments increased by 8.6%, 37.1%, and 40.0%, respectively, and 42.9%, 42.7%, and 39.3%, respectively, compared with that under CK treatment. Accordingly, AP under PM, FM, and PM+FM treatments increased by 45.9%, 190%, and 277%, respectively, and 6.0%, 105%, and 84.1%, respectively, in the 0–10 cm and 10–20 cm soil layers, respectively. However, the variation trend of AN among treatments was contrary to other indexes (OM, TN, and AP) in the 0–10 cm soil layer. The AN in mulched and organic

fertilizer treatment was lower than that in the control treatment, which may be related to crop growth. Compared with that of CK treatment, AN under PM, FM, and PM+FM treatments decreased by 34.5%, 36.5%, and 38.9%, respectively, while for the soil layer of 10–20 cm, PM, FM, and PM+FM treatments increased by 52.7%, 87.6%, and 107% compared with CK treatment, respectively.

Table 3. Soil nutrients under different treatments.

Soil Depth (cm)	Treatment	OM (g/kg)	TN (g/kg)	AN(mg/kg)	AP (mg/kg)
0–10	CK	4.87 ± 0.42 c	0.35 ± 0.04 b	112.58 ± 11.41 a	16.08 ± 6.71 c
	PM	5.81 ± 0.50 b	0.38 ± 0.01 b	73.78 ± 19.4 b	23.46 ± 1.30 c
	FM	7.67 ± 1.02 a	0.48 ± 0.03 a	71.51 ± 20.5 b	46.56 ± 1.21 b
	FM+PM	7.38 ± 0.68 a	0.49 ± 0.10 a	70.26 ± 28.6 b	60.19 ± 3.91 a
10–20	CK	4.70 ± 0.25 c	0.28 ± 0.05 b	30.71 ± 3.11 b	13.62 ± 1.90 b
	PM	5.76 ± 0.50 b	0.40 ± 0.13 a	46.89 ± 10.21 a	14.44 ± 4.91 b
	FM	7.47 ± 1.09 a	0.40 ± 0.28 a	57.60 ± 22.63 a	27.97 ± 6.82 a
	FM+PM	6.29 ± 0.42 b	0.39 ± 0.04 a	63.55 ± 9.90 a	25.08 ± 7.41 a

Values are the means ± standard deviations; values within a column followed by the same letter are not significantly different (LSD, $p < 0.05$); CK: control treatment, PM: plastic film mulch, FM: farmyard manure, PM+FM: plastic film mulch combined with farmyard manure, OM: soil organic matter, TN: total nitrogen, AN: available nitrogen, AP: available phosphorus.

3.5. Plant Height

The maize height in two growing seasons is presented in Figure 4. For each season, plants were much taller under the FM+PM, PM, and FM treatments than that under CK treatment. There was no significance between the FM+PM and FM treatments, but they were significantly taller than that under PM and CK treatments. The plant height in the growing season of 2016 was higher than that in the growing season of 2017 under the corresponding treatment, This may be related to the higher rainfall in 2016 than in 2017 (Figure 1).

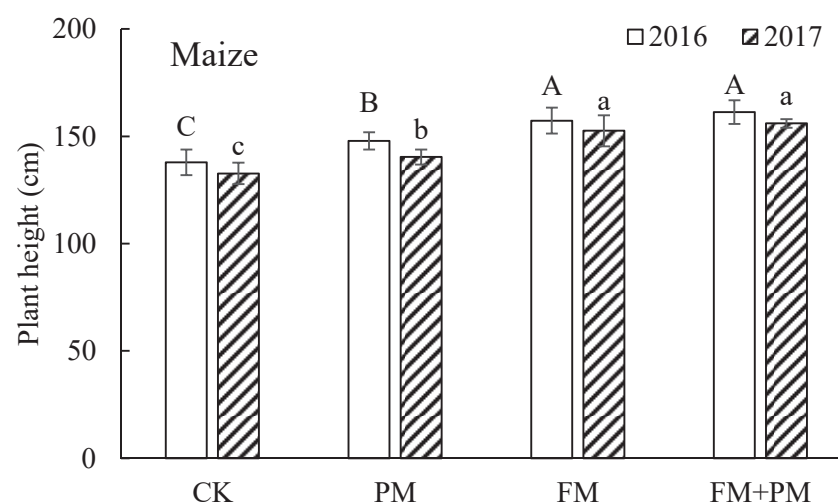


Figure 4. Cont.

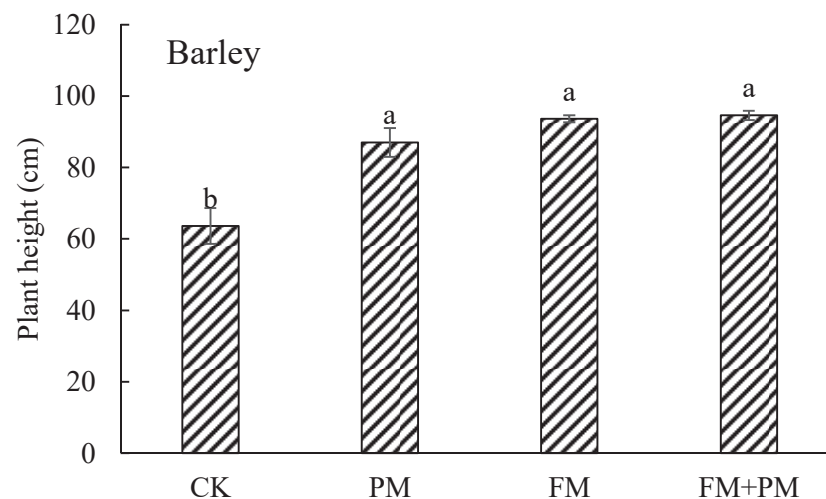


Figure 4. Plant height under CK, PM, FM, and PM+FM treatments. CK: control treatment, PM: plastic film mulch, FM: farmyard manure, PM+FM: plastic film mulch combined with farmyard manure. The vertical bars represent the standard deviations of the data and the values followed by the same letter are not significantly different (LSD, $p < 0.05$).

The barley height was significantly higher under the FM+PM, PM, and FM treatments than that under CK treatment. It was found the height under the FM+PM treatment was the highest, but there was no significant difference among the FM+PM, FM, and PM treatments.

3.6. Biomass and Grain Yield

The biomass of maize varied significantly among the treatments (Table 4). The biomass under the FM+PM, FM, and PM treatments was always higher than that under CK treatment, but only that of the FM+PM and FM treatments was significantly higher than that of CK in both growing seasons. Averaging the results for the two years, the biomass under FM+PM treatment was 29.5%, 79.7%, and 106% higher than that of FM, PM, and CK treatment, respectively. For barley, the biomass under FM+PM treatment was 12.2%, 30.3%, and 133% higher than that under FM, PM, and CK treatments, respectively, and the difference was also significant.

Table 4. Biomass (kg/ha) and yield (kg/ha) under different treatments during the 2016–2017 growing seasons.

	Treatment	Maize			Barley
		2016	2017	Average	
Biomass	CK	3943 c	3256 c	3600 c	6080 c
	PM	4296 b	3960 c	4128 c	10,890 b
	FM	5826 b	5633 b	5730 b	12,649 ab
	FM+PM	7965 a	6869 a	7417 a	14192 a
Yield	CK	1675 c	1749 c	1712 c	2053 c
	PM	2009 c	2000 c	2005 c	3233 b
	FM	2696 b	2967 b	2832 b	3415 b
	FM+PM	4372 a	3729 a	4051 a	4231 a

Values within a column followed by the same letter are not significantly different (LSD, $p < 0.05$).

The results of maize yields' variation among different treatments were consistent over two years. The yields under FM+PM, FM, and PM treatments were always higher than that under CK treatment, but there was no significant difference between PM and CK treatments. Averaged for the two growing seasons, FM+PM treatment improved the yield by 43.1%, 102%, and 137% compared with FM, PM, and CK treatments, respectively. The

barley yield under FM+PM, FM, and PM treatments was 106%, 66.3%, and 57.5% higher than that under CK treatment, respectively.

4. Discussion

4.1. Soil Water and Salt Content

Soil water content increased under mulch treatment, because mulch can reduce evaporation from soil surface and reserve soil water content. Many studies have reported that mulching can reserve soil water and reduce evaporation. Zhang et al. (2021) used the AquaCrop model assessed the mulching effects at the regional scale, which indicated that plastic film mulching improved soil water storage and significantly decreased nonproductive evaporation [30]. Li et al. (2018) presented that the average soil water storage during the jointing stage under the plastic film, gravel-sand, and straw mulching treatments was 34% higher than the control treatment [22]. The results also showed an increase in soil water content under the FM treatment compared with the CK treatment. This is because of loosening soil, decreasing its density and increasing its ability to conserve water. It was reported that the application of manure significantly increased capillary water holding capacity, SWC, and K_s , and decreased BD and cone index [6]. In our study, BD under the PM and FM treatment was decreased by 2.1% and 4.6%, respectively, while K_s and SWC under the PM and FM treatment were increased by 8.2% and 17.7% and 1.1% and 2.2%, respectively. The average soil water content under the FM+PM treatment was the highest owing to the double effect of mulch and manure, which was 5.8% and 3.6% higher than that in CK treatment at the 0–20 cm and 20–40 cm soil depth, respectively. Duan et al. (2022) reported that organic amendments and the ridge–furrow mulching system improved soil water storage in the 0–120 cm soil layer [24].

The change in surface soil salinity is closely related to meteorological conditions (Figure 1). From September to October in 2016, soil salinity increased and then began to decrease. This is because rainfall began to decrease after September, while evaporation was still relatively strong, causing salt to rise. After October, the temperature drops, soil evaporation and root water absorption also decrease, and soil salinity reaches its lowest level in April of the following year. Then, the temperature rises, evaporation becomes stronger, and soil salinity begins to rise gradually.

In the present study, it was found that the reduction in BD and the improvement in hydraulic parameters were conducive to salt leaching. The soil salt content was positively correlated with BD ($R^2 = 0.060$) and negatively correlated with K_s ($R^2 = -0.064$) and SWC ($R^2 = -0.100$). The average salt content under the PM treatment was 35.8% and 6.3% lower than that in the CK treatment during the experiment at the 0–20 cm and 20–40 cm soil layers, respectively. This was because of the decrease in soil evaporation, where the mulching measures not only increased the soil water content (Figure 2), but also contributed to the leaching of soil salt and reduced soil salt content. Similarly, Mohammad et al. (2018) showed that the electrical conductivity of soil was significantly reduced by film mulching in south coastal saline soils of Bangladesh, regardless of film materials and color [31]. El-Mageed et al. (2016) showed that all mulch materials (without mulch, farmyard manure, rice straw, and white polyethylene) effectively reduced salt accumulation in the root zone [32]. In addition, the average soil salt content in the 0–20 cm and 20–40 cm soil layers under FM treatment increased by 6.5% and 3.8%, respectively, compared with the CK treatment, indicating that the soil salt content was increased by the application of manure alone, because the farmyard manure contained salt. Hao and Chang (2003) indicated that high rates of manure application are not sustainable as they cause soil salinization under non-irrigated conditions [33]. Yao et al. (2007) also assessed the possibility of secondary soil salinization by continuous application of chicken manure and pigeon manure on a garden soil, resulting in an increase in soil salinity from low to moderate levels and a slight decrease in soil pH [34]. However, the use of farmyard manure and film mulch together can not only avoid the increase of soil salt content caused by the application of organic fertilizer alone, but also reduce soil salt and increase soil fertility. In this study, the average soil salt

content in the 0–20 cm and 20–40 cm soil layers under FM+PM treatment was reduced by 20.2% and 10.0%, respectively.

4.2. Soil Properties

Soil bulk density, saturated hydraulic conductivity, and saturated water content play important roles in soil water–salt movement. Organic fertilizer application can significantly reduce BD, enhance soil porosity, and improve saturated hydraulic characteristics [35,36]. In the present study, manure application (FM and FM+PM treatments) significantly decreased BD and improved K_s and SWC at 0–20 cm soil depth compared with the control treatment (CK), except for BD at 10–20 cm soil depth (Table 2). However, there were no significant effects of film mulch (PM) on BD, K_s , and SWC at 0–20 cm soil depth compared with CK. Khaliq and Kaleen Abbasi (2015) indicated that soil amendments significantly decreased surface BD and increased K_s [37]. Bilong et al. (2022) showed that the application of poultry manure decreased BD by 21.5–26.2% and increased the water holding capacity by 13.3–30.3% [38]. Duan et al. (2022) reported that organic amendment significantly decreased BD and increased K_s at 0–60 cm soil depth [24]. Zhang et al. (2022) reported that straw returning combined with nitrogen application under plastic film mulch significantly improved soil hydrothermal conditions and maize yield [39], consistent with our results.

Soil organic matter, total nitrogen, available nitrogen, and available phosphorus are basic indicators of soil nutrients that affect soil fertility and crop production. Organic fertilizer application can directly improve the soil nutrient content [24,40], while film mulching can indirectly affect the soil nutrient content by improving crop growth and development [21], thus the root biomass and plant residues were increased; ultimately, the soil organic matter and total nitrogen content were improved. In this study, the influence of manure on soil nutrients is greater than that of film mulching, because organic fertilizer can not only directly increase soil nutrient content, but also improve crop growth and ultimately improve root residue inputs [41]. Similarly, Wu et al. (2022) also reported that the application of 100% cow manure significantly increased nitrogen and carbon from full fruiting to the end-fruiting period [35].

4.3. Plant Growth and Yield

These beneficial effects on soil water content and soil salinity probably explain some of the positive effects on plant growth and yield. Film mulching and manure application promoted the growth and biomass of crops. Although the effect of manure application alone is better than that of film mulch alone, the effect of mulch combined with manure was better than that of film mulch or manure alone. Meanwhile, film mulch and manure treatment also leads to a significantly higher crop yield and biomass than other treatments. For maize, the biomass and yield under PM treatment were improved, but there was no significant difference compared with CK treatment.

In terms of plant height and yield of each treatment, the effect of FM treatment was better than that of PM treatment, indicating that the application of manure was more conducive to promoting crop growth and yield improvement. However, both manure and film mulch work better together than either alone. All of this was possibly attributed to improved hydraulic parameters and increased soil nutrients while applying manure and mulching during the time of the experiment (Tables 2 and 3). OM, nitrogen, and phosphorus are the direct suppliers of nutrients for crop growth, so plant height, biomass, and yield are positively correlated with OM, TN, and AP (Table 5). However, there was a negative correlation between plant height, biomass, and yield and AN, which may also be related to crop growth. The better the crop growth and the higher the crop yield, the higher the content of AN absorbed by crop, resulting in less residual AN in the soil.

Table 5. Pearson correlation coefficient between the yield, biomass, plant height, and soil properties.

	Salt Content	BD	K _s	SWC	OM	TN	AN	AP
Yield	−0.109	−0.876 **	0.879 **	0.892 **	0.778 **	0.837 **	−0.701 *	0.897 **
Biomass	−0.052	−0.558	0.559	0.562	0.518	0.535	−0.482	0.550
Plant height	−0.155	−0.314	0.313	0.312	0.306	0.301	−0.296	0.294

* Correlation is significant at the 0.05 level. ** Correlation is significant at the 0.01 level.

Plastic film mulch is likely to create favorable soil moisture conditions and a low salinity root zone for the crop growth. Ramadhan (2021) reported similar results, finding that straw mulch increased grain yield significantly compared with the control treatment [16]. Wang et al. (2020) reported that the annual yield of the winter wheat–summer maize system can be maintained or even increased by replacing mineral nitrogen with manure [42].

5. Conclusions

Three seasons of field study confirmed that the combined use of plastic film mulch and manure fertilizer significantly improved crop growth and production. It was found plastic film mulch or manure fertilizer application decreased the soil bulk density (BD) and increased the saturated water conductivity (K_s) and saturated water content (SWC), and the effect was strengthened when plastic film mulch and manure fertilizer were combined. In addition, organic matter (OM), total nitrogen (TN), and available phosphorus (AP) were increased with plastic film mulch and manure fertilizer application, while available nitrogen (AN) was decreased as a result of plant uptake. The improved soil properties (BD, K_s, SWC, OM, TN, AN, and AP) in turn improved plant growth and crop production. Therefore, combined plastic film mulch and manure fertilizer application could be a better agronomy practice for improving saline-alkali land and increasing crop yield in saline-alkali land.

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Article

The Effect and Influence Mechanism of Soil Salinity on Phosphorus Availability in Coastal Salt-Affected Soils

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Abstract: Soil salinization is a problem that arouses the world's attention. Soil salinity is an important limitation for agriculture production in coastal area. Phosphorus is a very important nutrient element in the process of plant growth, and its effectiveness affects plant growth to a great extent. In this study, soil available phosphorus and its component in Hedley phosphorus classification were found to be affected by soil salinity in coastal areas of Jiangsu Province. Several key environmental factors changed under the saline environment of the coastal areas, such as soil salinity, soil pH, and soil alkaline phosphatase activity. These environmental factors were significantly correlated with soil available phosphorus. Results showed that there were significant correlations between soil salinity and other environmental factors, and soil salinity and alkaline phosphatase activity were the main influencing factors of soil available phosphorus in this study. Significant positive correlation was found between alkaline phosphatase activity and soil salt content, and soil salinity was considered as the most important impact factor for soil available phosphorus as it affected the surrounding environment, and the soil alkaline phosphatase could be considered as the direct influencing factor for soil available phosphorus. Analysis between the soil alkaline phosphatase activity and phosphorus component showed that soil alkaline phosphatase activity could increase the proportion of active inorganic phosphorus and medium active inorganic phosphorus in soil phosphorus pool, which explained the effect of soil alkaline phosphatase activity on soil available phosphorus.

Keywords: salt-affected soil; available phosphorus; phosphorus classification in Hedley; soil salinity; alkaline phosphatase activity

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1. Introduction

Soil salinization has become a worldwide resource and environmental problem [1–3], which seriously affects the stability of the agricultural ecosystem and the development of agricultural economy [4]. About 9.30×10^8 ha of land is currently threatened by soil salinization [5,6]. About 9.9×10^7 hectares of land in China are under the threat of soil salinization [7], and the coastal region is one of the regions with a wide distribution of salinized soil in China [8].

In saline soil, due to the influence of soil salinity or alkalinity, the phosphorus applied to the soil existed in the form of insoluble phosphate with low availability [9,10]. The increase of electrical conductivity not only affected soil physical and chemical properties such as soil structure, bulk density, and permeability [11], but also reduced the activities of soil microbial biomass and alkaline phosphatase [12,13], affected the transformation of phosphorus in soil and hinders the absorption of phosphorus by crops, resulting in the reduction of chemical and biological availability of phosphorus. Phosphorus deficiency and saline alkali were two major ecological problems limiting crop production. The adsorption of phosphorus on the soil surface was strengthened due to the existence of salt, and this adsorption was enhanced with the increase of soil pH. Therefore, under saline conditions, due to factors such as high pH, high conductivity, and low soil organic

matter, the availability of phosphorus was reduced, aggravating the degree of phosphorus deficiency in plants [14,15]. Plants mainly absorb HPO_4^{2-} or H_2PO_4^- , while PO_4^{3-} was not easy to be absorbed. Due to the existence of high pH, the available phosphorus will be quickly changed into invalid phosphorus through adsorption fixation, precipitation, or microbial absorption.

Obstacle factors of soil saline and alkali of coastal saline soil in Northern Jiangsu seriously restricted crop growth. The existence of a large amount of Na^+ and Cl^- in the soil had a toxic effect on plants, inhibiting the growth of crop roots and their absorption of nutrients such as Ca^{2+} , K^+ , N, and P. At least, the growth was limited and the yield was reduced. Seriously, it would affect the emergence of seedlings and result in no harvest [16]. In addition, obstacle factors of soil saline and alkali also had a direct impact on the soil's physical and chemical properties and reduced soil nutrient availability. The results of the second national soil survey showed that the content of available phosphorus in coastal saline farmland in Northern Jiangsu was very low, and the average content of the whole region was 4.91 mg/kg, and nearly 70% of the soil was generally lacking in phosphorus. In recent years, with the large-scale application of chemical phosphorus fertilizer, the total amount of phosphorus in farmland soil increased [17]. However, due to the characteristics of coastal saline soil, a large amount of phosphorus was fixed in the soil, which was difficult to migrate to the crop rhizosphere, resulting in the phosphorus utilization rate of only 10–25% in that season [18]. A large number of studies pointed out that the increase of soil conductivity led to the destruction of soil structure, resulting in soil compaction and expansion, poor ventilation and water permeability, and easy hardening of topsoil [11]. In addition, the existence of high soil salinity and pH would also affect the structure and activity of the soil microbial community, reduce the activities of soil microbial biomass and alkaline phosphatase [12], seriously restrict the availability of soil nutrients, especially phosphorus, hinder the absorption of phosphorus by crops, and reduce the utilization rate of phosphorus. Therefore, at present, it seemed that soil salinization and low nutrient availability were important problems in the agricultural production process of coastal farmland in Northern Jiangsu [19].

Our study focused on the influence of salinity soil on phosphorus availability, the possible impact factors of soil available phosphorus in coastal area, and the possible influence mechanism of possible factors on phosphorus availability and provide possible measures for improving the availability of phosphorus.

2. Material and Methods

2.1. Soil Properties

Soil samples were collected from newly reclaimed coastal area of Tiaozini in Dongtai county, Jiangsu Province ($120^\circ 54' 8.04''$ E, $32^\circ 38' 42.01''$ N). This farmland is located nearly 1 km from the Yellow Sea. The soils which represented the characteristics of three different salt contents were collected and showed in Table 1.

Table 1. Main properties of the survey soil.

Salinity Classification	pH	Soil Salt Content (g kg^{-1})	Total Phosphorus (mg kg^{-1})	Available Phosphorus (mg kg^{-1})
Non-saline soil	8.77	0.51	812.45	44.41
Slightly salinized soil	9.00	1.55	709.95	21.04
Moderately salinized soil	9.30	2.53	651.20	11.05

Note: In the table, non-saline soil represented the soil with salt content less than 1 g kg^{-1} ; slightly salinized soil represented soil with salt content between 1 g kg^{-1} and 2 g kg^{-1} ; moderately salinized soil represented with salt content more than 2 g kg^{-1} [20].

2.2. Soil Properties Analysis Method

(1) Available phosphorus: Soil total P was determined using the molybdenum blue colorimetric method [21]. After extraction by 0.5 mol/L NaHCO_3 , soil available P was measured using the same method as total P [22].

(2) Soil Electrical conductivity and pH: Soil pH and EC were analyzed in a 1:5 soil-water extract using probes provided by Mettler-Toledo Ltd.

(3) Soil salt ion composition: Soluble Na^+ and K^+ were estimated with a flame photometry. Concentrations of Ca^{2+} , Mg^{2+} , SO_4^{2-} , Cl^- , HCO_3^- , and CO_3^{2-} were analyzed by titration.

(4) Alkaline phosphatase activity: Alkaline phosphatase was determined by P-Nitrobenzene phosphate method.

(5) Soil Hedley phosphorus classification

The forms of phosphorus in soil determined the phosphorus supply capacity of soil to the crops. Phosphorus classification proposed by Hedley was applied in our research, as this method took into account both soil inorganic phosphorus and organic phosphorus, which is more reasonable and widely recognized abroad.

Soil phosphorus classification: using Hedley phosphorus classification method modified by Tissen and Moir (1993), soil was extracted by deionized water, 0.5 mol/L NaHCO_3 (pH 8.5), 0.1 mol/L NaOH , and 1 mol/L HCl in turn. The contents of inorganic phosphorus (P_i) in the above extracts ($\text{H}_2\text{O}-\text{P}_i$, $\text{NaHCO}_3-\text{P}_i$, $\text{NaOH}-\text{P}_i$, and $\text{HCl}-\text{P}_i$) were determined by molybdenum antimony anti-colorimetric method, and then the NaHCO_3 and NaOH extracts were digested with sulfuric acid–ammonium persulfate. After the determination of total phosphorus (P_t) content, the organophosphorus (P_o) content (the difference between P_t and P_i) ($\text{H}_2\text{O}-\text{P}_o$, $\text{NaHCO}_3-\text{P}_o$, and $\text{NaOH}-\text{P}_o$) was calculated. Finally, the residual phosphorus content ($\text{R}-\text{P}$) was determined by $\text{H}_2\text{SO}_4\text{-HClO}_4$ digestion-molybdenum-antimony anti-colorimetric method.

2.3. Data Processing and Analysis

The experimental data were statistically analyzed using Microsoft Excel 2010. The data were analyzed using a single-factor analysis of variance (ANOVA) and the correlation analysis was processed using SPSS Version 16.0. Diagrams were created using Excel 2010, the Origin8.0 software, R software and tools on hiplot website.

3. Result and Discussion

3.1. Available Phosphorus (AP) in Coastal Saline Soil with Different Salt Content

We chose three salt gradients of soils, and they were named the soils NSS (non-salinized soil), SSS (slightly salinized soil), MSS (moderately salinized soil), with the salt content of 0.51 g kg^{-1} , 1.55 g kg^{-1} , and 2.53 g kg^{-1} , respectively. It was obvious that there were significant differences in salt content among different soils, and there were also significant differences in available phosphorus in corresponding soils. Results showed that the available phosphorus of non-salinized soil was significantly higher than that of salinized soil, and the phosphorus availability of MSS was the lowest among the three (Figure 1). Assumption could be made that the available phosphorus decreased significantly as soil salinity increased, and we could infer that soil phosphorus availability maybe inhibited by soil salinization. Meanwhile, a negative correlation between salt content and available phosphorus was found. The result was similar to some relevant research. Relevant research showed that soil salinization indicators observed had a positive correlation with soil nutrients [23]. Salinization generally decreased fluxes of soluble reactive phosphorus from both sediments and soils [24].

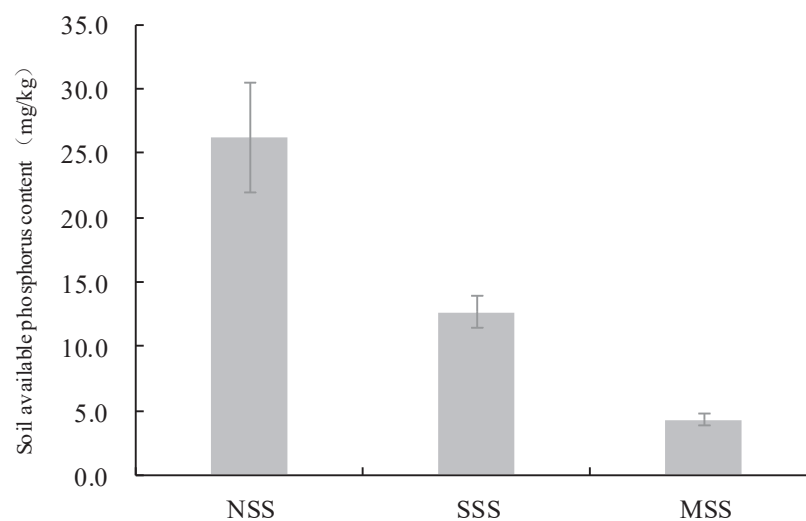


Figure 1. Soil available phosphorus under different soil salinity environment.

3.2. Characteristics of Various Forms of Phosphorus in Hedley Phosphorus Classification in Coastal Saline Soil with Different Salt Content

The occurrence form of phosphorus in soil determines the supply capacity of soil to crop phosphorus. It can be seen from Table 2 that, phosphorus in the phosphorus pool of coastal saline soil mainly existed in the form of HCl-P_i , accounting for about 65~78% of the extractable phosphorus content. Compared with non-saline soil, the proportion of soil $\text{H}_2\text{O-P}_i$ and $\text{NaHCO}_3\text{-P}_i$ reduced as the salt content increased, which represented active inorganic phosphorus decreased. Additionally, the proportion of $\text{NaHCO}_3\text{-P}_o$, NaOH-P_o , and NaOH-P_i was the lowest on moderately saline soil. In Hedley's phosphorus classification method, $\text{H}_2\text{O-P}_i$ and $\text{NaHCO}_3\text{-P}_i$ are the main forms of phosphorus absorbed and utilized by plants and are the main components of soil active phosphorus pool. NaOH-P_i can be used as a potential phosphorus source to slowly mineralize and supplement available phosphorus in soil owing to its low availability to plants, and it belonged to moderately active inorganic phosphorus [25]. $\text{NaHCO}_3\text{-P}_o$ is mainly kind of soluble organic phosphorus, which can supplement available phosphorus to soil solution. However, NaOH-P_o is mainly the organic phosphorus combined with humic acid in soil [26]. HCl-P_i is difficult to be transformed into available phosphorus and used by plants, so it is considered as stable phosphorus [27].

Table 2. The proportion of various forms of phosphorus in Hedley under different soil salinity environment.

Soil Type	$\text{H}_2\text{O-P}_i$	$\text{NaHCO}_3\text{-P}_i$	NaOH-P_i	HCl-P_i	$\text{NaHCO}_3\text{-P}_o$	NaOH-P_o	R-P
NSS	1.34	8.79	0.48	3.70	2.02	64.78	18.89
SSS	0.61	4.60	0.82	2.74	1.31	69.09	20.81
MSS	0.32	1.87	0.85	1.66	1.09	77.90	16.31

In conclusion, with the increase of soil salinity, the proportion of soil active inorganic phosphorus decreased and the proportion of stable inorganic phosphorus increased (Figure 2), which was consistent with the regulation of available phosphorus affected by soil salinity described in 3.1.

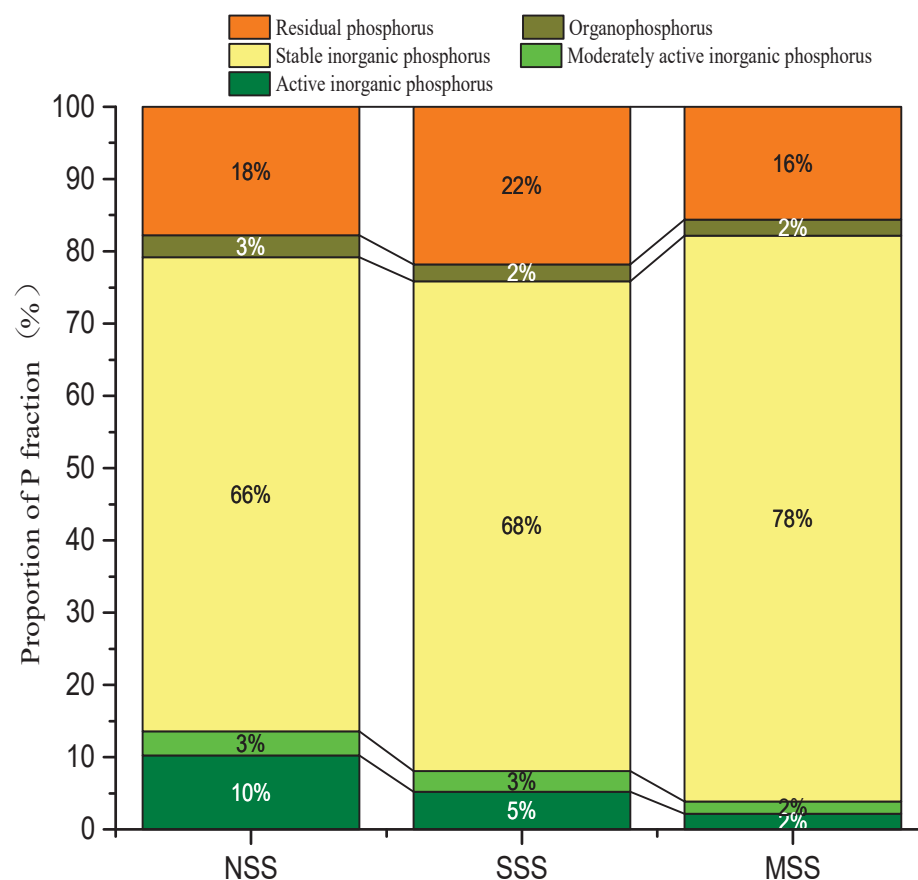


Figure 2. Proportion of various phosphorus forms in Hedley classification.

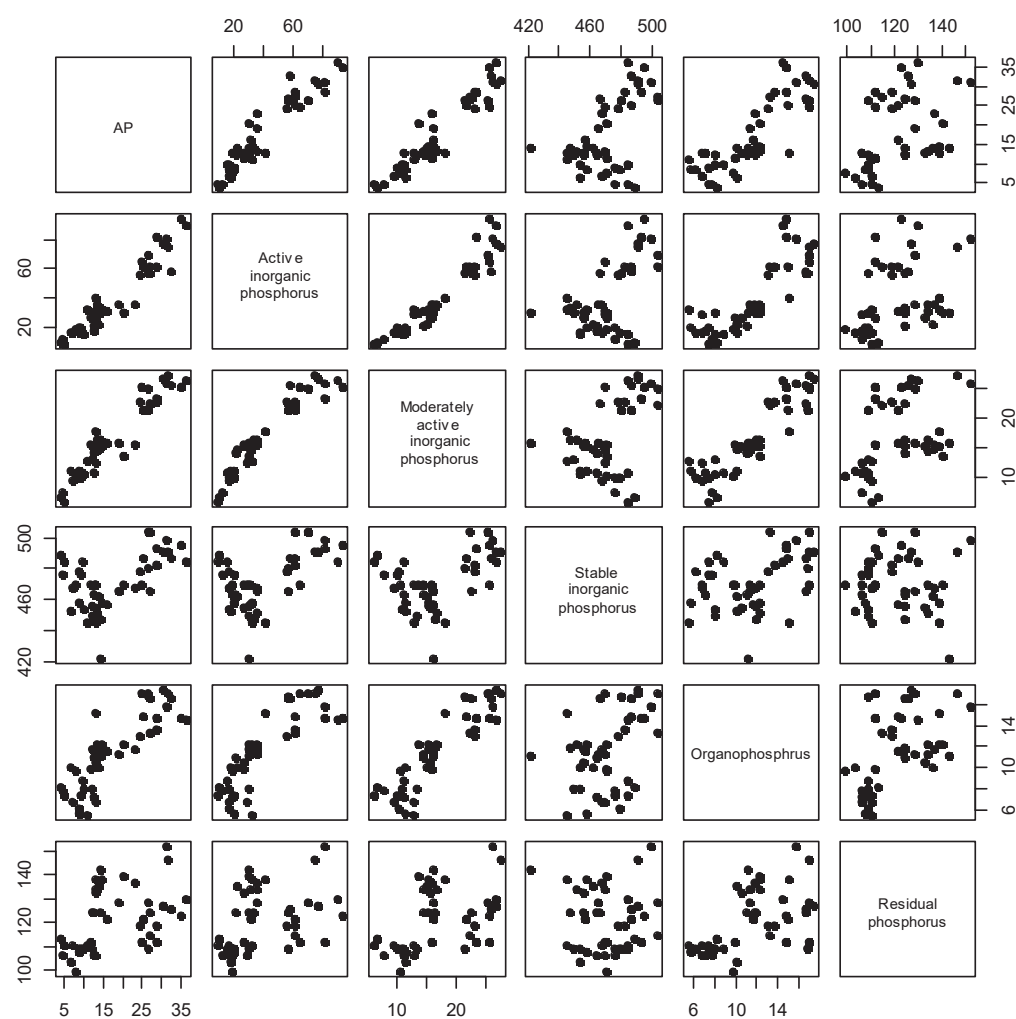
3.3. Possible Influencing Factors of Soil Available Phosphorus in Different Salinization Degrees

3.3.1. Relationship between Available Phosphorus and Different Phosphorus Forms in Hedley Phosphorus Classification

Correlations between soil available phosphorus content and various forms of phosphorus were analyzed (Table 3). The results showed that the content of available phosphorus was positively correlated with $\text{H}_2\text{O-P}_i$, $\text{NaHCO}_3\text{-P}_i$, NaOH-P_i , and NaOH-P_o ($p < 0.01$), and the order of the correlation was $\text{NaHCO}_3\text{-P}_i > \text{NaOH-P}_i > \text{H}_2\text{O-P}_i > \text{NaOH-P}_o$. Correlation analysis was performed between available phosphorus and similar P forms (Figure 3). Results showed that the correlation between available phosphorus and active inorganic phosphorus and moderately active inorganic phosphorus reached was 0.951 ($p < 0.001$) and 0.949 ($p < 0.001$). This illustrated that active inorganic phosphorus ($\text{H}_2\text{O-P}_i$ and $\text{NaHCO}_3\text{-P}_i$) and moderately active inorganic phosphorus (NaOH-P_i) were effective and direct phosphorus sources in saline soil. There were significant correlations between the content of available phosphorus and $\text{NaHCO}_3\text{-P}_o$, NaOH-P_o , and the correlation coefficient between available phosphorus and organophosphorus ($\text{NaHCO}_3\text{-P}_o$ and NaOH-P_o) reached 0.841 ($p < 0.001$). And NaOH-P_o in organophosphorus could be transformed to available phosphorus to some extent. However, the correlation coefficients between the content of available phosphorus and HCl-P_i reached 0.534 ($p < 0.001$), and the correlation coefficients between the content of available phosphorus and R-P was 0.442 ($p < 0.05$), which meant that the contribution of the two forms to the available phosphorus was small.

Table 3. Correlation between available phosphorus and various forms of phosphorus in Hedley classification.

	H ₂ O-P _i	NaHCO ₃ -P _i	NaHCO ₃ -P _o	NaOH-P _i	NaOH-P _o	HCL-P _i	R-P
Pearson Correlation with AP	0.805	0.954	0.560	0.949	0.878	0.534	0.442
Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.002

**Figure 3.** Correlation diagram between available phosphorus and various forms of phosphorus in Hedley classification.

We classified the components with large contribution together and found that active inorganic phosphorus and moderately active inorganic phosphorus had the greatest contribution to available phosphorus in phosphorus classification. While organophosphorus had a certain impact on available phosphorus, which may be related to the fact that organophosphorus could provide available phosphorus through the transformation process.

3.3.2. Soil Salinity

We analyzed the soil ion composition, and result showed that the slightly salinized and moderately salinized soils were mainly dominated by chloride ions and sodium ions (Figure 4). The contents of sodium and chloride ions in non-salinized soil, mild salinized soil and medium and severe salinized soil showed significant differences. The contents of chloride and sodium ions in moderate salinized soil were the highest, followed by those in slight salinized soil, and the contents of sodium and chloride ions in non-salinized soil

were lowest among the three soils. A large amount of chloride ion has ion antagonism with dihydrogen phosphate ion in soil solution and inhibits the absorption of phosphate ions by crops [28]

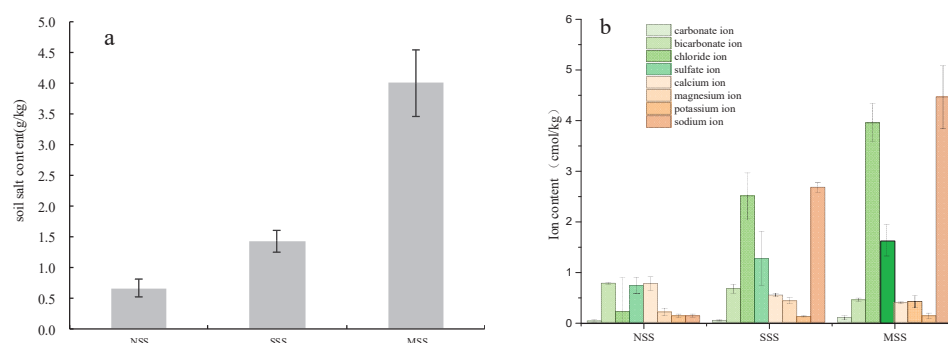


Figure 4. Salt content and soluble ion under different salinity environment. ((a): salt content; (b): soluble ion).

Correlation between soil salt content and available phosphorus was analyzed using soil survey data of different salt gradients (Figure 5). Result showed that there was significant negative correlation ($R = 0.714$, $p < 0.001$) between soil salt content and available phosphorus. Available phosphorus showed a downward trend with the increase of soil salt, so it could be inferred that salt was a very important environmental factor affecting available phosphorus. The mechanism of reducing the bioavailability of phosphorus under saline alkali barrier maybe mainly due to two reasons [29]: Crop ion toxicity and nutrient deficiency caused by salt. Under the influence of soil parent material and soil forming process, the salt ion composition of coastal saline soil is mainly sodium chloride. On the one hand, sodium ion in saline soil can directly poison plants. On the other hand, under salt stress, salt ions in soil can compete and inhibit mineral nutrition, resulting in imbalance of nutrient ion absorption by plants. Salinization unexpectedly led to a dose dependent decreased availability of phosphorus in the sediment, both in the short and in the long term [30].

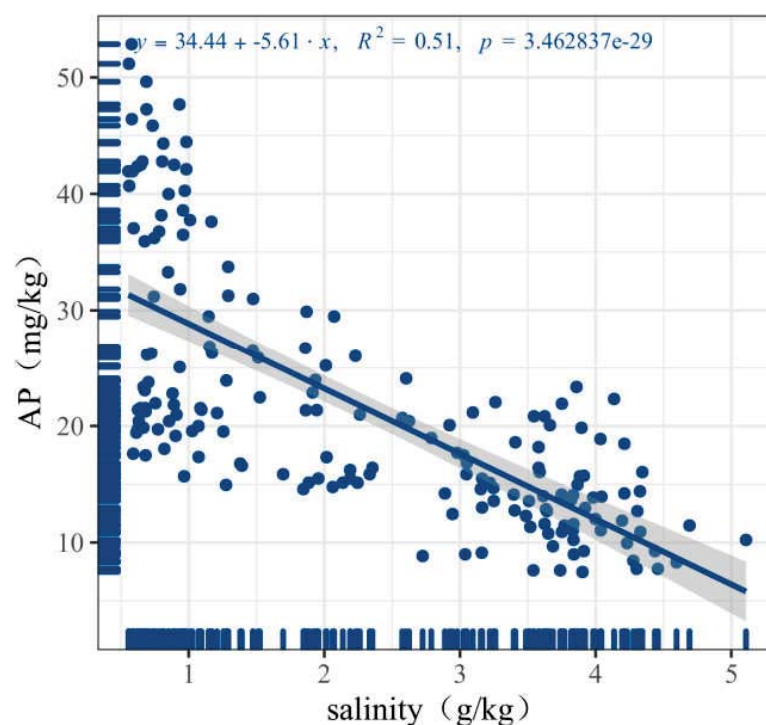


Figure 5. Scatter diagram between soil salt content and available phosphorus.

3.3.3. Soil pH Value

In saline soil, the available phosphorus decreased as the soil pH increased. In our study, the correlation between pH and soil available phosphorus was analyzed (Figure 6), and the result showed that there was significant negative correlation between them ($R = 0.3$, $p < 0.001$). Generally speaking, availability of soil phosphorus was closely related to soil pH value. As it was saline soil, soil pH was always above 8. Due to the influence of high pH value of saline soil, more than 75% of phosphorus fertilizer was combined with calcium in the soil to form a series of phosphates with low solubility, resulting in the reduction of phosphorus availability and phosphorus fertilizer utilization [31]. Soil pH is an important factor that affects the occurrence and transformation of phosphorus forms in soil and affects many processes such as chemical fixation and precipitation dissolution of phosphorus in soil [32].

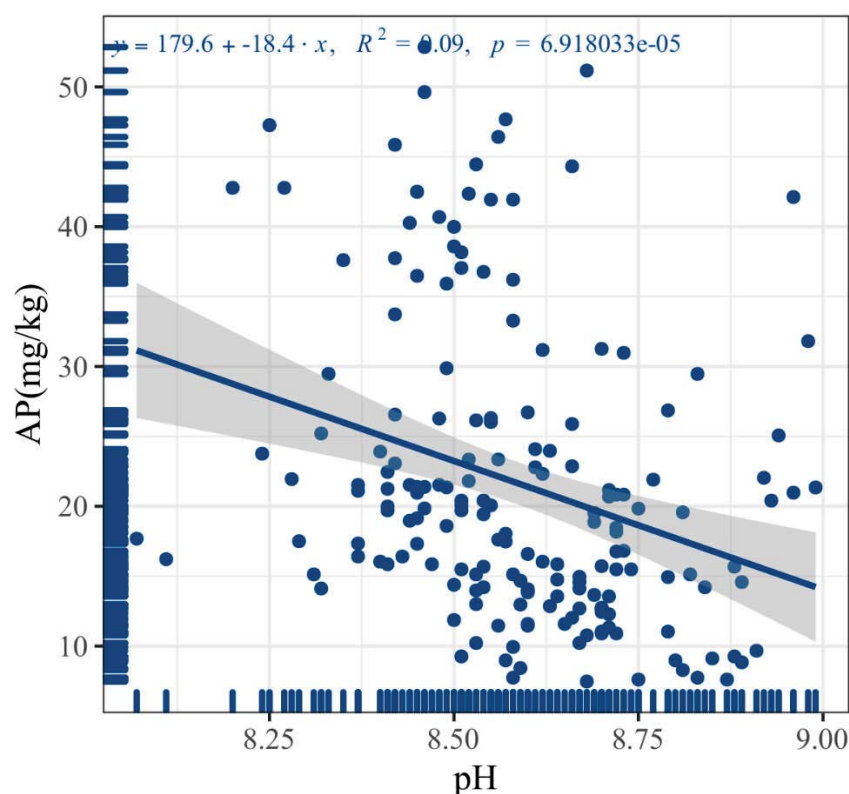


Figure 6. Scatter diagram between soil pH and soil available phosphorus.

3.3.4. Soil Alkaline Phosphatase Activity

Soil phosphatase is a kind of enzyme that catalyzes the mineralization of soil organic phosphorus. Its activity directly affects the form and bioavailability of organic phosphorus in soil. It is an index to evaluate the direction and intensity of soil phosphorus biotransformation [33]. Due to the relatively high pH of saline soil, alkaline phosphatase is dominant in soil phosphatase [34]. We analyzed the alkaline phosphatase activity of three gradient saline soils, and results showed that the alkaline phosphatase activity of non-salinized soil was the highest, that of slightly salinized soil was lower, and that of moderately salinized soil was the lowest (Figure 7). The correlation between soil available phosphorus and alkaline phosphatase activity was analyzed (Figure 8), and soil available phosphorus was found to be significantly positive correlated with the alkaline phosphatase activity ($R = 0.842$, $p < 0.001$). In conclusion, the activity of alkaline phosphatase could be inferred as one of the impact factors of available phosphorus. Soil enzymes may persist for a long time, as they are protected by clay minerals and/or humic colloids, which provide them with a great resistance against thermal denaturation, dehydration, and proteolysis [35].

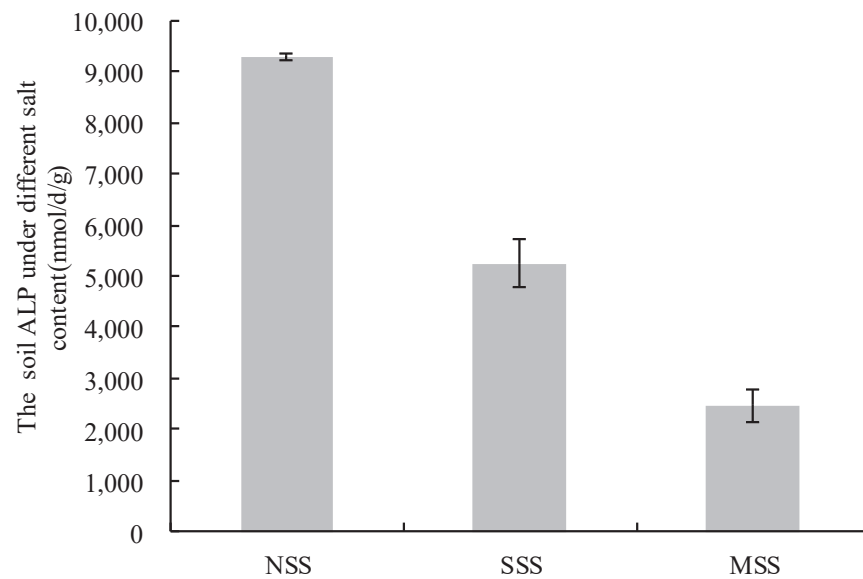


Figure 7. Soil alkaline phosphatase activity under different soil salinity environment.

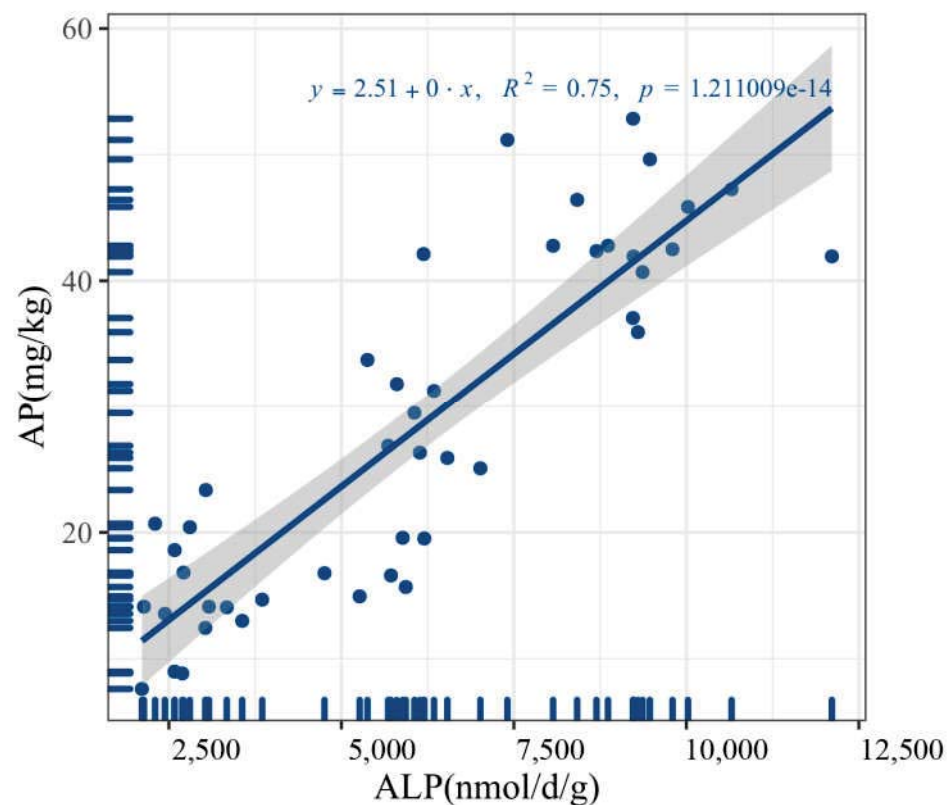


Figure 8. Scatter diagram between soil alkaline phosphatase activity and available phosphorus.

3.4. Relationships between Possible Impact Factors of Soil Available Phosphorus

As from the results above, while soil available phosphorus decreased with the increase of soil salinity, other factors which may affect the content of soil available phosphorus also showed the same or opposite trend. The results in Section 3.3 showed that available phosphorus had a very significant negative correlation with soil salt content and soil pH value, and a significant correlation with alkaline phosphatase activity. Active inorganic phosphorus and moderately active inorganic phosphorus in Hedley phosphorus classification contributed most part of available phosphorus.

We gathered all the possible factors together and found that the correlation coefficient between soil salinity and soil available phosphorus was the best among all the environmental factors, followed by soil alkaline phosphatase activity, and the lowest was soil pH value (Figure 9). It was reflected from the side that soil salt and alkaline phosphatase activity are the main influencing factors of soil available phosphorus in this study, while the effects of soil pH on soil available phosphorus were less than that of soil salinity. Moreover, the influencing factors are also closely related. In the correlation diagram, soil salinity was negatively correlated with alkaline phosphatase activity, and the correlation coefficient reached -0.922 ($p < 0.01$), which showed that alkaline phosphatase activity was affected by soil salinity. Additionally, there was a significant correlation between soil salinity and soil pH, which showed that pH was also affected by soil salinity.

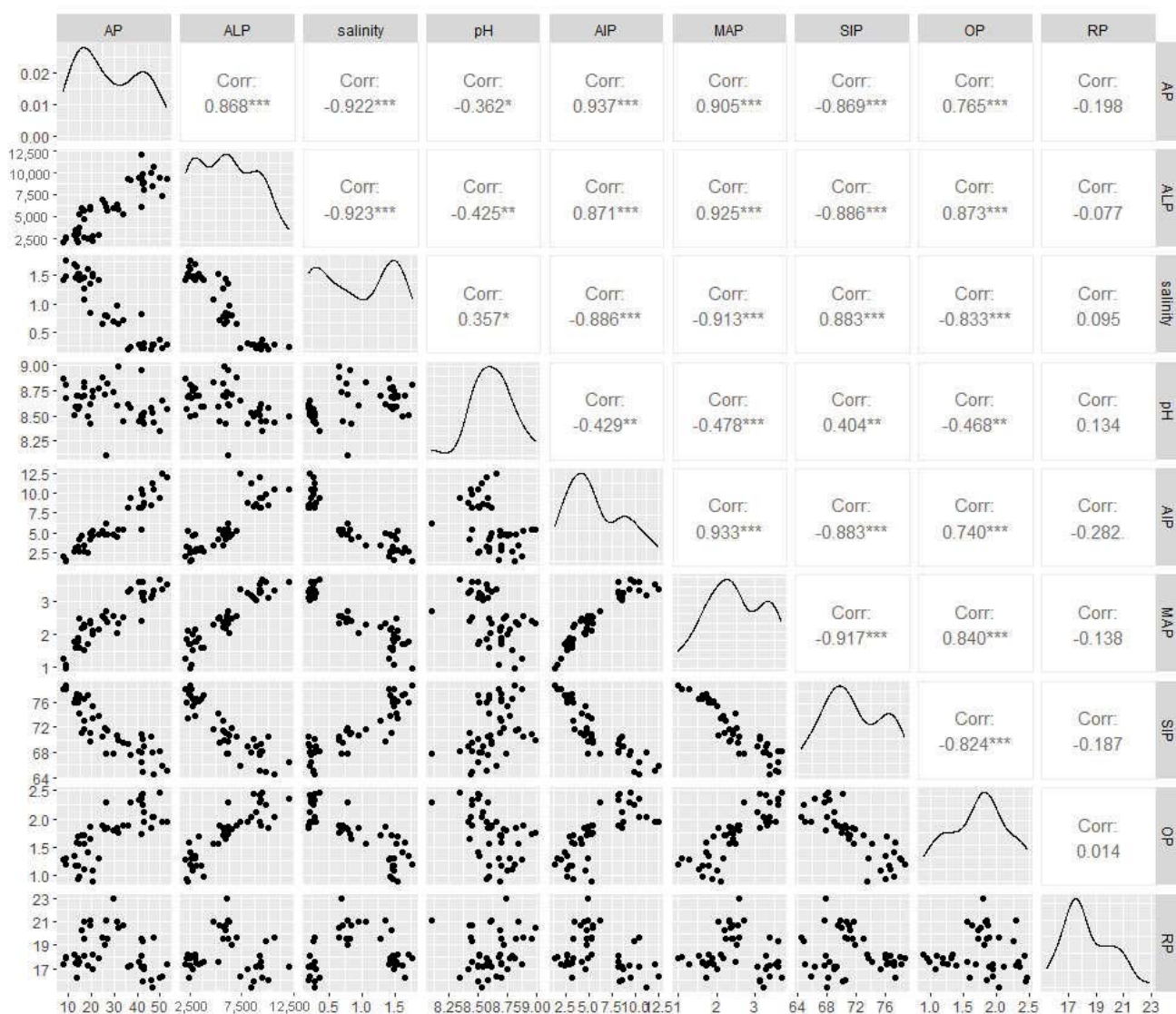


Figure 9. Correlation diagram among possible influence factors. Note: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, level of significance (two-tailed) by least significant difference (LSD).

Among all the phosphorus classification, active inorganic phosphorus contributed most part of available phosphorus, followed by moderate active phosphorus and organophosphorus. While active inorganic phosphorus, moderate active phosphorus, and organophosphorus were all correlated with soil salinity, soil alkaline phosphatase activity, and pH value. And result showed that soil alkaline phosphatase activity was a little more important than soil salinity in the process of affecting active inorganic phosphorus, moderate active

phosphorus and organophosphorus. The results showed that the increase of soil alkaline phosphatase activity could increase the proportion of active inorganic phosphorus and medium active inorganic phosphorus in soil phosphorus pool, promote the transformation of stable phosphorus inorganic phosphorus to other forms of phosphorus, and then improve the availability of phosphorus in saline soil.

We can conclude that soil salinity changed the soil salinity environment, affected soil alkaline phosphatase activity, and indirectly influenced the soil available phosphorus by changing the inorganic phosphorus pool.

The cluster analysis method was used to analyze all relevant indicators, to study and verify the most important environmental indicators among these environmental indicators, as well as the relationship between indicators. The heat map showed that different factors were distinguished obviously by salt differences. RP and pH were clustered together and presented higher content in SSS, while SIP, salinity, and pH were clustered together and presented higher content in MSS. AP, relatively active phosphorus fraction (e.g., AIP, MAP, and OP) and ALP were clustered together (Figure 10), and showed the lowest value in MSS, slightly higher in SSS, but the highest in NSS. The result that relatively active phosphorus fraction (e.g., AIP, MAP, and OP) and ALP were clustered together echoed the conclusion that ALP was more closely related to phosphorus components in the previous paragraph, which verified the direct effect of ALP on the components of available phosphorus.

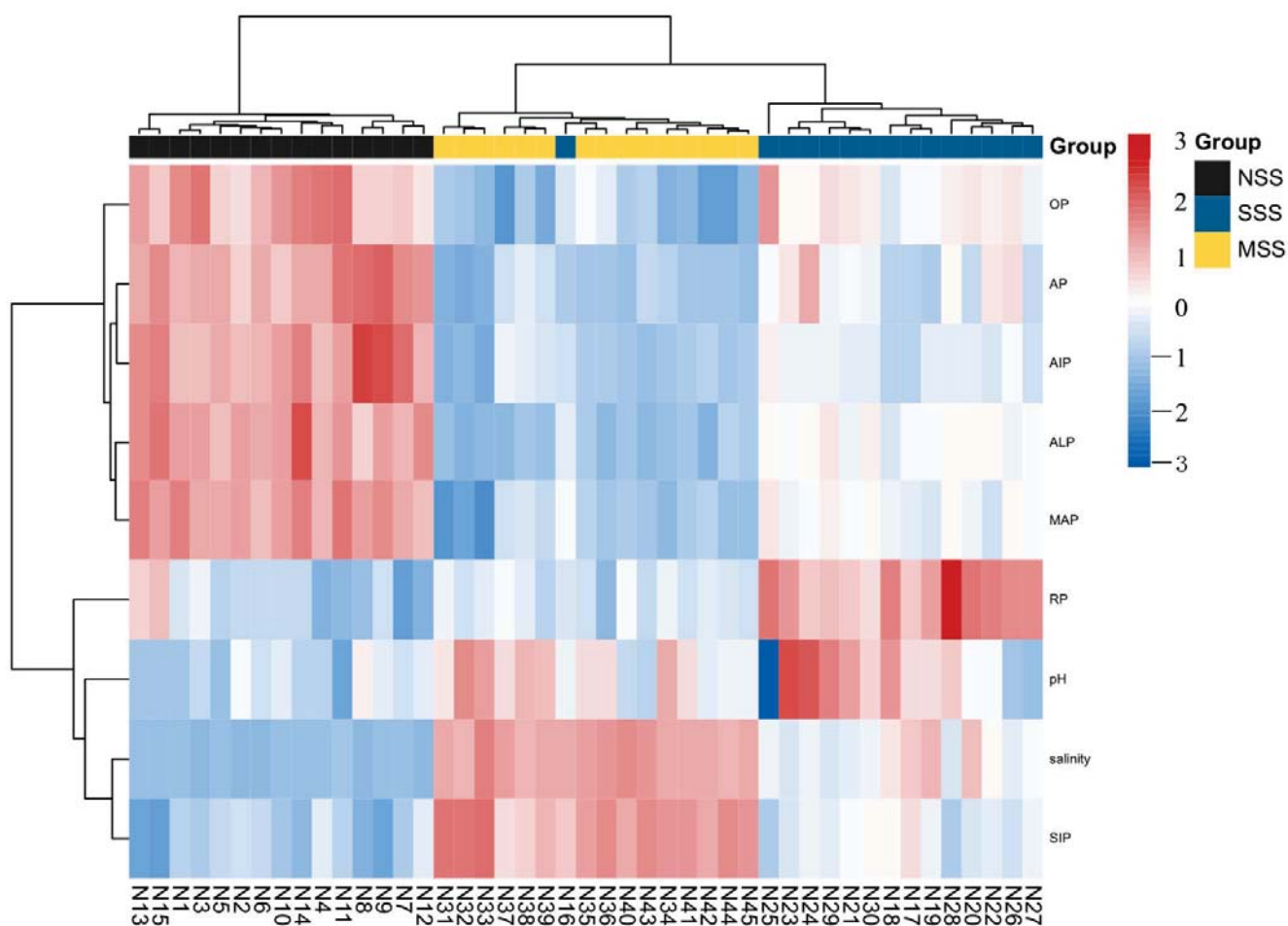


Figure 10. Heat map of relative impact factors in different degree of saline soil. Note: The clustering heatmap represented values of impact factors in different degree of saline soil, and data of different indicators are normalized due to the range of different measured values of indicators.

In conclusion, soil salt content changed the soil salinity environment, affected soil alkaline phosphatase activity, and indirectly influenced the soil available phosphorus by changing the inorganic phosphorus pool. Soil salinity was the most important factor in affecting relative indicators. AP, ALP, and relatively active phosphorus in Hedley classification were clustered together, which explained ALP was the direct environmental factor affecting available phosphorus. Additionally, ALP also affected the content of active phosphorus, which provided a source of AP.

4. Discussion

Our study showed that soil salinity affected the soil environment led to the lack of soil nutrient conditions and affected the alkaline phosphatase activity and the content of Hedley labile phosphorus, thus comprehensively affected the content of soil available phosphorus.

Inorganic phosphorus in Hedley classification was positively correlated with available phosphorus, which determined the change of available phosphorus. Active inorganic phosphorus, moderately active inorganic phosphorus, and part of organophosphorus were effective phosphorus sources in saline soil. The content of stable phosphorus in saline soil was high, and active inorganic phosphorus, moderately active inorganic phosphorus and NaOH-P_o were relatively low. The research of Xu et al. [36] chose similar coastal area of the Yellow River Delta and found that the occluded forms (Dil.-HCl-P) of P constitute the major total P whereas the labile and moderately labile forms are relatively minor, suggesting that availability of P to plants in these soils was low.

In our study, sodium ion and chloride ion were the main salt ions in SSS and MSS, and available phosphorus in MSS was significantly lower than that in SSS, and available phosphorus in NSS was the highest. It was reflected from the side that the phosphorus supply of salt inhibited soil was limited. Previous studies showed that salinity stress was the main factor affecting crop growth and rhizosphere nutrient availability in saline soil [37,38], which was similar to our research results. Review paper of Li Y and Li G [39] put forward that there had been intense efforts to counter the salinity and improve the phosphorus availability of saline soils, which reflected the negative effect of salt on phosphorus availability.

Additionally, pH was one of important factors that affected the available phosphorus in our research. The research of Ye et al. [40] showed that salinity, pH value, and other relevant factors were important influencing factors of available phosphorus. The species and concentration of ions in soil solution were affected by soil pH, which made the form of soil phosphorus different [41].

Soil alkaline phosphatase activity was one of the most important factors in affecting soil available phosphorus, with a positive correlation between them. Soil alkaline phosphatase activities decreased significantly with the increase in salinity, while available phosphorus concentration increased significantly [42]. This result supported the conclusion that alkaline phosphatase was affected by soil salinity. While the reason why the results were inconsistent with our research may be attributed to different areas and soil forming processes, as the land we focused on was formed with high sediment content and lack of nutrients, which resulted in low background content of phosphorus in soil. Alkaline phosphatase activity was found to be closely connected with available phosphorus and ECe [43], which was similar to our results.

Previous studies showed that the activity of soil phosphatase was affected by soil pH value [44], and result showed that alkaline phosphatase activity was negatively correlated with soil pH value. We also found from the result that there was negative correlation between pH and alkaline phosphatase activity, which was consistent with the result of previous study. However, the effect of salt on alkaline phosphatase activity was significantly higher than that of pH in the coastal area with more obvious characteristics of salinity. Impact factors were distinguished obviously by soil salinity in our study, and salinity was the dominant factor, affecting the relevant environmental factors. Soil salinity affected environmental indicators. ALP and relatively active phosphorus in Hedley classification

were more closely related to AP. Additionally, AP, ALP and the fact that relatively active phosphorus in Hedley classification were clustered together, which explained ALP was the direct environmental factor affecting available phosphorus, affected the content of active phosphorus, which provided a source of AP.

5. Conclusions

In conclusion, soil available phosphorus decreased, and the availability of phosphorus was inhibited in coastal areas, Jiangsu Province, China. With the increase of soil salinity, the proportion of soil active inorganic phosphorus decreased and the proportion of stable inorganic phosphorus increased, which explained the regulation of available phosphorus.

Soil available phosphorus was affected by several factors, such as soil salinity, soil pH, and soil alkaline phosphatase activity. All the factors were correlated with the soil available phosphorus. However, salinity was the soil salt and alkaline phosphatase activity were the main influencing factors of soil available phosphorus in this study. As there was a very significant positive correlation between alkaline phosphatase activity and soil salt, salt content could be considered as the environmental factor and the soil alkaline phosphatase could be considered as the direct influencing factor. The increase of soil alkaline phosphatase activity could increase the proportion of active inorganic phosphorus and medium active inorganic phosphorus in soil phosphorus pool, promote the transformation of stable phosphorus inorganic phosphorus to other forms of phosphorus, and then improve the availability of phosphorus in saline soil. Soil salinity was the most influential factor of AP in coastal salt-affected soil in Jiangsu Province, China. Due to the influence of salt restriction factors, relevant environmental factors have changed significantly, containing soil pH, alkaline phosphatase activity, etc. Among all the factors, soil alkaline phosphatase had the closest relationship with available phosphorus. In terms of internal mechanism, the change of soil available phosphorus was mainly controlled by the change of active phosphorus pool, which was also affected by salinity and surrounding environmental factors. Soil salinity affected influenced the surrounding environment, changed the soil alkaline phosphatase activity and liable phosphorus pool, and finally reduced soil AP.

Nevertheless, as affected by the soil forming process and parent material, coastal saline soil has a series of characteristics. The whole coastal soil profile contains a large amount of soluble salt, and the composition of soil salt ions is mainly sodium chloride, which is similar to that of seawater. There may be differences in the influencing factors of available phosphorus in salt-affected soil with alkaline characteristics, as coastal soils are mainly characterized by salinity, while saline soils in some inland areas are mainly characterized by alkalinity. High pH of the alkaline soil reduced the solubility of inorganic P, and adversely influenced processes involved in the transformation and release of available P by affecting its microbial community structure, biomass, carbon content, phosphatase, and other enzyme activities [45,46]. Therefore, relevant studies in other non-coastal saline areas need to be reconsidered because of different salinization process.

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Abbreviations

Indicators	Abbreviation
available phosphorus	AP
alkaline phosphatase activity	ALP
active inorganic phosphorus	AIP
moderately active inorganic phosphorus	MAP
stable inorganic phosphorus	SIP
Organophosphorus	OP

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