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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 of 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 and 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 occured 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.

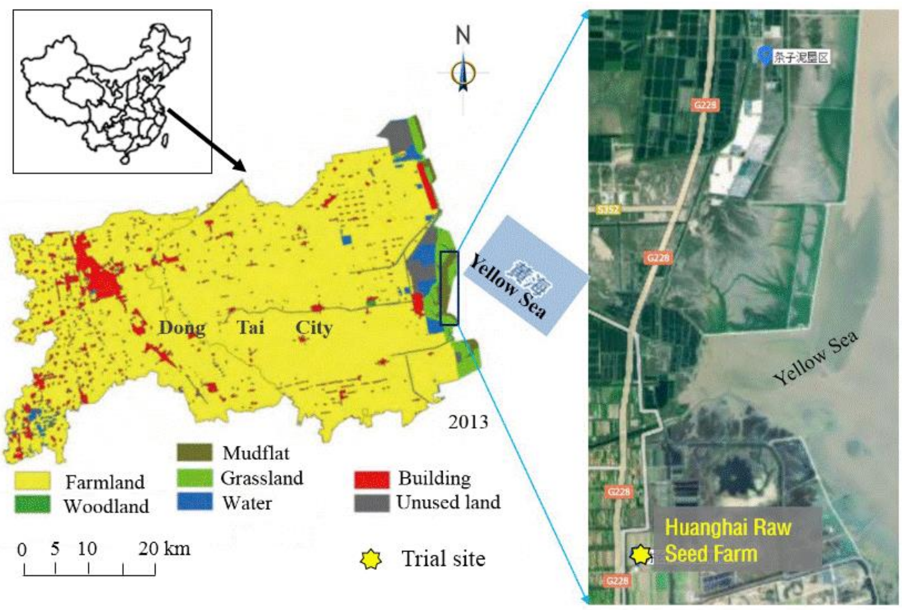

Figure 1. Location of study area.

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} P_2O_5, 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 cm^3) 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 (0.25–2 mm); (3) micro-aggregates (0.25–0.053 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.

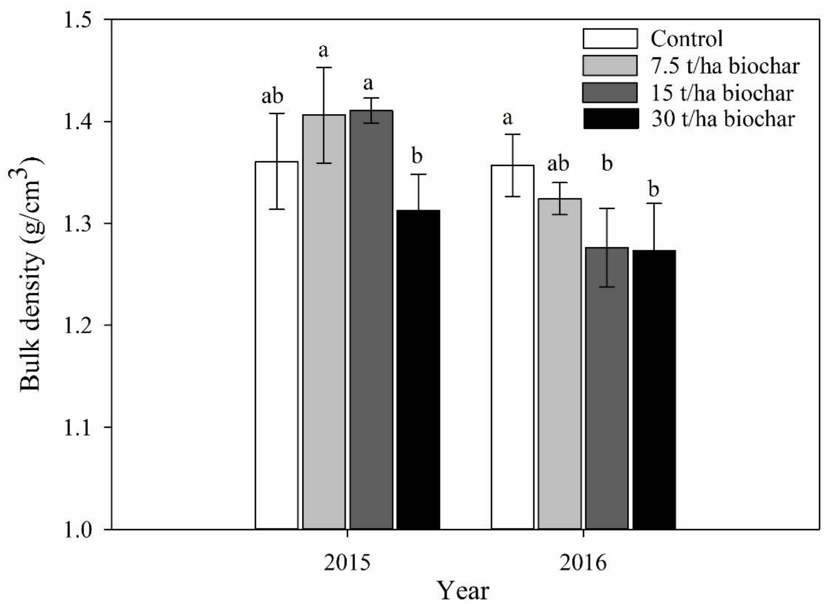

Figure 2. Bulk density (BD) as affected by biochar (BC) treatment. Error bars respresent one standard deviation from the mean. Different letters indicate significant difference ($p < 0.05$) between control and treatments in different years.

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.

		Maize			Barley	
Biochar Rate	**WC**	**SWC**	**FC**	**WC**	**SWC**	**FC**
Mg ha^{-1}	**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.

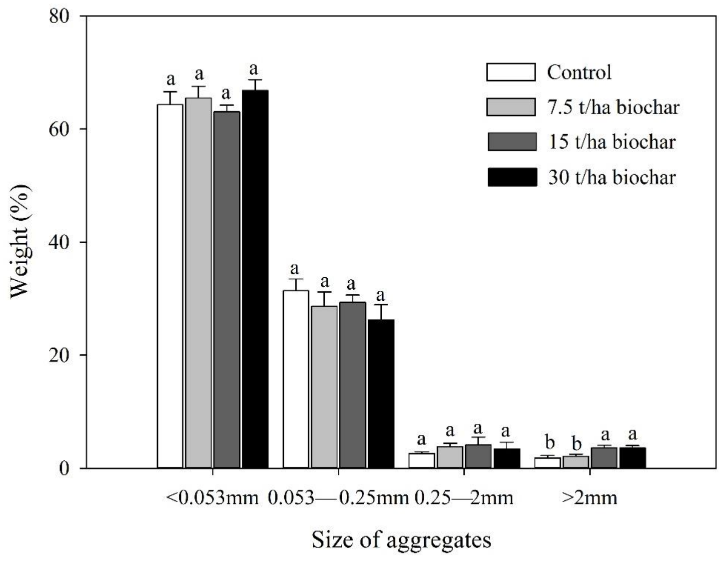

Figure 3. Changes in water stable aggregate percentages of soil as affected by biochar (BC) treatment. Error bars represent one standard deviation from the mean. Different letters indicate significant difference ($p < 0.05$) between control and treatments in different years.

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 ripping 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.

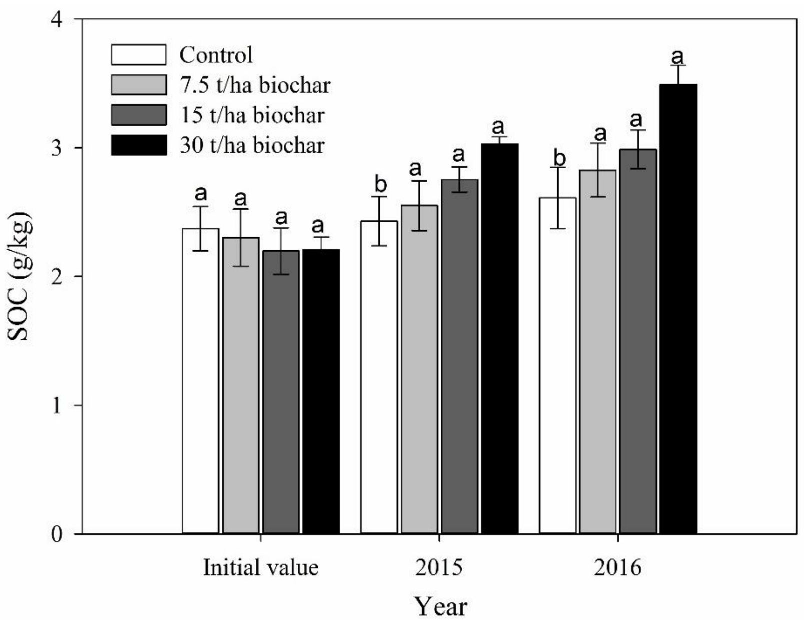

Figure 4. Soil organic carbon (SOC) as affected by biochar (BC) treatment. Values are means ± SD (n = 3). Bars with different letters in each year are significantly different according to LSD at $p < 0.05$.

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	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	
	Rate Mg ha^{-1}	0~20 cm	20~40 cm	0~20 cm	20~40 cm	0~20 cm	20~40 cm	0~20 cm	20~40 cm	0~20 cm	20~40 cm
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	0.49 ± 0.19 a	0.56 ± 0.25 a	0.68 ± 0.27 a	0.52 ± 0.32 c	0.25 ± 0.06 a	0.48 ± 0.26 a
	7.5	0.51 ± 0.34 a	0.79 ± 0.29 a	0.36 ± 0.12 a	0.48 ± 0.17 a	0.47 ± 0.21 a	0.69 ± 0.33 a	0.79 ± 0.30 a	0.66 ± 0.34 a	0.30 ± 0.14 a	0.51 ± 0.22 a
	15	0.50 ± 0.54 a	0.78 ± 0.20 a	0.34 ± 0.18 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	0.32 ± 0.07 a	0.60 ± 0.11 a
	30	0.47 ± 0.14 a	0.83 ± 0.19 a	0.39 ± 0.25 a	0.53 ± 0.23 a	0.58 ± 0.25 a	0.50 ± 0.08 a	0.82 ± 0.24 a	0.62 ± 0.20 a	0.33 ± 0.03 a	0.54 ± 0.11 a
pH	0	9.8 ± 0.3 a	9.3 ± 0.1 a	9.3 ± 0.1 a	9.2 ± 0.2 a	9.1 ± 0.3 a	9.0 ± 0.1 b	8.9 ± 0.1 a	9.1 ± 0.1 a	9.2 ± 0.1 a	9.3 ± 0.1 a
	7.5	9.5 ± 0.7 a	9.5 ± 0.5 a	9.1 ± 0.3 a	9.4 ± 0.4 a	9.2 ± 0.2 a	9.3 ± 0.4 ab	9.1 ± 0.6 a	9.4 ± 0.5 a	9.2 ± 0.3 a	9.4 ± 0.3 a
	15	9.7 ± 0.4 a	9.2 ± 0.3 a	9.2 ± 0.2 a	9.2 ± 0.1 a	9.1 ± 0.1 a	9.0 ± 0.0 ab	8.9 ± 0.1 a	9.2 ± 0.1 a	9.0 ± 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	9.3 ± 0.3 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

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.

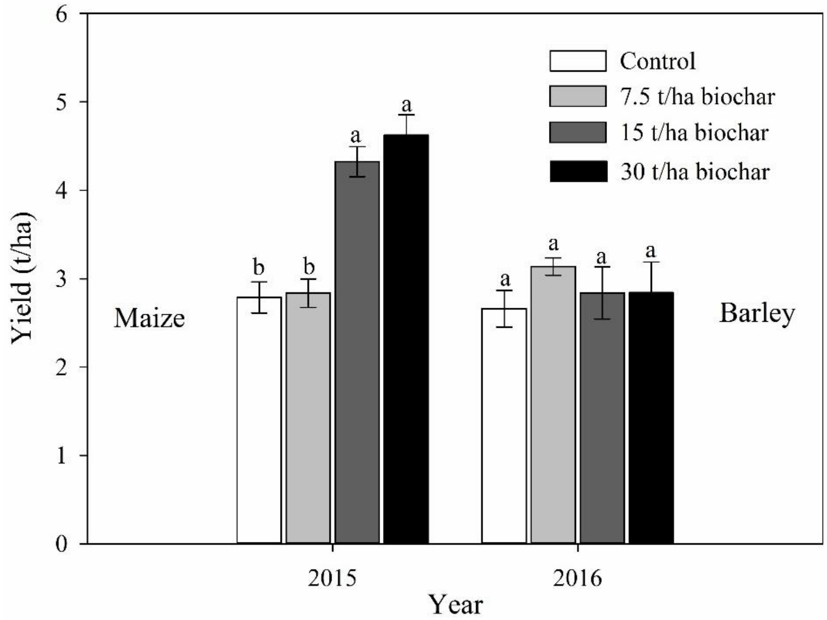

Figure 5. Crop yields of maize and barley as affected by biochar (BC) treatment. Values are means ± SD (n = 3). Bars with different letters in each year are significantly different according to LSD at $p < 0.05$.

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-CO_2 greenhouse gas (GHG) emissions [62]. Some reports have shown that biochar application decreased soil GHGs, including CH_4, N_2O, 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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