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Soil Respiration Response to Long-Term Freezing Saline Water Irrigation with Plastic Mulching in Coastal Saline Plain

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Abstract: The technology of freezing saline water irrigation (FSWI) with plastic mulching has been regarded as an effective way to reclaim the highly saline soil in coastal plains, which enabled the growth of crops in heavy saline soil that was not suitable for any crop growth before. However, after long-term treatment with FSWI, the microenvironment of the soil has been found to be affected by the growth of crops, which will directly influence the balance of soil carbon emissions. In this study, the characteristics of soil respiration in a typical saline field (planted with cotton) under four treatments (FSWI in Winter with plastic mulching, FSWI + Mulch; FSWI in Winter without plastic mulching, FSWI; plastic mulching in Spring without FSWI, mulch; no plastic mulching and no FSWI, CK) were investigated between June and November from 2015 to 2016. The results suggested that the soil surface temperature was an important factor that affected the soil respiration rate in each treatment during the growth period of cotton. FSWI + Mulch can reduce the soil surface salinity to 0.4% during the seedling stage, which increased the survival rate and the abundance of bacteria, fungi, and actinomycetes in the cotton field and subsequently increased soil respiration. By examining the effects of FWSI and mulching on soil respiration and its influencing factors, this study provides practical and theoretical insight into the sustainable development of agriculture in coastal saline plains.

Keywords: soil respiration; freezing saline water irrigation; plastic mulching; coastal saline plain; Q_{10}

1. Introduction

Coastal saline wastelands in the northeast of China extending from Jiangsu province to Liaoning province are potential land resources for agriculture and ecological landscape construction [1]. However, most of them have not been utilized due to high soil salinity, fresh water shortage, and high sodium adsorption ratios (SAR). In addition, wind erosion, cold damage, and high groundwater tables are limiting factors in these regions [2], and, as a result, a variety of traditional improvement measures such as washing salt with fresh water and new-soil technology cannot be widely implemented [3,4]. Developing and utilizing the local rich underground saline water combined with other measures such as plastic film mulching is a new trend in reclaiming saline-alkaline soils [5,6]. Previous studies [7] found that reliance on the principle of freezing saline ice melt allowed for the separation of salt water from fresh water. The initially melted high salinity water infiltrated first, and then low-salinity water (or even fresh water) infiltrated later. In using the local saline groundwater, less than a 15 g/L concentration in the winter for irrigation had a significant effect that carried the leached salts out of the topsoil in saline soils. Furthermore, plastic mulching can not only inhibit the soil evaporation, but the backflow of water evaporation also can leach the salinity from the soil surface. The combination of two techniques has significantly promoted crop growth and improved the crop yield. It was regarded by the local people as an effective way to improve the saline-alkali land [8]. However, following the huge alteration of the soil salinity before and after the implementation of these measures, the soil microenvironment including microbial activity, may change. In addition, whether intensive human activity influences saline soil respiration also needs to be investigated [9,10].

Soil respiration makes up the primary output pathways of the terrestrial ecosystem carbon cycle [11]. Studying its spatial and temporal fluctuations along with controlling factors was regarded as an important topic that would directly influence terrestrial carbon cycling and assist in predicting global warming [12]. However, research on salinization has primarily focused on the mechanism and modeling of salt and water movements, salinization monitoring, and assessment or reclaim [13], and few studies have focused on the characteristics of soil respiration emissions and their effects on saline areas, in particular their relationships with salt and other factors [14]. In recent years, saline-alkali soil has been found to play 'sink' and 'source' roles in the carbon cycle, and research in this area has received more attention [15]. Thus, enhancing research on the soil respiration emission mechanism of saline soil will have great significance for understanding saline and saline formation during saline soil carbon storage or emission and for improving regional regulation measures regarding global carbon [16,17].

At the current stage, the characteristics of saline soil respiration under long-term treatment with freezing saline water irrigation based on trial research has been poorly understood, and, as a result, we were not able to evaluate the treatment in an exact and comprehensive manner. For this reason, this study employed cotton fields under typical coastal saline conditions and four treatments for eight years as a research object. The objectives of the study were as follows: (1) determine the difference of dynamic change in the soil respiration rate along with its influencing factors under each treatment and (2) clarify the relationships between the soil respiration rate and its influencing factors in order to evaluate this successful improvement measure correctly. The aim of this study was to provide theoretical suggestions for sustainable development in the coastal saline plain.

2. Materials and methods

2.1. Site Description

This study was conducted at the efficient utilization demonstration zone of a coastal saline environment (117°33′E, 38°10′N) at the Chinese Academy of Sciences, China, which is located in Haixing county of Hebei Province. This area has a semi-humid continental climate with an annual average air temperature of 12.1 °C. The extreme minimum temperature is −19.9 °C in January. The mean annual precipitation is 582.3 mm, with over 74% of the annual precipitation falling between July and August and less than 7% falling in the winter. This area belongs to the typical saline coastal region (Table 1), which is composed of many salt wastelands in which chloride and sodium account for 70–88% of the anion and cation concentrations, respectively, and the salinity in the soil changed significantly over temporal and spatial scales [18]. The vegetation primarily consists of some reeds and *Suaeda salsa* communities. The groundwater level is 0.9–1.5 m with changes through the months [19]. The salinity concentration of the groundwater is approximately 7–27 g/L [20].

Table 1. Basic physico-chemical properties of the experimental surface soil (0–100 cm).

	Abandoned Saline Soil
Salinity (g/kg)	7.74 ± 1.83
Organic matter (g/kg)	3.61 ± 0.05
Available P (mg/kg)	2.81 ± 0.36
Available K (mg/kg)	29.9 ± 2.95

Table 1. *Cont.*

	Abandoned Saline Soil
Ammonium N (mg/kg)	1.78 ± 0.33
Nitrate N (mg/kg)	14.5 ± 1.11
Bulk density (g/cm^3)	1.57 ± 0.07
pH (H_2O, 1:5)	8.15 ± 0.17

Notes: These properties were measured in January 2008 before the experimental treatments were implemented. Values are represented as mean ± Standard Deviation (n = 3).

2.2. Experimental Design and Measurement

Four treatments were initially implemented on 17 January 2008, which included freezing saline water irrigation in Winter with plastic mulching (FSWI + Mulch), freezing saline water irrigation in Winter without plastic mulching (FSWI), plastic mulching in Spring without FSWI (Mulch), and no FSWI without plastic mulching (CK). Each treatment was done in triplicate in a randomized block design, and there were 12 plots in total. Each plot had a length of 6 m and a width of 5 m, and there was ribbing between each plot that was 1 m wide and 0.5 m high to prevent lateral seepage and interoperability overflow. The salinity of the irrigation water in the FSWI + Mulch and FSWI treatments was 9.59 g/L, and the temperature was −10.3 °C when irrigating during the winter. To ensure the freezing uniformity in the irrigation water, the amount of water irrigated that was pumped from ditches beside each plot was increased by several times, and thus each plot was irrigated with a small amount of water each day for three days to complete the experimental design requirements. A 180 mm high freezing layer formed after irrigation, and the soil surface ice melt and infiltration were completed in early March. Salt cotton 28 (*Gossypiumhirsutum* Linn.) was selected as the test breed, using a tilling machine to turn over the earth in each plot and furrow sowing three cotton seeds in each hole on 23 April of each year. The row spacing was 30 cm and planting distance was 50 cm in each plot. Plastic film mulching [Non-degradable (0.07 mm)] was installed in the FSWI + Mulch and Mulch treatments. We tore a small hole on the plastic film to let the cotton out in the early time of the seedling stage.

The test began early in June 2015, and the soil respiration was measured using an automated soil CO_2 flux system (LI-6400, LI-COR, USA) equipped with a portable chamber (Model 6400-09). Within each plot, three polyvinyl chloride (PVC) collars (10 cm inside diameter × 7 cm height) were placed at a diagonal for soil respiration measurements. The PVC collars were inserted 6 cm deep into the soil and were left there throughout the measurement period. This depth ensured collar stability, and it was assumed to be sufficient for minimizing the potential soil respiration underestimation due to lateral CO_2 diffusion [21,22]. The plants within the collars were clipped at the ground level regularly, and the litter inside the collars was removed before measurement. The soil respiration rate of each treatment measured two years from June 2015 to November 2016 during four critical growth stages, including the seedling stage, the bud stage, the flowering and boll-forming stage, and the boll opening stage, which were defined by the growth characteristics of cotton. In each stage, we took measurements on two sunny and windless dates separated by approximately 15 days. Measurements were taken between 9:00 a.m. and 11:00 a.m. To avoid the effect of a dramatic temperature decrease on the relationship between the soil respiration rate and soil surface temperature, we took measurements three times during the boll opening stage from mid-October to early November. The values from three replicate plots represented the average soil respiration rate of each treatment in the cotton field. To determine the diurnal variation in the soil respiration response to soil temperature, we selected one collar in each plot to measure the daily dynamics of the soil respiration rate during each growth period from June 2015 to November 2016. Continuous measurements were made once in the middle of each growth stage at two-hour intervals from 8:00 a.m. to 18:00 p.m. (Beijing standard time). Soil temperatures around 10–20 cm of each PVC collar in the 10 cm depth were monitored simultaneously using the temperature sensor attached to the LI-6400, the values represented the soil surface temperature in the cotton field [23–25].

2.3. Laboratory Analysis

We obtained soil from each layer (0 to 10, 10 to 20, 20 to 40, 40 to 60, 60 to 100 cm) by auger around 10–30 cm from the sample point at every assessment time, and all soil samples were taken to the laboratory, sifted through a 1-mm sieve, and analyzed for soil salinity and soil water content. The water contents of the soil samples were determined by an oven-drying method. The cation and anion contents of the saline soils were determined according to the methods of Lao [26], which tested the salt of soil using a 1:5 soil:water suspension. The contents of Na^+ and K^+ were determined by atomic absorption spectrometry and the total salt content was calculated as the sum of the cations and anions. At the cotton seedling stage of each year, we collected the surface soil (0–10 cm) from each treatment to detect the abundance of bacteria, fungi, and actinomycetes using Real-time PCR (Polymerase Chain Reaction) (Table 2). DNA was extracted from the soil using a Fast DNA_Spin Kit for Soil (MP Biomedical, Santa Ana, CA, USA) according to the manufacturer's instructions. Bacterial 16S rRNA genes were quantified according to the TaqMan Q-PCR (Quantitative Polymerase Chain Reaction) method. In a final 20 μL volume, the reaction mixtures contained 2×premix ExTaq™ (Takara Biotech, Dalian, China), 2 μM of each primer, 3 μM of probe TM1389F, and DNA template (about 10 ng/μL). The reaction conditions were an initial cycle of 95 °C for 2 min and 40 cycles of 15 s at 95 °C and 60 s at 56 °C. Fungi and actinomycetes were quantified by Q-PCR using a SYBR Green approach. Quantitative PCR (Q-PCR) was carried out in a volume of 20 μL, containing 2×SYBR Premix Ex Taq (Takara Biotech, Dalian, China), 1 μM of each primer, and template DNA (about 10 ng/μL). The Q-PCR program consisted of an initial cycle of 95 °C for 2 min and 40 cycles of 30 s at 95 °C for denaturation, 20 s at 57 °C for annealing, 30 s at 72 °C for extension, and 10 s at 85 °C for collection of the fluorescent signals. Melting curves were generated with continuous fluorescence acquisition from 57 to 95 °C at a rate of 0.5 °C per 10 s. All Q-PCR reactions were done in triplicate for both the standards and the microbial community DNA samples. The Q-PCR efficiencies (106.9% for bacteria, 83.1% for fungi, 97.6% for actinomycetes gene) were examined to test for inhibition. R^2 values were more than 0.997 for all calibration curves.

Table 2. Oligonucleotides of bacteria (16S), fungi (18s) and actinomycetes.

Target Group	Primers	Sequences	
Bacteria (16S)	1369F 1492R Probe TM1389F	CGGTGAATACGTTCYCGG GGWTACCTTGTTACGACTT CTTGTACACACCGCCCGTC	[27]
Fungi (18S)	FungiQuant-F FungiQuant-R	GGRAAACTCACCAGGTCCAG GSWCTATCCCCAKCACGA	[28]
Actinomycetes	243F 513R	GGATGAGCCCGCGGCCTA CGGCCGCGGCTGCTGGCACGTA	[29]

The growth conditions of the cotton in each plot were recorded when measuring the soil respiration rate at each time. We calculated cotton production in November in each year, as classified by the mass of leaves, stems, and roots of three samples from each plot. All of the samples were dried to a stable weight.

2.4. Statistical Analysis

All statistical tests were conducted using SPSS version 18.0 (SPSS Inc., Chicago, IL, USA) and SigmaPlot 12.5 software for figures. The soil physico-chemical properties were presented as mean ± standard deviation and the coefficient of variation in all of the soil samples. Significant differences were evaluated at the 0.05 levels using the least significant differences (LSD).

We used regression techniques to analyze the relationships between soil respiration and soil surface temperature, soil surface salt content, and soil surface water content ($p < 0.05$ as a threshold for statistical significance). We used first-order exponential regression analysis to examine the soil respiration-soil temperature relationship:

$$\mathrm{SR} = \alpha e^{\beta T} \tag{1}$$

where SR is the measured soil respiration rate, T is the measured soil temperature at a 10 cm depth, α is the soil respiration rate when the soil temperature is 0 °C, and β is the reaction coefficient of the temperature [30].

The Q_{10} value, which is defined as the increment of SR at which the temperature is increased by 10 °C, was used to describe the temperature sensitivity of SR. Q_{10s} and Q_{10y} are normally used to represent the degree of the soil respiration rate in response to soil surface temperature at daily and seasonal scales [31], respectively. However, Q_{10y} not only represents the relationship between the soil respiration rate and soil temperature, but it also considers other factors such as the soil water content, root biomass, microbial content and litter inputs among different seasons. Comparatively, the Q_{10s} value only considers the relationship between the soil respiration rate and soil temperature on a daily scale, with all of the other external factors being in minimal fluctuation. Thus, this study uses Q_{10s} to illustrate the degree of the soil respiration rate in response to soil temperature. In this study, Q_{10s} were calculated as [32]:

$$Q_{10} = e^{10\beta} \tag{2}$$

We used linear regression analysis to examine the relationship between soil respiration and soil salt and water content.

3. Results

3.1. Changes in Influencing Factors of Soil Respiration Rate among Different Treatments

3.1.1. Changes in Soil Surface Temperature

During the bud stage and the flowering and boll-forming stage, soil surface temperatures in the FSWI + Mulch treatment were significantly lower than the FWSI and CK treatments, which were not significantly different from each other during any growth period but were similar to the FWSI and CK treatments during the first growth period (Figure 1). Soil surface temperatures in the FSWI + Mulch and Mulch treatments were significantly higher than the FWSI and CK treatments during the last growth period.

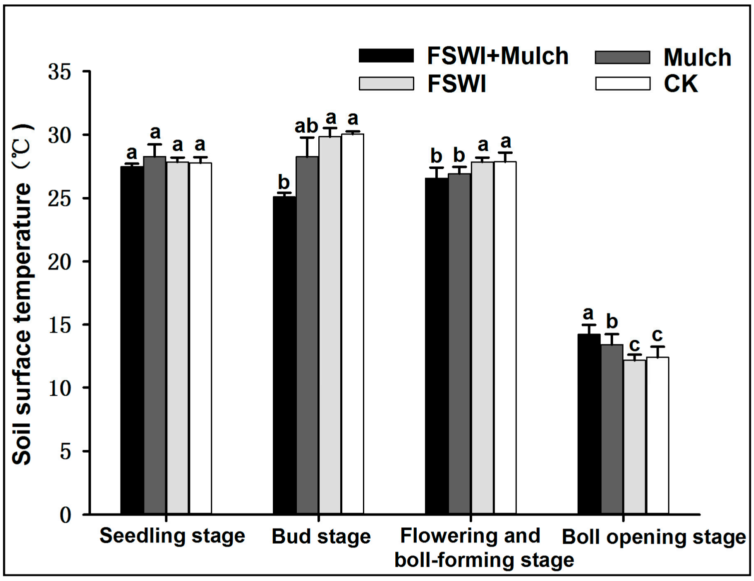

Figure 1. Soil surface temperature in each treatment during the growth period. The error bars represent the standard deviation of the mean (n = 3). Different letters (a, b, c) indicate significant differences among four treatments at $p < 0.05$.

3.1.2. Changes in Soil Salt Contents and Soil Water Contents

Soil salt contents were significantly lower in the FSWI + Mulch and Mulch treatments than in the FWSI and CK treatments during the seedling stage and the bud stage (Figure 2). Soil salt contents were not significantly different from each other during the flowering and boll-forming stage and the boll opening stage. Soil water contents in the four treatments during the flowering and boll-forming stage were significantly higher than in the other three growth periods.

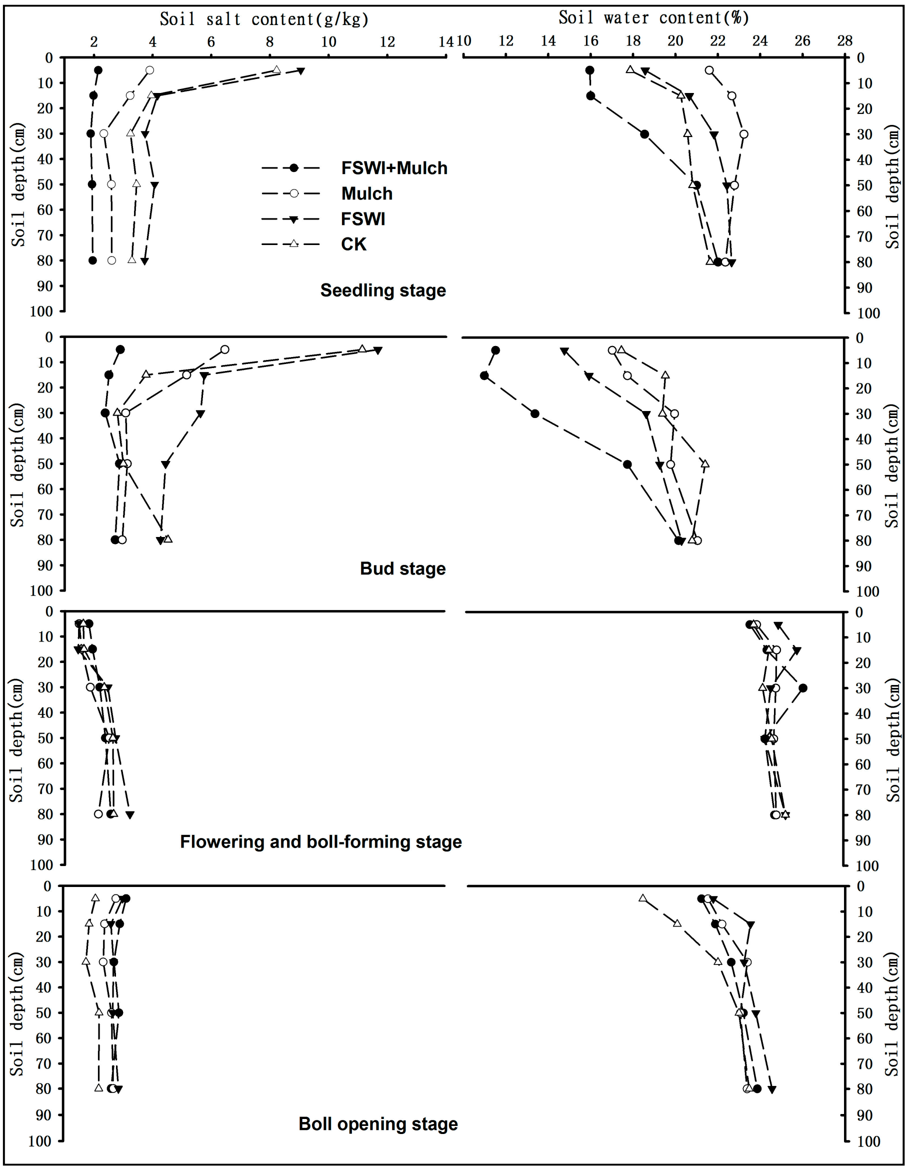

Figure 2. Changes of soil salt and water content during the growth period.

3.1.3. Abundance of Bacteria, Fungi and Actinomycetes among the Four Treatments

The quantitative distribution characteristics of bacteria, fungi and actinomycetes were consistent among the four treatments, which was in the order of bacteria > actinomycetes > fungi (Figure 3). The quantity of bacteria in the four treatments had a trend of FSWI + Mulch > Mulch > CK > FSWI. The abundance of fungi and actinomycetes was significantly higher in the FSWI + Mulch treatment than in the Mulch and CK treatments, which were not significantly different from each other. The abundance of bacteria, fungi, and actinomycetes in the FSWI treatment was significantly lower than in the other three treatments.

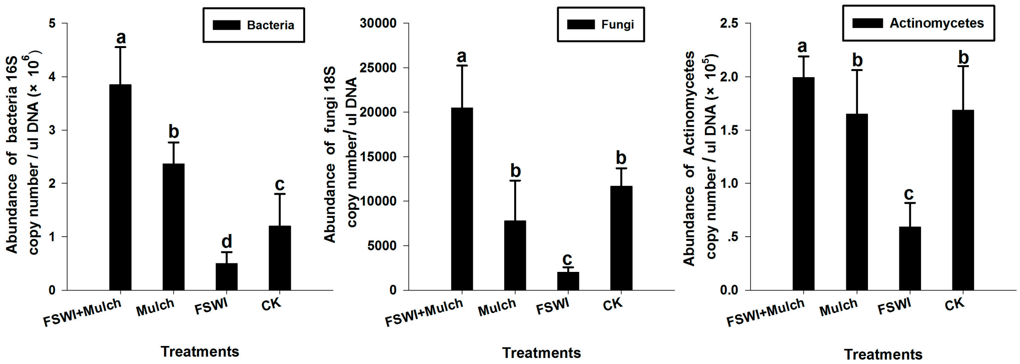

Figure 3. Abundance of bacteria, fungi, and actinomycetes in the four treatments. The error bars represent the standard deviation of the mean (n = 3). Different letters (a, b, c) indicate significant differences among four treatments at $p < 0.05$.

3.2. Change in Soil Respiration Rate between Each Treatment during the Cotton Growth Period

The soil respiration rate was significantly different between each treatment during the cotton growth period, ranging from 0.46 to 8.88 μmol/(m^2·s). Soil respiration was significantly higher in the FSWI + Mulch treatment than in the other treatments for the first three growth periods (seedling stage, bud stage, and flowering and boll-forming stage) and higher, although not significantly, in the final growth stage (boll opening stage) (Figure 4). During the bud stage and the flowering and boll-forming stage, soil respiration in the Mulch treatment was higher than the FWSI and CK treatments, which were not significantly different from each other during any growth period, but was similar to the FWSI and CK treatments during the first and last growth periods. The FSWI + Mulch treatment peaked during the flowering and boll-forming stage, whereas soil respiration in the other treatments peaked in the bud stage.

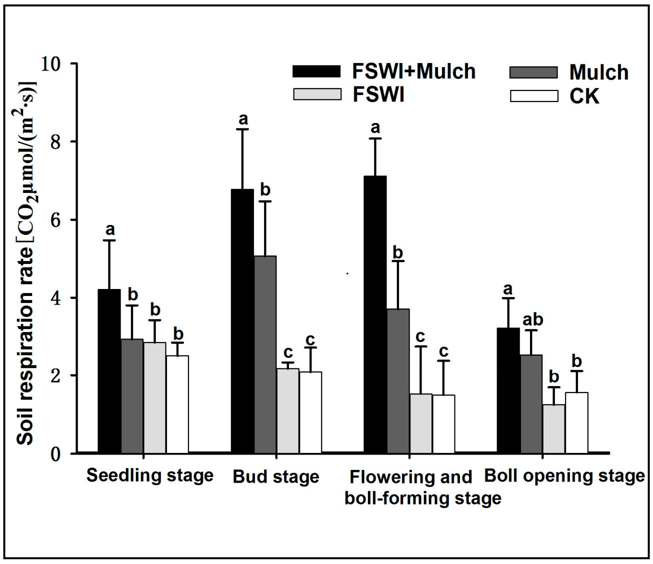

Figure 4. Changes in soil respiration rate in the four treatments during the growth period. The error bars represent the standard deviation of the mean (n = 3). Different letters (a, b, c) indicate significant differences among four treatments at $p < 0.05$.

3.3. Soil Respiration Rate Response to the Soil Surface Temperature during the Cotton Growth Period

Across all growth periods, soil respiration increased significantly and exponentially with soil temperature (Figure 5). When analyzed seasonally, however, there was a positive relationship between soil respiration and soil temperature during the last growing period (the period with the lowest soil temperature), no relationship in the earliest growing period, and negative relationships in the middle growing periods.

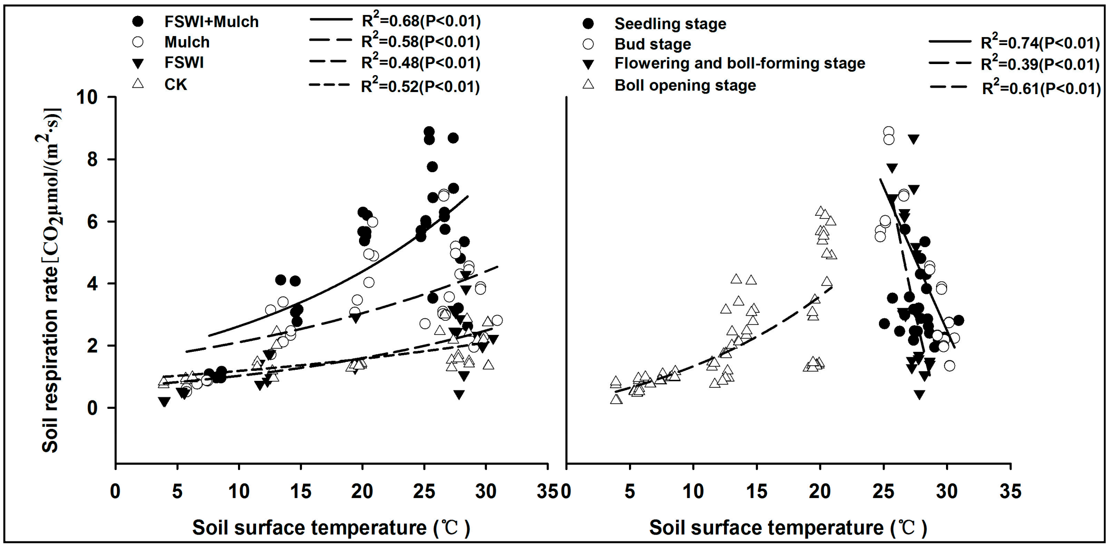

Figure 5. The relationship between soil respiration rate and soil surface temperature among four treatments during the growth period. $p < 0.05$ indicates reaching the significance level, $p < 0.01$ indicates reaching the extreme significance level.

Q_{10} in the FSWI + Mulch treatment was lower than the FWSI and CK treatments for the last three growth periods (bud stage, flowering and boll-forming stage, and boll opening stage), which were not significantly different from each other during any growth period but were similar to the Mulch treatment during the growth period of cotton (Table 3).

Table 3. Soil respiration rate response to soil surface temperature (Q_{10}) on daily scale during the growth period.

Treatments	Seedling Stage	Bud Stage	Flowering Boll-Forming Stage	Boll Opening Stage
FSWI + Mulch	1.26 ± 0.07a	1.13 ± 0.08b	1.29 ± 0.12b	1.23 ± 0.04b
Mulch	1.42 ± 0.25a	1.20 ± 0.17b	1.41 ± 0.35ab	1.47 ± 0.16ab
FSWI	1.24 ± 0.16a	1.43 ± 0.07a	1.60 ± 0.29a	1.63 ± 0.29a
CK	1.46 ± 0.29a	1.46 ± 0.05a	1.59 ± 0.24a	1.60 ± 0.07a

Notes: FSWI + Mulch: FSWI in Winter with plastic mulching; Mulch: plastic mulching in Spring without FSWI; FSWI: FSWI in Winter without mulching; CK: no plastic mulching or FSWI; Values are represented as mean ± Standard Deviation ($n = 3$). Different letters (a, b) indicate significant differences among four treatments at $p < 0.05$.

3.4. Soil Respiration Rate Response to Soil Surface Salt and Water Contents during the Cotton Growth Period

Across all growth periods, soil respiration was negatively related to soil surface salt content in the FSWI + Mulch treatment (but not significantly related for any other treatment), whereas soil respiration was negatively related with soil water content in the Mulch, FSWI, and CK treatments (but not significantly related in the FSWI + Mulch treatment) (Figure 6). Across all four treatments, there was a negative relationship between soil respiration and soil surface salt content in the earliest two growth periods but not in the later growth periods, and there were no seasonal relationships between soil respiration and soil water content.

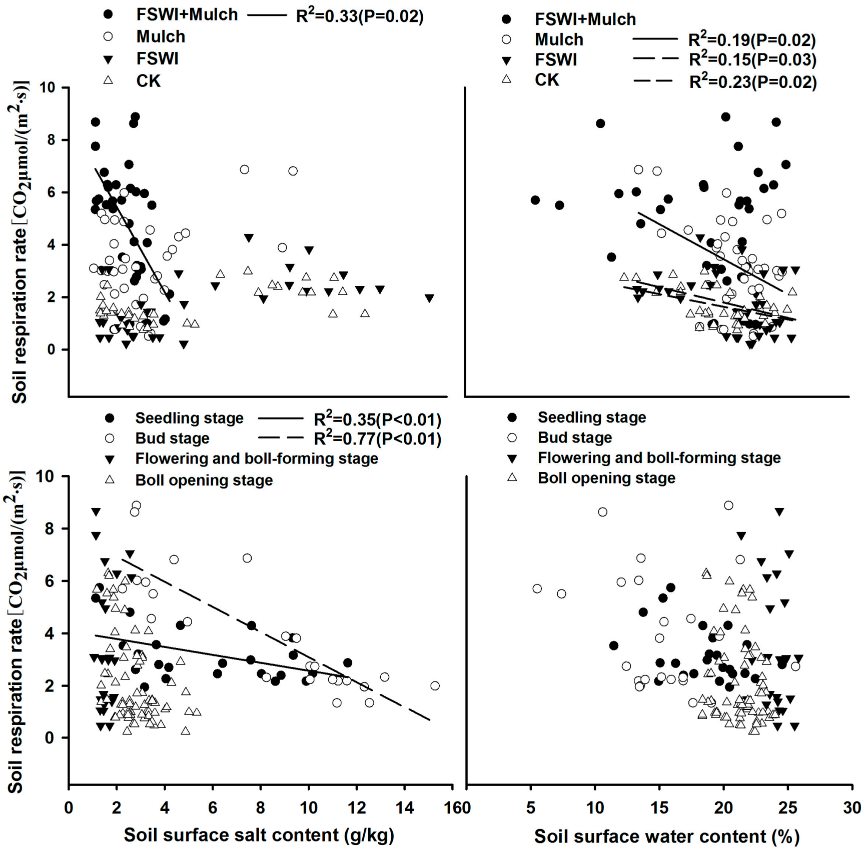

Figure 6. The relationships between soil respiration rate, soil salt content, and soil water content among four treatments during the growth period. $p < 0.05$ indicates reaching the significance level, $p < 0.01$ indicates reaching the extreme significance level.

4. Discussion

4.1. Changes in Influencing Factors of Soil Respiration Rate between Each Treatment

During the seedling stage, the soybean plants were small and unable to intercept much light, which led to no treatment-related differences in soil surface temperature (Figure 1). Due to the increasing vegetation coverage rate and the effect of mulch in the FSWI + Mulch and Mulch treatments, the soil surface temperature was maintained in a stable state and was lower than it was in the other treatments during the bud stage and flowering and boll-forming stage. Due to the reduced daylight and significant reduction in the soil surface temperature, mulching helped keep the soil warm during the boll opening stage.

Phenomenon of serious soil resalinization occurred in the FWSI and CK treatments during the seedling stage and the bud stage. Plants of cotton were at the early growth stage with high soil surface salt, which lead to decreased plant health and survival. However, FSWI + Mulch and Mulch reduced the soil surface salinity to 0.4% during the seedling stage. Under the freezing saline water irrigation, the later-melting brackish and fresh water had a leaching effect on the soil surface salt, and the mulching treatment can not only inhibit the soil evaporation, but the backflow of water evaporation can also leach the salinity from the soil surface and increase the survival and soil respiration rate of the cotton field significantly. It is worth mentioning that the soil surface salt in the Mulch treatment (6.46 g/kg) was significantly higher than in the FSWI + Mulch treatment (2.90 g/kg) during the bud stage, which was the key factor that led to further differences between the two treatments. Soil water contents reached the peak in the four treatments during the flowering and boll-forming stage due to high levels of rainfall, which washed salt into the lower layers of the soil. The phenomenon of soil resalinization was not severe during the boll opening stage, perhaps because of low temperatures and evaporation rates. Our results suggest that temperature and plant growth prior were interrelated and had the most influence on soil respiration in this experiment [33].

Plastic Mulching only increased the abundance of bacteria in the soil compared with the CK treatment, and there was no significant difference in the percentage of fungi and actinomycetes under Mulch and CK. These findings showed that Freezing Saline Water Irrigation was the requisite treatment for increasing the abundance of fungi and actinomycetes to improve the soil quality, even with the higher initial costs corresponding to Mulch treatment.

Initially, the average cotton survival rates under FSWI + Mulch and Mulch were 72.78% and 19.44%. There were no surviving cotton plants in the FSWI and CK treatments, only some reeds and *Suaeda salsa* plants, with average coverage of 10% and 7%. It should be noted that the taproots of individual cotton plants under the Mulch treatment had less mass than those under the FSWI + Mulch treatment because they had a higher salt content and the roots could not go any deeper (Table 4). Conversely, the limbs and foliage values of individual cotton plants under the Mulch treatment outweighed those of the FSWI + Mulch treatment because there was little shade between the plant leaves, whereas the Mulch treatment had a higher photosynthetic production [34]. The order of the average soil respiration rates from different treatments was positively related with the amount of fine root biomass in each treatment. Evidences suggest that root respiration accounts for 30–90% of the total respiration and closely relates to root biomass [35–37].

Table 4. Cotton yield and biomass of a single plant under FSWI + Mulch and Mulch.

Treatments	Taproot (g)	Limb (g)	Foliage (g)	Yield (hm^2/kg)
FSWI + Mulch	22.07 ± 2.35a	92.86 ± 5.67b	74.86 ± 3.89b	10.55 ± 0.54a
Mulch	15.97 ± 1.98b	104.21 ± 3.78a	88.58 ± 4.23a	4.21 ± 0.21b

Notes: FSWI + Mulch: FSWI in Winter with plastic mulching; Mulch: plastic mulching in Spring without FSWI; Values are represented as mean ± Standard Deviation (n = 3). Different letters (a, b) indicate significant differences among the two treatments at $p < 0.05$.

4.2. Effects of Different Treatments on Soil Respiration Rate

Soil respiration varied among different treatments in our study. It can be seen from the order of the average soil respiration rate from different treatments (FSWI + Mulch > Mulch > FSWI = CK) that plastic mulching in the spring was the key measure that affected the soil respiration rate, while freezing saline water irrigation was an important further step affecting the soil respiration rate. The soil respiration rate was higher in the FSWI + Mulch treatment than in the other treatments during the seedling stage because many roots remained from the high cotton survival rate. The bud stage is the critical period for measuring the growth speed of cotton, and the plant heights, crown diameters, and leaf numbers increased significantly compared to those of the seedling stage [38,39]. The soil respiration rates under FSWI + Mulch and Mulch were significantly higher than in the other treatments. The soil respiration rate in the FSWI + Mulch treatment decreased significantly during the last growth period. The cotton was in a period of increasing production, and, at that time, as the roots ceased to grow, the soil respiration under other treatments was maintained at a lower rate.

Land use change can affect energy flow, biogeochemical, and hydrological cycling in terrestrial ecosystems through altering the physical and chemical properties of soil and become one of the most concerning environmental problems for scientists, land managers, and policy makers [40–42]. In this study, the heavy coastal saline soil was reclaimed for cotton fields through freezing saline water irrigation and plastic mulching, and the soil reparation increased greatly. In general, the difference between the soil respiration rates under different land treatments were consistent with their growing conditions [43,44]; many studies suggest that the survival rate of plants can greatly increase the soil carbon emissions [45], which is consistent with our results that high vegetation coverage through freezing saline water irrigation and plastic mulching correspond to high soil respiration rate. From the point of carbon sequestration, the results had a negative effects on carbon residues in the soil, but the photosynthetic production from crops on the ground should not be ignored [46,47]. It also gave a contribution to soil respiration. However, the soil organic matter contents were 5.28 g/kg and 4.39 g/kg in the FSWI + Mulch and Mulch treatments, respectively, which were lower than the average soil organic matter content levels of the whole nation (China) [48]. In order to make the salt water easy to freeze in the winter, we always uproot the cotton plants during harvest, leaving only a small amount of crop litter to decay in the soil, which cannot increase substrate supply. It may be a feasible technique to grind the plants and plow them under the soil surface, which would not only maintain the soil surface temperature and cut down on the soil surface salt but would also increase the supply of carbon. The system of plant-soil may be a process of carbon sequestration, so the whole growing period of the photosynthetic data of cotton needs to be further researched. Due to weather and other factors, we did not measure soil respiration in winter; thus the quantitative relationship between the treatments and soil respiration on an annual basis remains uncertain. This type of uncertainty can cause discrepancies in the estimation of terrestrial ecosystem CO_2 fluxes and warrants further research [49–51].

4.3. Relationship between Soil Respiration Rate and Its Influencing Factors between Each Treatment

There was a positive exponential correlation between soil respiration rate and soil surface temperature, as has been suggested by a number of studies [52,53]. The results suggested that soil surface temperature was the important factor for the soil respiration rate and was a good indicator for estimating soil respiration in this specific ecosystem in a coastal saline plain. It also explained that mulching not only affects the surface soil temperature but can also affect the rate of soil carbon emissions, which will lead to an impact on the regional carbon cycle. With the rising atmospheric temperature, mulching reduced the soil surface temperature effectively, which is accompanied by decreasing soil carbon emissions. By contrast, when the outside temperature decreases, mulch can retain soil heat, which promotes a higher soil carbon emission rate. This result implies that removing the plastic mulching during the last growth period may be a feasible technique to control soil carbon emissions but that further research would be necessary to test the implications on carbon dynamics of such a management technique.

Q_{10} was used to show the sensitivity of the soil respiration to the soil temperature [54,55]. Proper Q_{10} values will help to improve the accuracy of ecosystem carbon flux estimation [56]. FSWI + Mulch can stabilize the soil surface temperature at a daily scale through mulch and substantial vegetation coverage, which would reduce the value of Q_{10}. In the context of aggravating global temperature change, further exploration and understanding of the dynamic change mechanism of Q_{10} during special periods is important for relieving global climate change and engaging in saline-alkali land reform for the purpose of carbon sequestration [57–62].

Although FSWI + Mulch can reduce the soil surface salinity significantly and lead to normal cotton growth, it is sensitive to the phenomenon in which salt is returned through water evaporation during the boll opening stage. The soil surface moisture had a negative correlation with the soil respiration rate in the Mulch, FSWI, and CK treatments (Figure 6) for the possible reason that there was a good deal of rain but less vegetation coverage; much of the water could not be consumed through plant transpiration in the three treatments. The soil water content may exceed the field water holding capacity, and, therefore, it would affect the soil respiration rate. The relationship between the soil respiration rate and soil surface water content was not significant during the cotton growing period (Figure 6). The soil water contents were similar at the same stage in the four treatments, but the soil respiration rates were different because of the different soil salt contents and root distribution. This finding illustrated that the water on the soil surface is not a critical factor that causes differences in the soil respiration rate under different treatments in the cotton field.

The abundance of bacteria, fungi, and actinomycetes was an important indicator of environmental quality, which would be affected by crop type, irrigation, and some other measures [63]. In this study, FSWI + Mulch contributed to a higher survival rate and root biomass, which provided adequate carbon to promote growth of bacteria, fungi, and actinomycetes. This finding corresponds to a previous study [64], which reported the abundance of bacteria, fungi, and actinomycetes after freezing saline water irrigation increased compared to not irrigating.

5. Conclusions

Our study suggested that the soil surface temperature was an important factor that affected the soil respiration rate in each treatment during the growth periods. FSWI + Mulch can stabilize the soil surface temperature through mulch and substantial vegetation coverage. FSWI + Mulch also can reduce the soil surface salinity to 0.4% during the seedling stage, which not only increased the survival rate and provides adequate carbon to promote growth of bacteria, fungi, and actinomycetes but also causes a higher rate of soil respiration. In short, freezing saline water irrigation with plastic mulching corresponding to high soil quality with crop growth not only played an important role in soil surface temperature maintenance and cutting down on the soil surface salt but also provides practical and theoretical suggestions for the sustainable development of coastal saline plains.

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