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Soil Water-Salt Dynamics and Maize Growth as Affected by Cutting Length of Topsoil Incorporation Straw under Brackish Water Irrigation

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Received: 9 December 2019; Accepted: 4 February 2020; Published: 6 February 2020



Abstract: Brackish water has been utilized extensively in agriculture around the world to cope with the global water deficit, but soil salt accumulation caused by brackish water irrigation cannot be ignored. Straw incorporation has been confirmed an effective sustainable means to inhibit soil salt accumulation. An experiment was conducted in growth tanks over two consecutive growing seasons to investigate the effects of wheat straw incorporation on soil moisture and salinity under brackish water irrigation (5g NaCl L⁻¹). Furthermore, the trial investigated the effects of three wheat straw cutting lengths (CK = 0 cm; L1 = 5 cm, L2 = 10 cm, and L3 = 20 cm) on soil water-salt dynamics and summer maize growth. The results showed that soil properties and maize yields were favorably and significantly affected by the shorter straw segments incorporated into the cultivated field ($p < 0.05$), as indicated in the decrease in soil bulk density (7.47%–7.79%) and the rise of soil organic matter (SOM) content (2.4–4.5g kg⁻¹) and soil total porosity (4.34%–4.72%) under treatment L1. Meanwhile, treatment L1 produced the greatest dry above-ground biomass (14447 ± 571 kg ha⁻¹), 100-grain weight (34.52 ± 1.20 g) and grain yield (7251 ± 204 kg ha⁻¹) of summer maize. Soil water content in the cultivated layer increased 4.79%–25.44%, and the soil salt accumulation rate decreased significantly due to the straw incorporation and the highest value of soil moisture content (19.10%–21.84%), as well as the lowest value of soil salt accumulation rates (2.12–9.06) obtained at treatment L1. Straw incorporation with cutting length in 5 cm is the optimal choice for alleviating the adverse effects due to brackish water irrigation and improving soil properties, which could be helpful for agricultural mechanization and straw field-returning practices.

Keywords: straw incorporation; straw cutting length; brackish water irrigation; soil water-salt dynamics; soil properties; summer maize yield

1. Introduction

Freshwater has long played an important role in sustainable agricultural development and crop growth throughout history; the consumption of freshwater in agriculture accounts for about 75% around the world [1,2]. With the acceleration of urban modernization and the increasing population, more water, especially freshwater, is used for traditional industrial and other high and new technology industrial productions; less freshwater used in agriculture and larger populations will lead people to suffer a serious food crisis [3,4]. Facing an extreme shortage of freshwater used for agricultural irrigation, more countries and regions have joined in the promotion of water-saving irrigation technology, such as drip irrigation, sprinkler irrigation and micro-irrigation, in order to ensure the sustainable development

of agriculture [5–7]. However, water-saving practices are still insufficient for satisfying the demands of agriculture irrigation, which force people eagerly to explore low-quality water resources, such as municipal wastewater, agricultural drainage water and brackish water for agricultural irrigation [8,9].

There is a 20 billion $\text{m}^3 \text{a}^{-1}$ brackish water resource stored underground in China, of which about 13 billion m^3 is available [10]. Brackish water is water owning more salinity than freshwater, and its salinity ranges from 2 to 5 g L^{-1} [11], which contains large amounts of ions like Na^+ , Ca^{2+} and Mg^{2+} , as well as Cl^- , SO_4^{2-} , HCO_3^- and so forth [12,13]. Using brackish water for agricultural irrigation is common in regions such as the North China Plain, where there is a freshwater deficit [14]. Brackish water is significantly more trustworthy compared to the wastewater generated by urban life and industry, which contains a variety of potential toxic elements, heavy metals, pathogenic viruses, bacteria and so on that can pose damage to the natural environment and cause harm to public health [15]. Maggio et al. [16] found that brackish water with low salinity did not significantly affect tomato grain yield; rather, the quality of tomato was improved, as reflected by the higher acidity and sugar content. Even so, the use of brackish water for irrigation is still harmful to sustainable agricultural development, because brackish water irrigation in conjunction with no protective measures is more likely to cause salt accumulation in soil [17], which may depress the growth of crops and the final grain yields. Besides, more freshwater will be essential to leach the additional salt accumulated in the cultivated soil layer [18,19]. Appropriate crop irrigation management therefore is particularly important.

Crop growth is sensitive to soil salinity, especially in the germination and seeding stages of crops. Brackish water irrigation with high salinity and excess salt in the soil not only inhibits the emergence of crops in the seeding stage [20] but also decreases the water uptake by crops during the growing seasons and disrupts the ion balance, leading to toxicity [21]. The negative effects of soil salinity on crops can be alleviated by selecting suitable crops as salt-tolerant varieties, adjusting the irrigation regime of brackish water reasonably, and adopting agronomy, hydraulic and other measures to adjust the transport and distribution of salt in cultivated soil layers [22,23]. Huang et al. [11] demonstrated that the impact of brackish water irrigation on soil salinity and crop yield can be minimized by using brackish water for irrigation in the later period of maize growth rather than at the germination or early seeding stage. However, the problem with brackish water utilization is that it is not sustainable; brackish water irrigation may not adversely affect soil quality and crop growth in a short time [24], but the ecological environment will be damaged in the long-term if the salt brought into the soil is not adequately leached. Subsurface drainage is considered to be a very effective system for salt leaching. Feng et al. [25] reported that when the drain depth is set at 0.8 m, no salt accumulation occurred under brackish water irrigation during the maize growing seasons. Zhang et al. [13] also confirmed that brackish water can be used for salt leaching, and when the irrigation volume is $4000 \text{ m}^3 \text{ ha}^{-1}$, brackish water can obtain better performances in producing favorable soil chemical properties than well water. Nevertheless, the application of subsurface drainage is expensive and environmentally unfriendly, because it is made from plastic and needs to be buried at a deeper soil layer, which will cost a large amount of money and labor.

In recent studies, straw materials are widely seen as important due to their large quantity, low price and excellent performance in field management. Straw return in fields can improve soil properties in various aspects, such as soil bulk density, soil porosity, the stability of soil aggregates, soil organic matters and so forth [26–28]. Straw direct application into fields can be divided into three main forms: straw mulching, buried straw and straw incorporation. Straw mulching has been confirmed effective in increasing the soil water content in the plough layer of farmlands to guarantee crop high yields [26,29], but the improvement of the soil quality by straw mulching is not as good as buried straw and straw incorporation. Buried straw can also prevent salt from moving up due to phreatic evaporation [30], but the high burial depth requires a large amount of financial and material resources. Straw incorporation is widely applied in sustainable agricultural production due to its convenience to operate and realize. Compared to the straw mulching and buried straw, straw is more likely to decompose under the condition of straw incorporation [31], thus releasing more organic matter to

promote the formation of soil aggregates and help the root system of crops develop deeper to increase crop yields [32]. Zhu et al. [33] demonstrated that straw incorporation in the upland soil could increase the water-holding capacity in the 10–15 cm soil layer, causing the rise of sweet tomato and rapeseed yields by about 10% and 20%, respectively. Getahun et al. [27] revealed incorporation of straw into the upper subsoil could result in higher soil organic matter content, as well as the increase in spring wheat grain yield. Therefore, straw incorporation was an effective practice in field management.

Meanwhile, due to the development of mechanization, straw incorporation technology has formed an integrated scheme of stubble removal, crushing and rotary tillage. However, there is no uniform standard for the cutting length of straw, which can be improved to promote sustainable agricultural development [34]. Few researchers have investigated the potential of the straw length in improving the soil properties, as well as enhancing the crop yields under brackish water irrigation systems. A two-year plot experiment therefore was established to evaluate (1) the dynamics of soil water-salt under brackish water irrigation and straw incorporation with different lengths of wheat straw segments during the summer maize growing seasons, (2) the capability of wheat straw incorporation to improve soil properties and alleviate soil salt stress, (3) the effects of topsoil incorporated with different lengths of wheat straw segments on the summer maize growth and yield production under brackish water irrigation.

2. Materials and Methods

2.1. Study Site Description

Field experiments were carried out during the summer maize growing season (June to September) of 2017 and 2018 at the Water-Saving Park of Hohai University (118°50' E, 31°57' N) in Nanjing, China. The experimental area has a subtropical humid monsoon climate with four distinct seasons. The annual average temperature of the area is 15.3 °C, the mean annual precipitation is approximately 1073 mm and the mean annual evaporation is around 900 mm [35]. During the experiment study, the daily meteorological data, including air temperature, wind speed, relative humidity, precipitation, total solar radiation and so on, were collected by an automated weather station in the study site [36]. The main physical properties of the pre-experiment soil are listed in Table 1.

Table 1. Physical characters of the initial tested soil.

Soil Depth cm	Soil Texture	Soil Particles/%			Bulk Density g cm ⁻³	Field Capacity cm ³ cm ⁻³	Willing Point cm ³ cm ⁻³	EC _{1:5} dS m ⁻¹
		Sand	Silt	Clay				
0–20	Clay loam	31.93	37.88	30.19	1.37	0.39	0.15	0.074
20–40	Clay loam	28.49	39.05	32.46	1.48	0.36	0.14	0.084
40–60	Clay loam	26.39	38.42	35.19	1.53	0.34	0.11	0.085
60–80	Clay loam	24.93	37.18	37.89	1.57	0.34	0.11	0.098

2.2. Experimental Design

The treatments of the experiment comprised three lengths of wheat straw segments with 5 cm (L1), 10 cm (L2), 20 cm (L3) and no straw incorporation (CK). The experiment was laid out in a randomized complete block design with three replications. Suyu 29, a maize cultivar currently used in local production, was grown in tanks during the summer maize growing season (June to September) of 2017 and repeated at the same sites in 2018. Each tank measured 10 m³ (2 m wide, 2.5 m long and 2 m high) and was constructed from concrete block with a waterproof paint to minimize the effects of lateral water and salt movement between tanks [37]. The bottom of each rank was filled with a 20 cm layer of coarse gravel, separated from soil by a water-permeable membrane to allow free drainage and connected with a Marriott bottle system to maintain the water table at 1.5 m during the whole growing season in two years.

Before maize sowing, the tanks were ploughed to a depth of 20 cm, and heavy soil lumps were broken up by harrow. Then, the treated wheat straw with 6000 kg ha⁻¹ was arranged uniformly

into each tank, and the tillage work was repeated again to mix the soil and straw evenly, forming a 20 cm straw-soil incorporation layer. According to the local fertilizer practices, a total of 250 kg ha⁻¹ compound fertilizer (N:P₂O₅:K₂O = 28:10:8) was applied before cultivation. The maize was sown with a row spacing of 40 cm, and each tank had 24 maize plants. Since most crops were sensitive to salinity in the early stages of growth, fresh water was applied at 30 mm in all treatments at pre-sowing to enhance germination. Since no suitable brackish water resource could be obtained near the study site, brackish water thus was designed with a salinity of 5 g NaCl L⁻¹, according to previous researches [38,39], which demonstrated that sodium and chloride were the primary ions of the brackish water resource. For all treatments, brackish water (5 g NaCl L⁻¹) with a total amount of 320 mm was applied from seeding to full ripeness (Table 2). Both of the fresh and brackish waters were applied by means of flood irrigation via a pump, and the exact amount of supplied water was controlled by water meters. In order to accurately explore the effects of straw incorporation with different lengths and brackish water irrigation on soil moisture and salinity, a large automatic awning was used to cover all tanks to avoid the impacts of rain during the whole growing season. In detail, before the rain came, the awning would automatically close to prevent tanks from receiving precipitation. When the weather was clear, the awning would also automatically open to allow the maize to photosynthesize better in the sun.

Table 2. Irrigation regime in the two growing seasons (mm).

Year		Sowing Stage	Seeding Stage	Jointing Stage	Tasseling Stage	Flowering Stage	Filling Stage	Yellow Maturity Stage	Full Ripe Stage	Total Amount
2017	Date	24 June	10 July	20 July	30 July	9 August	19 August	29 August	15 September	350
	Amount	30	40	40	40	40	40	60	60	
2018	Date	27 June	7 July	17 July	27 July	6 August	16 August	26 August	12 September	350
	Amount	30	40	40	40	40	40	60	60	

Maize was sown on 24 June 2017, 27 June 2018 and harvested on 25 September 2017 and 30 September 2018. After harvest, the maize stalks were removed, and each tank was ploughed to a depth of 20 cm. In winter between 2017 and 2018, no crops were planted, and the awning was opened to utilize rainfall to leach the salinity of the soil by brackish water irrigation until June of the following year. For comparison, the same experimental treatment was repeated in 2018, including tillage, fertilization and wheat straw incorporation practice, so that the treatment effects persisted. Through this design, the cross-year effect of wheat straw incorporation can be statistically analyzed in terms of variation with years. Before maize sown in 2018, all soil parameters, including soil water-salt content, bulk density, soil porosity and soil organic matter content, were remeasured and recorded.

2.3. Sampling and Measurements

The soil samples were collected one day before irrigation or harvest and two days after irrigation at soil depths of 0–20 cm and 20–40 cm on three random points in each tank using a soil auger. All collecting holes in the tanks were refilled with the surrounding soil layer by layer to guarantee the consistency of soil conditions. The soil samples for measuring gravimetric water content were put into an oven at 105 °C for 24 h and samples for soil salinity testing were air-dried. Air-dried soil samples then were ground to pass a 1 mm sieve to measure the electrical conductivity of 1:5 soil-water leachate (EC_{1:5}) using a digital conductivity meter (DDBJ-350, Shanghai, China). The undisturbed soil core was collected using a cutting ring (diameter: 100 mm, height: 63.7 mm) at the soil depths of 0–20 cm and 20–40 cm in each treatment for measuring the soil bulk density [33]. The soil porosity was calculated from soil bulk density with an estimated soil particle density (2.65 g cm⁻³). Soil organic matter (SOM) content was determined using an oil bath K₂Cr₂O₇ titration method [38]. Before harvest, the plant height was measured using a steel rule, and a Vernier caliper was adopted for measuring the summer maize stem diameters. After harvest, five maize plants were randomly chosen in each tank to measure the dry above-ground biomass, one hundred-grain weight and grain yields. The plant samples were

oven dried at 105 °C for 30 min for ceasing biological enzyme activity and then at 75 °C for about two days until a constant weight.

2.4. Evaluation Methods

The soil salt accumulation rate (SAR) during each of the summer maize growing seasons was calculated by the following equation:

$$\text{SAR} = \frac{C - C_0}{C_0}$$

where C_0 is the soil electrical conductivity ($EC_{1:5}$) before the summer maize sowing in $dS\ m^{-1}$ and C is the soil electrical conductivity ($EC_{1:5}$) at the summer maize harvest in $dS\ m^{-1}$.

2.5. Statistical Analysis

Significant differences of treatments on the measured parameters within each individual year were analyzed using one-way ANOVA. Two-way analysis of variance (ANOVA) was performed to test the main effects of year and treatment, as well as their interactions on maize growth and grain yield parameters. The statistical significance of treatment effects was determined using the least significant difference (LSD; $p < 0.05$). Statistical analyses of the collected data were conducted with the SPSS 18.0.

3. Results and Discussion

3.1. Dynamics of Soil Moisture

The effects of straw incorporation with different straw lengths on soil moisture are shown in Figure 1. Soil moisture content dynamics within the soil depth of 0–40 cm showed clear patterns of change with large variations during the two maize growing seasons.

As Figure 1 indicated, within the soil depth of 0–20 cm, the soil moisture content under L1 and L2 had greater values than that under CK during each stage of maize growth in 2017. The results in the present study were in agreement with the previous studies, which found that the soil moisture of the cultivated layer could be increased due to straw incorporation [39]. For example, the soil moisture content within 0–20 cm was 17.37%, 10.10% and 4.79% higher under L1, L2 and L3 than that under CK on average in 2017. However, no evident difference of soil moisture content was observed between L3 and CK during the later period. The reasons why straw incorporation can improve soil moisture content can be explained as follows: On the one hand, the capillary of the soil was cut off by straw amendment, preventing water upper movement from the subsurface soil layer [40,41]. On the other hand, straw amendment destroyed the original pore structure of the soil and increased the retention time of irrigation water, delaying the infiltration of irrigation water [42]. When the chopped straw segment was too long, it was difficult for the straw to be mixed into the soil adequately, thus resulting in most of straw segments exposed to the ground, so the role played by L3 tended to be that of straw mulching. The treatment L3 therefore showed a similar ability to improve the soil moisture content as treatments L1 and L2 in the early stage of maize growth. In the later stage of maize growth, the advantage of straw mulching that L3 partly showed was weakened, because the surface soil layer gained shade due to the maize growth, leading to the decrease of ability to improve soil water content under the L3 treatment.

The soil moisture dynamics of 2018 showed similar rules with that of 2017. The treatments L1, L2 and L3 increased the soil moisture content by 25.44%, 18.94% and 12.15% on average at the 0–20 cm soil layer compared to CK in 2018. However, the soil moisture content under treatments L1, L2 and L3 in 2018 were obviously greater than that in 2017. Moreover, no evident difference was found in the soil moisture content under treatment CK between 2017 and 2018. The results might indicate that the soil properties were improved with the increase of the years of straw incorporation, the advantages of straw incorporation were further enhanced and the treatment difference between L3 and CK was gradually evident. Yao et al. [43] reported that the increase of soil matter content due to straw incorporation could

increase the stability of soil structure, and soil moisture content was higher in the paddy soils with higher soil organic matter concentrations. Kuang et al. [31] revealed that straw incorporation was better for crop residues decomposition than straw mulching, and straw incorporation could release more soil organic matter. The straw decomposition rate might be the reason for the different performances in improving the soil water distribution between L1, L2 and L3. Results in the present study indicate that the straw decomposition rate might be related to the chopped length of straw segments.

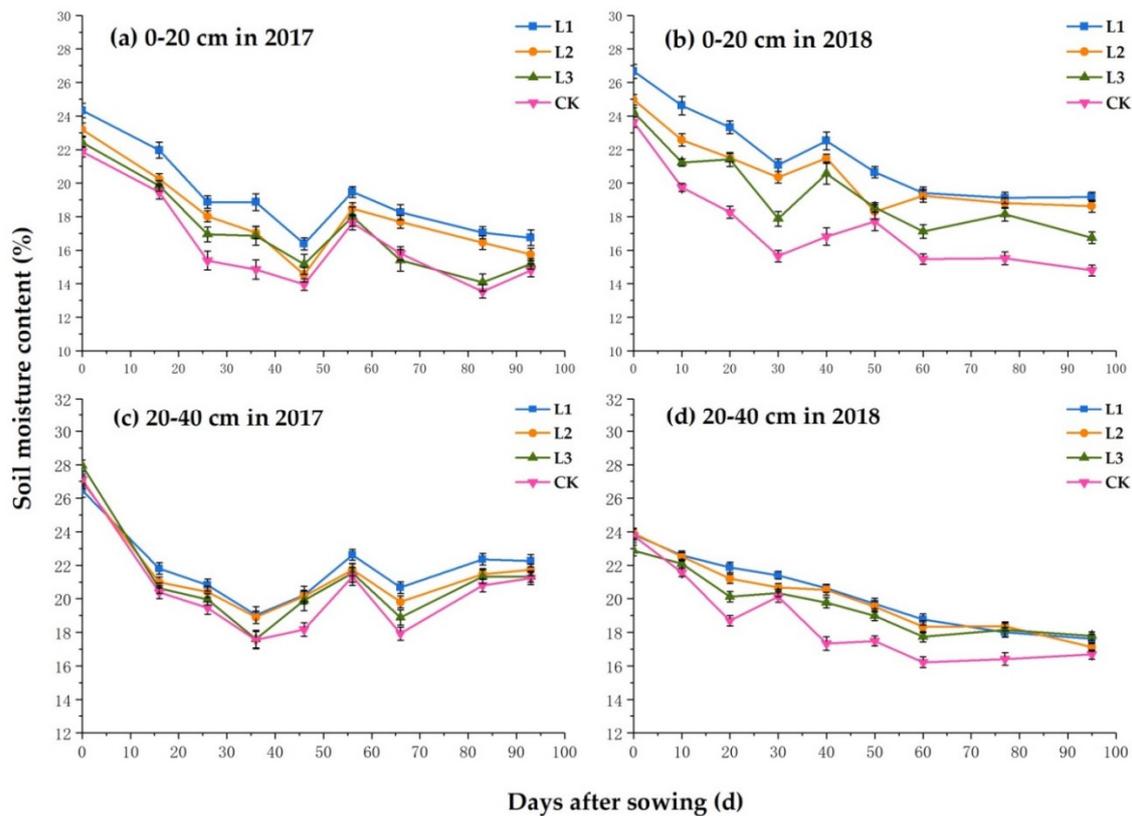


Figure 1. Soil moisture content at the soil depth of 0–20 cm and 20–40 cm over time under treatments L1, L2, L3 and no straw incorporation (CK) during the two summer maize growing seasons: 2017 and 2018. **L1:** The cut length of straw was 5 cm, **L2:** the cut length of straw was 10 cm, **L3:** the cut length of straw was 20 cm and **CK:** no straw incorporation. Values are means of three replications \pm standard deviation.

Within the soil depth of 20–40 cm, the patterns of soil moisture content were similar with that at 0–20 cm in 2017, except in 2018. The soil moisture content of 20–40 cm soil layer at most stages of maize growth in 2018 was lower than that in 2017, particularly in the later period of maize growth, though the differences were not evident. However, the lowest soil moisture content was always obtained under CK throughout two growing seasons. In 2017, the treatments L1, L2 and L3 increased soil moisture content by 7.24%, 4.88% and 2.91%, on average, compared to CK. Furthermore, in 2018, the soil moisture content under treatments L1, L2 and L3 were 10.14%, 8.78% and 6.31% higher than that under CK, respectively. The soil water content in the soil profile before irrigation follows the rule of a gradual increase from top to bottom due to the water evaporation from the topsoil. However, the rule of soil water distribution changed in 2018 compared to that in 2017. The reason for the change in soil water distribution might be that the straw incorporated into the cultivated soil last year had not decomposed completely, and new chopped straw segments were added in 2018, which promoted the recombination of the soil structure and further enhanced the water holding capacity of the 0–20 cm topsoil [33]. The straw incorporation had a more obvious inhibitory effect on the infiltration of irrigation water, and the retention time of irrigation water in the upper soil was longer. In our experiment, the amount of the irrigation water was 60 mm in the later stage of the maize growth;

therefore, the water infiltration to the 20–40 cm soil layer decreased, which further reduced the water content in the 20–40 cm soil layer. In addition, some reports have shown that straw incorporation was conducive to the downward development of crop roots [32], which may also be a reason for the decrease of water content in the soil layer of 20–40 cm. Although the water content of the 20–40 cm soil layer decreased slightly in 2018 compared to that in 2017, the water content of the 0–20 cm soil layer remained a relatively high level. The soil moisture content in the whole 0–40 cm soil layer where the summer maize root mainly developed was also higher in 2018 than that in 2017. This phenomenon may be related to the evaporation intensity, which needs to be further studied.

3.2. Variations of Soil Salinity

As shown in Table 3, salt in the soil depth of 0–40 cm continued to accumulate as brackish water irrigation amounts increased. All treatments had a similar trend of salt accumulated in soil, and the greatest salinity were obtained at harvest. The phenomenon of salt accumulation at each layer of soil was obvious, especially at the top soil layer of 0–20 cm, and shorter straw treatments showed stronger resistance to salt accumulation in soil.

In 2017, the soil salt accumulation rates (SAR) of treatments L1, L2, L3 and CK in the soil depth of 0–20 cm were 9.06, 9.24, 10.57 and 11.47, and the SAR of treatments L1, L2, L3 and CK in the soil depth of 20–40 cm were 2.38, 2.97, 3.07 and 3.60, respectively. Although no significant differences of SAR were found between L1 and L2 in the soil depth of 0–20 cm, between L2 and L3 in the soil depth of 20–40 cm in 2017, these values were all significantly lower than the SAR of treatment CK. The results in the present experiment indicated that the straw incorporation could inhibit salt accumulation in the topsoil, thus decreasing the salt content of the straw incorporation layer. This was because the straw incorporation extended the retention time of infiltration in the topsoil [42], so that the soluble salt in the topsoil could be dissolved, and moved to a depth of the field with the infiltration, improving the effect of salt leaching [19].

Salt accumulation in the cultivated soil under brackish water irrigation was mainly induced by the lack of salt leaching and salt upward movement caused by soil evaporation [19,44]. For treatment L1, the shorter straw segments showed a stronger ability to prevent water from seeping down compared to the other treatments, which was reflected by the higher soil moisture content. More water trapped in the straw incorporation layer meant that more soluble salt in the topsoil could be dissolved as the time of water infiltration increased. On the other hand, straw incorporation cut off the capillaries in the soil, which relieved the surface of salt deposition caused by evaporation of the underlying water [40]. For treatment L3, it showed less satisfactory soil improvement results, as expected. Since the cutting length of straw reached 20 cm, that brought difficulties to the implementation of straw incorporation [34]. Most straw segments bared in the field surface, making L3 show a similar effect to straw mulching. Nonetheless, L3 could not be equivalent to straw mulching in the real sense because it had less cover area than the straw mulching, and the straw incorporation uniformity of L3 was not as good as that of L1 and L2, which led to a diminished effect on soil improvement under treatment L3. It follows from what has been said that the long-chopped straw was not suitable for straw incorporation. Comparatively, the shorter straw was an optimization to be incorporated into the cultivated land. However, the present trial could not say for certain whether straw shorter than 5 cm have better improvement effects, especially those cut very fine as powder.

For all treatments, with the continuous irrigation of brackish water, the salinity in the soil has been accumulated at a fairly high level. Compared with the deeper soil, the salt accumulation in the 0–20 cm soil layer in each treatment was more obvious, which has been confirmed by the previous study [39]. Similar patterns were found in 2018, but the SAR of 0–20 cm (5.77, 7.04, 9.15 and 10.43) were obviously lower than that in 2017, and the effects of different lengths of straw incorporated into cultivated fields on soil salinity was more visible, which was likely induced by the impact of continuous straw incorporation [45]. Though we used brackish water for irrigation, some of the salt in the soil can still be leached [13,25], which would be the reason for the decrease of the SAR in 2018. In the present

study, we irrigated every ten days, and straw incorporation could also reduce the evaporation, which means high soil moisture in the topsoil, thus helping to promote the salt leaching. Meanwhile, with the decomposition of straw, more organic matter was released into the soil, and the soil structure is further improved, which might be another reason for the decrease of the SAR in 2018. She et al. [35] also reported that soil biochar amendments could increase SOM, which was essential for water retention in the soils for plant growth, alleviating the adverse effects of salinity. However, no significant differences in SAR were found in the soil depth of 20–40 cm between 2017 and 2018. This might indicate that it needs to take longer for deeper soil layers to reap the benefits of straw incorporation. From what has been discussed above, the results in our study indicated that the application of straw incorporation in agricultural production can help inhibit salt accumulation in the tillage layer, so as to alleviate the negative impact of salt on crop growth.

3.3. Effects of Straw Segment Length on Soil Properties

3.3.1. Main Effects of Straw Segment Length on Soil Properties

Table 4 listed the mean values of bulk density, soil porosity and soil organic matter content at soil depths of 0–20 cm and 20–40 cm through the two summer maize growing seasons and different treatments between two years. All these parameters were significantly influenced by different treatments, while interactive effects only were observed under SOM. For example, the treatments L1, L2 and L3 significantly decreased the bulk density by 7.79%, 5.19% and 3.25% at the top soil layer 0–20 cm and 7.47%, 4.60% and 1.72% at the 20–40 cm soil depth compared with CK, respectively. Similarly, soil porosity and SOM increased with the shorter length of straw incorporated into cultivated fields. For instance, at the soil depth of 0–20 cm, the soil porosity increased by 4.34%, 3.01% and 1.88%, and the SOM increased by 4.5 g kg⁻¹, 3.2 g kg⁻¹ and 2.6 g kg⁻¹ under treatments L1, L2 and L3 compared with CK, respectively. At the soil depth of 20–40 cm, the treatments L1, L2 and L3 increased the soil porosity by 4.72%, 3.02% and 0.94% and increased the SOM by 2.4 g kg⁻¹, 1.9 g kg⁻¹ and 1.5 g kg⁻¹ compared with CK, respectively.

In our experiment, with the straw incorporation and tillage practices, the soil structure was reorganized, resulting in the decrease in the soil bulk density and increase in the soil porosity. Yang et al. [46] revealed that straw incorporation after three years decreased the soil bulk density in the 0–30 cm soil layer by 1.6%–4.7%, which was consistent with our results. Choudhary et al. [47] also reported that soil application with crop residues could mitigate the adverse effect of saline water irrigation. Firstly, when the chopped straw incorporated into cultivated fields, the straw provided the skeleton structure for soil particles to stick together, which promoted the formation of soil aggregate, and the shorter chopped straw were more likely to mix well with the soil, which could provide better conditions for soil recombination [28]. Secondly, the shorter the straw was cut, the easier it was to decompose and release more organic matter in the soil, which had a positive effect on the stability of soil structure. Meanwhile, SOM was essential for plants to absorb water and nutrients from soil, which can help crops reduce adverse responses to salt stress [33]. Thirdly, the straw itself had the properties of porosity and low density. Therefore, the soil bulk density reduced, and the soil porosity increased under the treatments L1, L2 and L3 compared with that under treatment CK. However, the bulk density increased significantly with the comparison of the initial soil bulk density due to the brackish water irrigation.

Table 3. Measured soil EC_{1:5} (dS m⁻¹) under different treatments during each stage of the summer maize growth in 2017 and 2018.

Year	Soil Depth (cm)	Treatment	Seeding Stage	Jointing Stage	Tasseling Stage	Filling Stage	Full Ripe Stage	Soil Salt Accumulation Rate
2017	0–20	L1	10.3 a	52.4 d	62.0 d	74.5 d	103.6 d	9.06 c
		L2	11.3 a	68.4 c	78.5 c	91.6 c	115.7 c	9.24 c
		L3	10.4 a	72.6 b	84.1 b	99.9 b	120.3 b	10.57 b
		CK	10.3 a	78.9 a	91.3 a	108.3 a	128.4 a	11.47 a
	20–40	L1	14.6 a	21.7 c	28.9 d	36.9 d	49.4 d	2.38 c
		L2	14.5 a	23.7 c	35.9 c	40.9 c	57.6 c	2.97 b
		L3	16.1 a	31.5 b	49.5 b	54.9 b	65.6 b	3.07 b
		CK	16.7 a	47.8 a	63.3 a	73.4 a	76.8 a	3.60 a
2018	0–20	L1	19.3 a	49.8 d	70.9 d	101.1 d	130.6 d	5.77 d
		L2	18.6 a	54.2 c	84.2 c	118.0 c	149.6 c	7.04 c
		L3	19.5 a	63.3 b	94.1 b	139.1 b	197.9 b	9.15 b
		CK	18.5 a	92.3 a	123.4 a	170.2 a	211.4 a	10.43 a
	20–40	L1	20.7 a	41.0 d	44.3 d	50.6 d	64.6 d	2.12 d
		L2	18.3 a	49.8 c	54.0 c	61.4 c	72.6 c	2.96 c
		L3	20.8 a	57.5 b	62.2 b	67.7 b	89.8 b	3.31 b
		CK	19.6 a	67.7 a	71.7 a	76.7 a	96.7 a	3.93 a

Note: Different letters in the last column indicate a significant difference ($p < 0.05$) among the treatments in the same year. L1: The cut length of straw was 5 cm, L2: the cut length of straw was 10 cm and L3: the cut length of straw was 20 cm; CK: no straw incorporation.

Table 4. Mean values of soil property parameters, including bulk density, soil porosity and soil organic matter content at soil depths of 0–20 cm and 20–40 cm for different treatments in 2017 and 2018.

Variation	Bulk Density (g cm ⁻³)		Soil Porosity (%)		Soil Organic Matter Content (g kg ⁻¹)	
	0–20	20–40	0–20	20–40	0–20	20–40
Soil depth (cm)						
Year						
2017	1.48 a	1.69 a	44.25 a	36.42 a	6.85 a	5.53 a
2018	1.47 a	1.67 a	44.53 a	36.98 a	6.98 b	5.48 a
Treatment						
L1	1.42 a	1.61 a	46.42 a	39.25 a	8.85 a	6.45 a
L2	1.46 b	1.66 b	45.09 b	37.55 b	7.50 b	5.95 b
L3	1.49 c	1.71 c	43.96 c	35.47 c	6.95 c	5.55 c
CK	1.54 d	1.74 c	42.08 d	34.53 c	4.35 d	4.05 d
ANOVA						
Year	0.51	0.18	0.51	0.18	**	0.07
Treatment	**	**	**	**	**	**
Year × Treatment	0.21	0.59	0.21	0.59	**	**

Note: Values are the average across years or treatments. Different letters in each column indicate a significant difference ($p < 0.05$) among the treatments. Analysis of variation (ANOVA): * and ** mean significance at $p < 0.05$ and $p < 0.01$, and values in ANOVA section mean the level of significance. L1: The cut length of straw was 5 cm, L2: the cut length of straw was 10 cm and L3: the cut length of straw was 20 cm; CK: no straw incorporation.

3.3.2. Interaction Effects of Straw Segment Length and Incorporation Year on Soil Properties

The mean value of SOM at a 0–20 cm soil depth showed a significantly increasing trend as the years increased, and the value of SOM in 2018 was 1.90% higher than that in 2019. Without CK, the figure would be even higher, because continuous use of brackish water irrigation without protective measures could reduce the content of SOM. Yan et al. [48] also demonstrated that microbial activities in the soil were inhibited due to the accumulation of salt in the surface of fields, which was caused by long-term brackish water irrigation, resulting in the reduction of SOM. As presented in Figure 2, the SOM in CK decreased from 7.9 g kg⁻¹ in 2017 to 6.8 g kg⁻¹ in 2018 and from 7.6 g kg⁻¹ in 2017 to 6.5 g kg⁻¹ in 2018 at the soil depths of 0–20 cm and 20–40 cm, respectively. However, significantly increases of the SOM content between the two summer maize growing seasons could be observed in the other treatments. For instance, at the soil depth of 0–20 cm, the values of SOM under treatments L1, L2 and L3 were 3.5, 2.4 and 1.9 g kg⁻¹ larger than that under treatment CK in 2017 and 5.5, 3.9 and 3.3 g kg⁻¹ larger in 2018, respectively. Lower soil bulk density and higher soil porosity meant better soil structure, which guaranteed more water and oxygen in the topsoil for improving the activity of microorganisms and enzymes, thus helping the straw in the topsoil to decompose to produce more SOM [49].

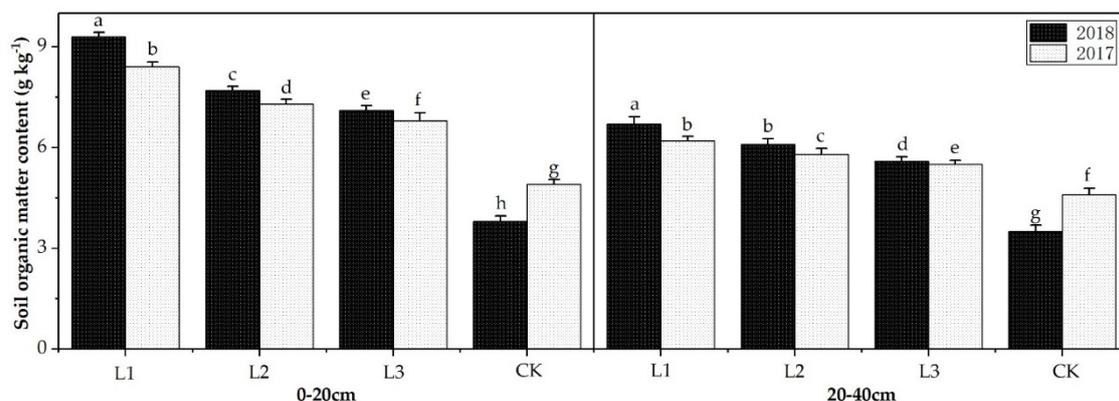


Figure 2. Interaction effect of year and treatment on soil organic matter (SOM) at the soil depths of 0–20 cm and 20–40 cm. Values are means of three replications \pm standard deviation. Different letters indicate a significant difference ($p < 0.05$). L1: The cut length of straw was 5 cm, L2: the cut length of straw was 10 cm and L3: the cut length of straw was 20 cm; CK: no straw incorporation.

The decomposition rate of straw in a high moisture environment was higher than that in a low moisture environment [31]. In the two-year experiment, straw incorporation improved the soil structure and the soil water distribution. More water was stored in the crop root growth layer, which was conducive to the decomposition of straw. Meanwhile, with the decomposition of straw, the soil properties would be further improved, which would form a virtuous cycle. However, the virtuous cycle could not last forever. Singh et al. [50] reported that when straw incorporation was applied to areas with a high carbon content, the improvement effect of straw incorporation on cultivated soil was no longer significant. A similar result was reported by Zhang et al. [51], who found that the soil nutrient and organic matter content increased with the straw incorporated into cultivated fields year after year, until the straw incorporation practice reached 10 years. The upper limit of year of straw incorporation therefore should also be considered.

3.3.3. Relationships between Straw Segment Length and Soil Properties

The linear regressions between soil property parameters and straw segment lengths were established in Figure 3. As Figure 3 illustrated, bulk density was positively correlated with straw length, as well as soil porosity, and the content of SOM negatively correlated to straw length. In the

aspects of bulk density and soil porosity, the slope of the 0–20 cm soil depth were both minor than that of the 0–40 cm soil depth. This might be explained by that the shorter straw segment length increased the response speed of straw incorporation effects on soil properties in the deeper soil depth. In addition, effects of straw incorporation with years on the soil properties could be reflected by the increase of the intercept in 2018 compared with that in 2017. The present study demonstrated that soil properties were further improved with the shorter straw segment length. However, only one variety of straw (wheat straw) was explored in the present study, and other varieties of straw with different compositions had different decomposition patterns. What is more, a trial about the shorter straw length such as straw powder is still needed to be studied further.

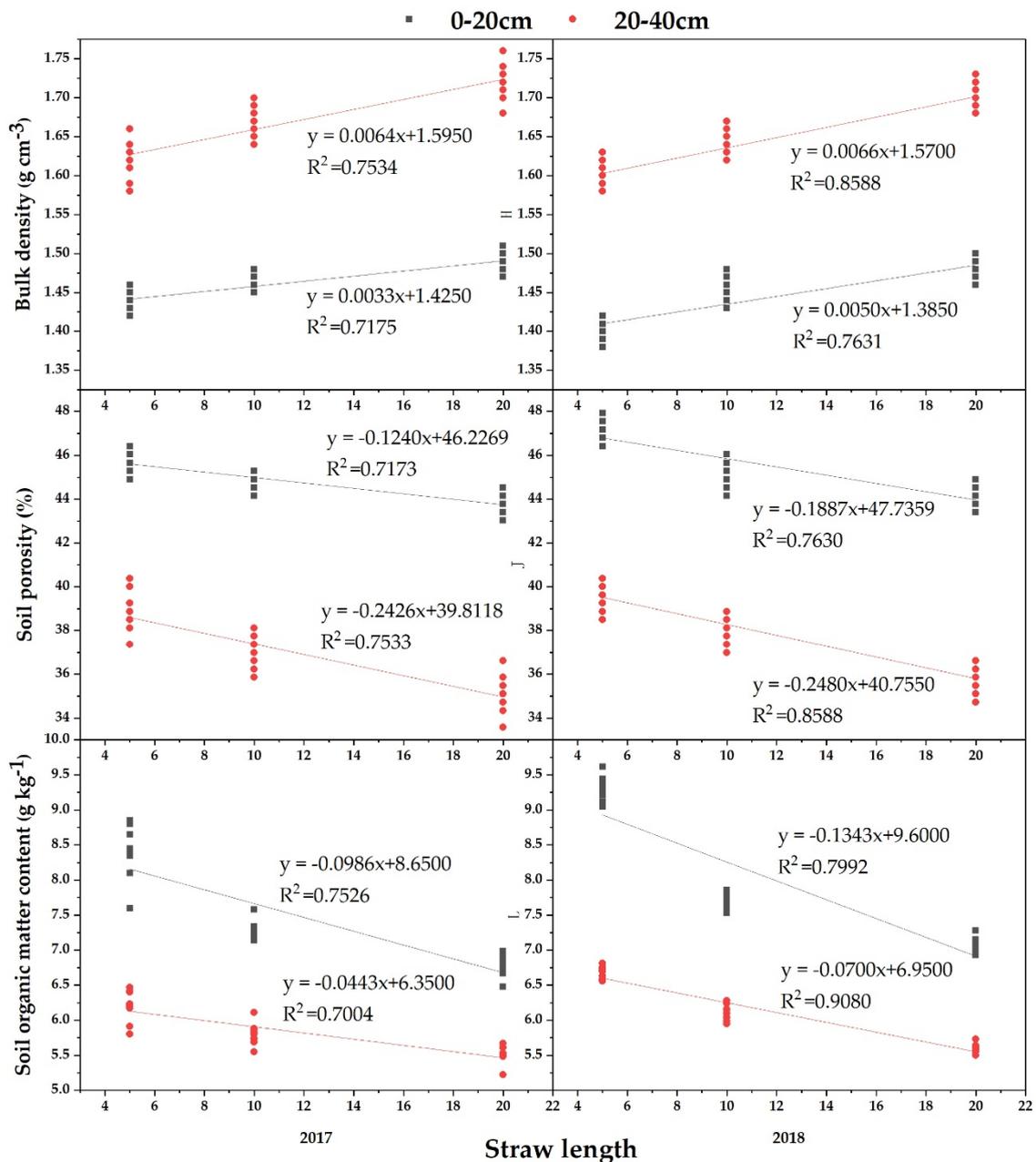


Figure 3. Linear regressions between straw segment lengths with bulk density, soil porosity and the content of SOM at different soil depths of 0–20 cm and 20–40 cm during the two summer maize growing seasons of 2017 and 2018.

3.4. Effects of Straw Length on Plant Growth and Grain Yield

Table 5 listed the mean values of plant height, stem diameter, dry above-ground biomass (DAGB), one hundred-grain weight (100-GW) and grain yield. Both plant growth and the summer maize yield were significantly influenced by different treatments, while no interactive effects were observed. These growth parameters showed a significant increasing trend with a decrease in the straw cut length, which could also be reflected by the greatest DAGB obtained under treatment L1 during the two growing seasons. For example, the mean plant heights under L1, L2 and L3 were 4.5%, 1.8% and 1.3% higher than that under CK, respectively, and the stem diameter showed a similar trend that the average values of 8.8%, 6.7% and 3.8% were significantly greater in L1, L2 and L3 than that in the CK. The better plant growth resulted in the greater DAGB. For instance, the mean value of DAGB under treatments L1, L2 and L3 were 15.5%, 10.3% and 3.7% higher than that under treatment CK. The results in the present study provided evidence that straw incorporation can promote plant growth under brackish water irrigation. In both two growing seasons, the summer maize grain yield significantly increased with the decrease in the straw segment length. The grain yield increment was associated with the increased 100-GW due to the straw incorporation. For example, the mean value of 100-GW under treatments L1, L2 and L3 were 19.0%, 11.2% and 4.7% significantly higher than that under treatment CK, and the average value of grain yield under treatments L1, L2 and L3 were 41.6%, 27.8% and 17.5% significantly higher than that under treatment CK, respectively.

Table 5. Mean values of summer maize growth and grain yield parameters, including plant height, stem diameter, dry above-ground biomass (DAGB) and 100-grain weight (100-GW), for different treatments in 2017 and 2018.

Variation	Plant Height (m)	Stem Diameter (cm)	DAGB (kg ha ⁻¹)	100-Grain Weight (g)	Grain Yield (kg ha ⁻¹)
Year					
2017	2.29 a	2.51 a	13,570 a	31.76 a	6392 a
2018	2.27 a	2.48 b	13,283 a	31.32 a	6070 b
Treatment					
L1	2.34 a	2.59 a	14,447 a	34.52 a	7251 a
L2	2.28 b	2.54 b	13,789 b	32.27 b	6541 b
L3	2.27 b c	2.47 c	12,967 c	30.36 c	6014 c
CK	2.24 c	2.38 d	12,503 c	29.01 d	5120 d
ANOVA					
Year	0.37	**	0.25	0.21	**
Treatment	**	**	**	**	**
Year×Treatment	0.89	0.10	0.31	0.69	0.61

Note: Values are the average across years or treatments. Different letters in each column indicate a significant difference ($p < 0.05$) among the treatments. Analysis of variation (ANOVA): * and ** mean significance at $p < 0.05$ and $p < 0.01$, and values in the ANOVA section mean the level of significance. L1: The cut length of straw was 5 cm, L2: the cut length of straw was 10 cm and L3: the cut length of straw was 20 cm; CK: no straw incorporation.

The effects of salt accumulation in the cultivated soil on the plant growth, which was induced by the brackish water irrigation, could be reflected by the response of the plant growth and grain yield parameters. The decrease in the stem diameter and the weakening of the water uptake ability of the summer maize due to salt stress resulted in the decrease of the DAGB and grain yield. Straw incorporation, as mentioned above, had an excellent performance in improving the soil properties, which can help crops alleviate the adverse effects due to salt stress [52,53]. In the present study, straw incorporation improved the distribution of soil water and enhanced the soil moisture content in the cultivated layer, which thus promoted the summer maize growth. Meanwhile, straw incorporation inhibited the salt accumulation, which created a relatively lower salinity environment for summer maize growth. In addition, straw incorporation promoted the reorganization of cultivated soil, helping

crop roots develop deeper to take low-salinity water in the deeper layers [32]. Additionally, the increase of SOM due to straw applications could increase the phosphorus content in the soil, because the SOM was a major resource of the phosphorus, which was essential for crop growth [54]. In the recent trial, the change of soil environment might be the main reason for the significant difference. Dahri et al. [55] reported that straw incorporation had significant effects on soil properties, as well as on the growth and yield of maize crops in short time. While Prosdocimi et al. [56] found that, after a recent straw application, no effects occurred on soil physical properties. This was not to deny that the straw incorporation method was ineffective. Results obtained in our investigation indicated that the response speed of the straw incorporation effect on soil properties and crop grain yield may be related to the chopped length of straw, and 5 cm could be an optimal length for straw cutting in the straw incorporation practice.

However, the negative impacts induced by brackish water irrigation could not be ignored, especially the reduction of maize grain yield, as straw incorporation just inhibited the salt accumulation in the root layer and thus helped alleviate the salt stress to the maize growth. Main effects of the year were also observed significantly on the stem diameters and grain yield, which could reflect the negative effects of consecutive brackish water irrigation. The stem diameter values decreased 1.21%, and the maize grain yield decreased 5.30% in 2018 compared to that in 2017, respectively. Xu et al. [57] also studied the effects of straw returning on maize yields, and they demonstrated that mean values of maize grain yield under straw returning conditions using freshwater irrigation through three years was 7884 kg ha⁻¹, which was about 10% higher than the grain yield obtained in the present study (6392 kg ha⁻¹ in 2017 and 6070 kg ha⁻¹ in 2018).

4. Conclusions

Brackish water irrigation could accumulate salt in the cultivated soil and induce secondary salinization, which resulted in a remarkable decrement to the summer maize growth and its grain yield. The results in the two-year experiment suggested that straw incorporation was an effective practice to inhibit salt accumulation in the cultivated soil layer, promote the soil properties and increase the summer maize yield under the condition of brackish water irrigation. Compared with the treatment CK, (1) straw incorporation significantly decreased the soil bulk density and increased the soil porosity and soil organic matter content, (2) straw incorporation significantly increased the soil moisture content and decreased the salt accumulation rate in the cultivated soil layer and (3) straw incorporation mitigated the salt stress for the summer maize to guarantee the plant growth and increased the grain yield. In addition, with the shorter cutting length of straw, straw incorporation obtained a better field management result.

The experiment results in our study suggested that 5 cm might be an optimization for straw incorporation practice, which could be helpful for agricultural mechanization to decide the straw cutting length. Compared with the 20 cm, straw with the cutting length of 5 cm could be evenly mixed with the soil, instead of 20 cm straw, most of which were exposed to the field ground, thus losing the respective advantages of standardized straw mulching and straw incorporation. Additionally, a study about whether the shorter straw as straw powder can obtain a better performance or not in agricultural production needs to be studied. Using brackish water for irrigation in the long-term can only be adopted under the condition that the leaching of salts from topsoil is adequate before the next crop season. In addition, only one variety of straw was used in the present study, and the decomposition patterns are different to other varieties. Thus, a longer-term experiment and trial about different varieties of straw is recommended to further evaluate the effects of salt accumulation.

Author Contributions: Conceptualization, Z.Z. (Zemin Zhang) and Z.Z. (Zhanyu Zhang); formal analysis, Z.Z. (Zemin Zhang) and P.L.; funding acquisition, Z.Z. (Zhanyu Zhang) and G.F.; investigation, Z.Z. (Zemin Zhang), P.L. and W.Q.; methodology, Z.Z. (Zemin Zhang) and P.L.; software, Z.Z. (Zemin Zhang) and G.F.; writing—original draft, Z.Z. (Zemin Zhang); and writing—review and editing, Z.Z. (Zhanyu Zhang) and P.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (grant numbers 51579069 and 51879071) and the Fundamental Research Funds for the Central Universities (2019B117114 and 2018B34014).

Acknowledgments: We are grateful for the help of Mingyi Huang and Chengxin Zheng in the implementation of the experiment, as well as the reviewers and editors for helping to improve the manuscript.

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

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