



Impact of biochar on red paddy soil physical and hydraulic properties and rice yield over 3 years

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Abstract

Purpose Biochar is a promising soil amendment to improve soil quality. This study was conducted to understand the effect of biochar on soil physical and hydraulic properties and rice yield in a 3-year field experiment in Hunan Province of southern China.

Materials and methods We carried out a field experiment at the red paddy soils for 3 years to study the impact of biochar with different adding rates (at 0, 10, 20, 30, and 40 t/ha) on soil physical and hydraulic properties and rice yield. The clay content, soil bulk density, soil pH, soil organic matter, soil total nitrogen, soil total phosphorus, soil aggregates, the field capacity, the wilting point, the soil available water, and the rice yield were determined to explore long-term improved effects of biochar on soil properties and rice yield.

Results and discussion The results indicated that soil bulk density decreased significantly, but total porosity increased with biochar amendment. Biochar addition also caused macro-aggregates (> 2 mm) to increase and micro-aggregates (< 0.25 mm) decrease significantly, hence improving mean weight diameter of soil aggregates. Biochar addition had positive impact on soil field capacity and soil available water but no effect on soil wilting point. Soil saturated hydraulic conductivity was increased after biochar addition. Consequently, rice yield was increased due to the improvement of soil physical and hydraulic properties.

Conclusions The results showed there were significant differences in soil properties between biochar treatments and the control treatments over the 3-year field experiment, suggesting biochar addition had long-term effect on soil physical and hydraulic properties, as well as increasing rice yield.

Keywords Biochar · Soil physical properties · Hydraulic properties · Soil aggregate · Rice yield

1 Introduction

Long-term application of chemical fertilizers and pesticides has had obvious side effects on the soil environment. A series of issues including diminishing chemical fertilizer efficacy, soil hardening, and alkalization have led researchers to explore sustainable methods to improve soil quality. Lee et al. (2010) investigated the effect of green manure in place of traditional fertilizers on improving rice productivity.

Fontoura et al. (2019) found that liming reduced soil acidity and increased soybean grain yield by 9%.

Biochar is the solid particles formed by pyrolysis of carbon-rich organic material under conditions of high temperature and little or no oxygen. Biochar is regarded presently as an effective soil amendment to reduce carbon dioxide emission, improve soil physical and chemical properties, and increase crop yield (Lin et al. 2017). Evidence shows that biochar has positive effect on soil physical and hydraulic properties (Villagra-Mendoza et al. 2018; Jien et al. 2013). Many studies agree that biochar can directly influence soil bulk density (BD). According to Bruun et al. (2012), smaller biochar particles could increase BD when added to sandy soil because biochar fills the common large pores in sandy soil; larger biochar particles decrease soil BD due to formation of pores between biochar and soil particles. So far, there is no specific classification standard for

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biochar particle size. The effect of biochar on each type of soil is diverse, and no final consensus has yet been reached on biochar's effect on soil hydraulic properties (Razzaghi et al. 2020). Lim et al. (2016) and Karhu et al. (2011) found that biochar addition increased water holding capacity; even at the lowest application rate (1%), water holding capacity of the sandy soil increased significantly. Lu et al. (2014) showed that biochar addition increased field capacity (FC) and soil available water (SAW) compared with no-biochar soil. Wang et al. (2019) analyzed the influence of softwood and walnut shell biochars and found that neither had a significant effect on wilting point of selected silty paddy loam soils. This result depends not only on types of soil but also properties of biochar.

Research on biochar's effects on soil properties is extensive, but most researchers have focused on the effects on soil properties in short-term (within a year) experiments (Tamilselvi et al. 2015; Glab et al. 2016). The experiment lasts a short time, and the effect of biochar over a long time on soil properties is unknown. However, it is noticeable that the contact between biochar and soil is a continuous interaction. In this process, biochar could take hundreds of years to fully decompose under various soil conditions and eventually become an important part of soil (Lehmann et al. 2011). Biochar properties change as it ages (Rechberger et al. 2017). In addition, biochar investigations usually have been too idealized to be different from field experiment in most trials (Zhao et al. 2014; Liu et al. 2016). Many factors affect soil properties and biochar aging. For example, ultraviolet light, rainfall, natural leaching, and changing temperature cannot be artificially simulated (Azwa et al. 2013; Tomak et al. 2018). These factors may cause short-term trial results to be opposite to the long-term results.

Therefore, the objectives of this work were to study effects of biochar addition on soil physical (bulk density (BD), total porosity (TP) and mean weight diameter (MWD)), and hydraulic properties (field capacity (FC), WP (wilting point), soil available water (SAW) and saturated hydraulic conductivity (SHC)) in paddy soil for 3 years after amendment at four biochar application rates; to determine rice yields in 2017, 2018, and 2019 after biochar amendment; and to explore relationships between biochar amendment and rice yield. In addition, long-term effects of biochar on soil properties and rice yield were also discussed to provide scientific information for sustainable agriculture.

2 Materials and methods

2.1 Study area

The study area is located at Chunlei Agricultural Science and Technology Development Co. LTD, in Changsha county (28°26' N, 113°3' E), Hunan Province, China. This area has a typical subtropical monsoon climate, with an average temperature of 16.8 ~ 18.5 °C, 260-day frost-free period, sunshine duration of 1750 h, and mean annual precipitation of about 1470 mm. The soil type is paddy soil, developed from quaternary red clay. The rice cultivar Shenyou 9519 is traditionally planted.

2.2 Soil and biochar materials

Soil samples in the surface layer (0–20 cm) were collected from the field by a random-sampling method each September of 2017, 2018, and 2019. Rice plant samples were collected at harvest every year. The biochar (BC) used for this study was made from wheat straw and produced at Sanli New Energy Co., LTD in Henan Province, China. The basic properties of soil and biochar are presented in Table 1.

BD Bulk density, *SOM* soil organic matter, *TN* total N content, *TP* total P content, *TK* total K content.

2.3 Field experimental design

In May 2017, the field experiment was set up. Four biochar application rates of BC1 (10 t/ha), BC2 (20 t/ha), BC3 (30 t/ha), and BC4 (40 t/ha) were mixed into the soil surface layer by conventional agricultural tillage and artificial mixing methods. A fifth treatment without biochar addition was the control (CK). Each of the 15 plots had an area of 12 m² (4 m × 3 m), within protective rows and walkways, comprising three replicates of each treatment. Each plot was provided with separate irrigation inlets and drainage outlets. After 25 days undisturbed, rice was transplanted into the field. Rice was transplanted every year in June and harvested in October. Fertilizers were applied at rates of 192 kg/ha K₂O, 120 kg/ha P₂O₅, and 240 kg/ha N. All field management followed local practices throughout the period of rice growth (Chen et al. 2016). Rice was flooded in July and August and drained in September.

Table 1 The basic properties of soil and biochar

Material	Clay content/%	BD/g/cm ³	SOM/g/kg	pH	CEC/cmole/kg	TN/g/kg	TP/g/kg	TK/g/kg
soil	23.9	1.45	15.07	4.70	14.95	1.39	-	-
biochar	-	0.65	467.3	10.41	217.2	5.9	14.5	34.97

2.4 Samples determination

Soil properties (clay content, pH, soil organic matter (SOM), total nitrogen (TN), and aggregates) were measured according to Bao (2000). Soil bulk density and saturated conductivity were measured by ring knife method. Soil pH was measured by pH potential method (water and soil ratio 2.5:1). Soil aggregates were determined by wet sieve method (Grunwald et al. 2017). Soil organic matter (SOM) was determined by potassium dichromate external heating (Bao 2000). The soil matrix potential at -33 kPa and -1.5 Mpa were considered as FC and WP by using method of moisture pressure membrane apparatus. The SAW is calculated by using FC minus WP.

2.5 Calculation of mean weight diameter

Mean weight diameter (Talita et al. 2019) is an index of degree of aggregation, defined as follows:

$$MWD = \sum_{i=1}^n x_i \cdot w_i \quad (1)$$

where x_i is mean diameter of each aggregate particle size (mm); w_i is weight percentage of each aggregate particle size (%).

2.6 Calculation of change values

The change value of soil properties (BD, TP, MWD, FC, SAW, and SHC) was calculated by equation:

$$\text{Change} = \frac{V_{BC} - V_{BC'}}{V_{BC}} \times 100\% \quad (2)$$

where V_{BC} is the value of each parameter of samples collected in 2017; $V_{BC'}$ is the value of each parameter of samples collected in 2019.

2.7 Statistical analysis

SPSS 22.0 and Excel were used for classical statistical analyses. Values are expressed as mean \pm STDEV. One-way analysis of variance was used to examine the differences among biochar treatments. In the case of significant effects, individual means were compared by using the Tukey–HSD test at the 0.05 level.

3 Results

3.1 Effects of biochar on BD, TP, and aggregates over 3 years

The effects, over 3 successive years, of one biochar addition on soil BD, TP are summarized in Fig. 1. Overall, biochar addition caused significant BD decrease, and increase of TP. The overall order of soil BD decrease was $BC4 > BC3 > BC2 > BC1 > CK$. In 2017, the BD of the BC1–BC4 treatments decreased by 1.6%, 5.5%, 10.4%, and 13.9% of the CK value, respectively; the change trends and ranges in 2018 and 2019 were basically the same as in 2017. BD change in the BC2, BC3, and BC4 treatments was significant ($P < 0.05$). At 40 t/ha (BC4), soil BD dropped to its lowest value.

Biochar addition had a positive effect on TP. In 2017, the total soil TP of the BC1–BC4 treatments increased by 1.45%, 5.07%, 8.69%, and 10.87% respectively, compared with CK. At 10 t/ha (BC1) and 20 t/ha (BC2), soil TP did not differ significantly ($P > 0.05$) from CK in the same year, but at 30 t/ha and 40 t/ha, soil TP was significantly increased.

Soil aggregates were also influenced by biochar amendment. Significant changes in the diameter distribution of soil aggregates were observed (Table 2). Biochar

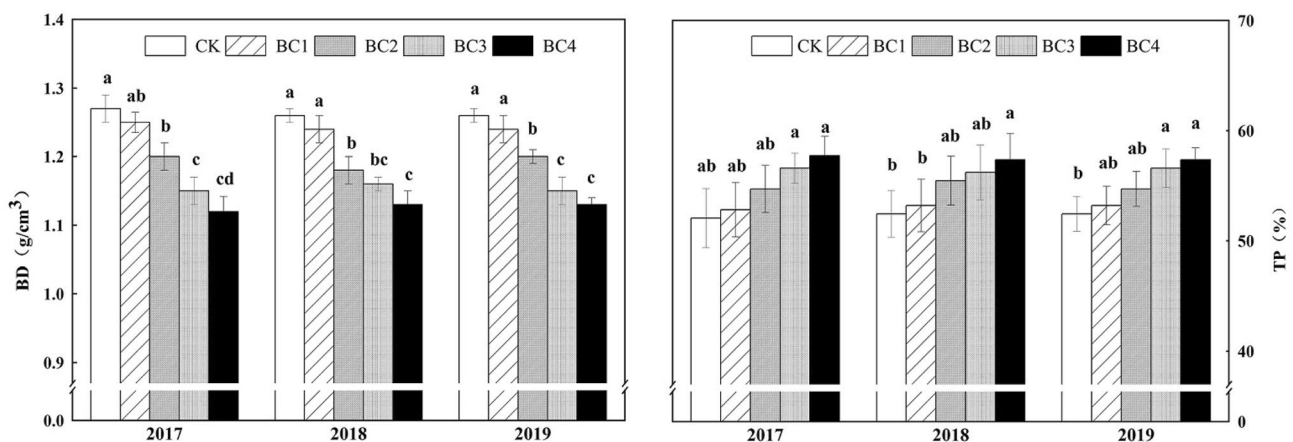


Fig. 1 Effect of biochar on bulk density and total porosity in 3 years. (Different letters indicate significant differences among treatments ($P < 0.05$))

addition increased macro-aggregates (diameter > 2 mm) while decreasing micro-aggregate content (diameter < 0.25 mm). MWD value indicates soil aggregate stability; greater soil aggregation has higher MWD values. On the whole, biochar increased soil macro-aggregates (> 2 mm) by 20–331% of the CK value in 2017. Aggregates sized 1–2 mm increased by 17.5–69.8% compared with CK in the same year. Aggregates of 0.25–1 mm increased by 21 to 35%. Smaller aggregates (0.053–0.25 mm) decreased by 15.2–24.86% and aggregates < 0.053 mm decreased by 1.0–22.5%.

3.2 Effects of biochar on FC, WP, SAW, and SHC in paddy soil

The effects of biochar on soil hydraulic properties FC, WP, SAW, and SHC over 3 successive years are presented in Fig. 2. Significant changes in FC, SAW, and SHC were observed in all 3 years. The biochar addition caused significant increases in FC, SAW, and SHC, and differences relative to CK in these hydraulic properties increased as biochar dosage increased. However, no significant change in WP was observed. Compared with CK in 2017, the FC of soil in the four biochar treatments increased by 5.1%, 8.2%, 13.2%, and 19.2%. Compared with 2017, the range of changes of FC in a given biochar treatment in 2018 and 2019 were 0.6 to 3.39%.

SAW increased significantly after biochar amendment. In 2017, the SAW in the BC1–BC4 treatments increased by 6.6%, 10.8%, 17.1%, and 25.37% respectively, compared with CK. Compared with the same treatment in 2017, SAW

decreased in 2018 and 2019; the decrease range of each treatment was within 0.01–4.62%, with no significant difference between 2 years ($P > 0.05$). These results show that a single biochar addition can affect the SAW in the study area for 3 consecutive years.

Compared with CK, the BC1–BC4 SHC in 2017 increased by 6.72%, 19.8%, 30.2%, and 41.37%, respectively. The SHC decreased in 2018 and 2019, especially in the 40 t/ha plots in 2019. The SHC decreased by 8% compared with that in 2017, and the difference between the CK and BC4 treatments was significant ($P < 0.05$). No significant change was observed in WP.

3.3 The effect of biochar on rice yield and yield components in 3 successive years

The effects of biochar addition on rice yield and yield components in paddy soil are summarized in Table 3. Biochar addition significantly increased rice yield ($P < 0.05$); greater biochar doses produced higher rice yields. The BC1–BC4 treatments in 2017 increased rice yield by 24.4, 27.8, 39.7, and 47.2% of the CK yield, respectively. Rice yields in the second year increased by 18.4, 24.6, 29.9, and 39.8%, respectively, and in the third year increased by 10.9, 13.7, 35.3, and 38.3%, respectively. Table 3 shows the effect of added biochar on rice yield components. Biochar addition significantly increased effective spike number ($P < 0.05$), but no significant changes were found in kernels per spike ($P > 0.05$). A positive effect on thousand seed weight was observed only at the higher biochar application rates (BC3 and BC4). There was no significant difference in thousand

Table 2 Effect of biochar on soil aggregate and mean weight diameters in 3 years (%)

		> 2 mm	1–2 mm	0.25–1 mm	0.053–0.25 mm	< 0.053 mm	MWD/mm
2017	CK	1.86 ± 0.25e	6.53 ± 1.40d	10.88 ± 0.73c	41.33 ± 2.51a	41.03 ± 0.45a	0.25 ± 0.02d
	BC1	2.30 ± 0.75d	7.67 ± 0.08c	13.17 ± 0.40b	35.03 ± 2.90b	40.6 ± 1.08ab	0.28 ± 0.02c
	BC2	3.93 ± 0.36c	10.9 ± 0.10b	13.8 ± 0.74ab	34.50 ± 1.70c	39.70 ± 0.56b	0.36 ± 0.03bc
	BC3	5.93 ± 0.32b	10.9 ± 2.69a	14.3 ± 0.86ab	31.44 ± 3.35c	37.3 ± 2.34bc	0.40 ± 0.02b
	BC4	7.94 ± 0.62a	11.0 ± 0.71a	14.72 ± 0.77a	31.08 ± 3.56c	31.81 ± 32c	0.45 ± 0.01a
2018	CK	5.12 ± 0.60c	7.58 ± 1.81b	16.1 ± 1.55bc	40.35 ± 1.61a	30.74 ± 2.63a	0.37 ± 0.02c
	BC1	5.84 ± 0.30bc	8.23 ± 1.08b	17.54 ± 0.66b	40.34 ± 2.41a	28.0 ± 2.23ab	0.40 ± 0.04bc
	BC2	6.84 ± 1.12b	8.5 ± 1.33ab	17.6 ± 1.83ab	39.95 ± 2.39a	27.08 ± 1.18b	0.43 ± 0.03b
	BC3	7.14 ± 2.51b	8.71 ± 0.85a	18.31 ± 1.93a	37.20 ± 1.16b	26.63 ± 1.07b	0.44 ± 0.02b
	BC4	14.02 ± 3.42a	9.61 ± 1.45a	21.18 ± 1.55a	33.30 ± 0.98c	21.86 ± 1.60c	0.59 ± 0.01a
2019	CK	5.42 ± 0.41d	7.58 ± 0.81c	15.13 ± 1.45c	41.26 ± 1.42a	29.90 ± 2.63a	0.36 ± 0.03c
	BC1	5.82 ± 0.43 cd	8.23 ± 0.43b	17.1 ± 1.02bc	40.43 ± 2.02a	28.35 ± 2.23a	0.38 ± 0.03bc
	BC2	6.44 ± 0.92c	8.4 ± 1.23ab	17.77 ± 1.63b	39.78 ± 1.31a	26.7 ± 2.18ab	0.40 ± 0.01bc
	BC3	7.12 ± 2.43b	8.77 ± 0.64a	19.2 ± 1.84ab	38.1 ± 1.16ab	25.14 ± 1.12b	0.42 ± 0.02b
	BC4	13.04 ± 2.53a	9.73 ± 1.25a	21.88 ± 1.45a	32.24 ± 0.93c	22.11 ± 1.21c	0.56 ± 0.02a

All data are expressed as means plus or minus one standard deviation. The different lowercase letters represent significant differences ($P < 0.05$) between biochar application treatments

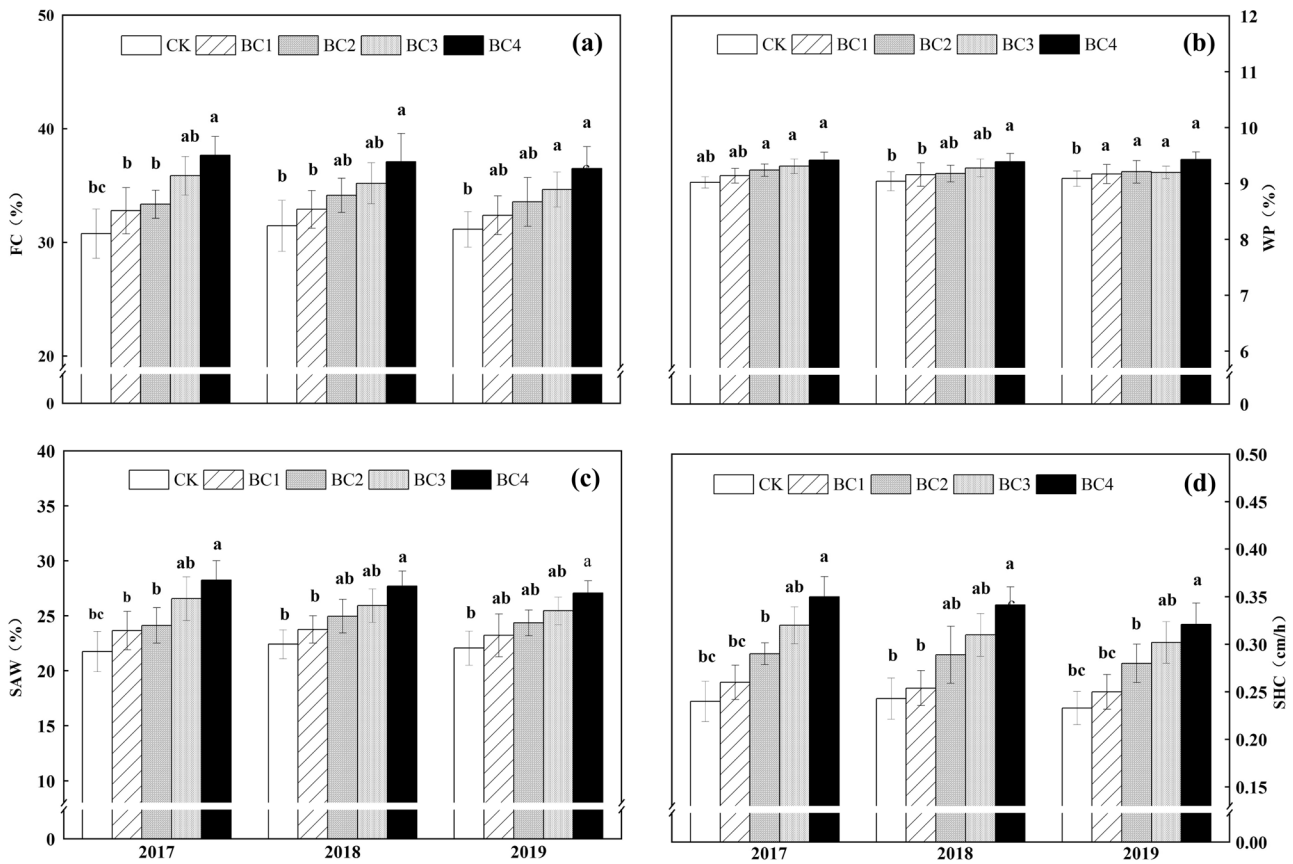


Fig. 2 Effect of biochar on field capacity, wilting point, plant available water, and saturated hydraulic conductivity in 3 years

seed weight at the lower biochar application rates (BC1 and BC2).

Results (Fig. 3) showed that rice yield was closely correlated with soil properties. TP, MWD, FC, SAW, and SHC

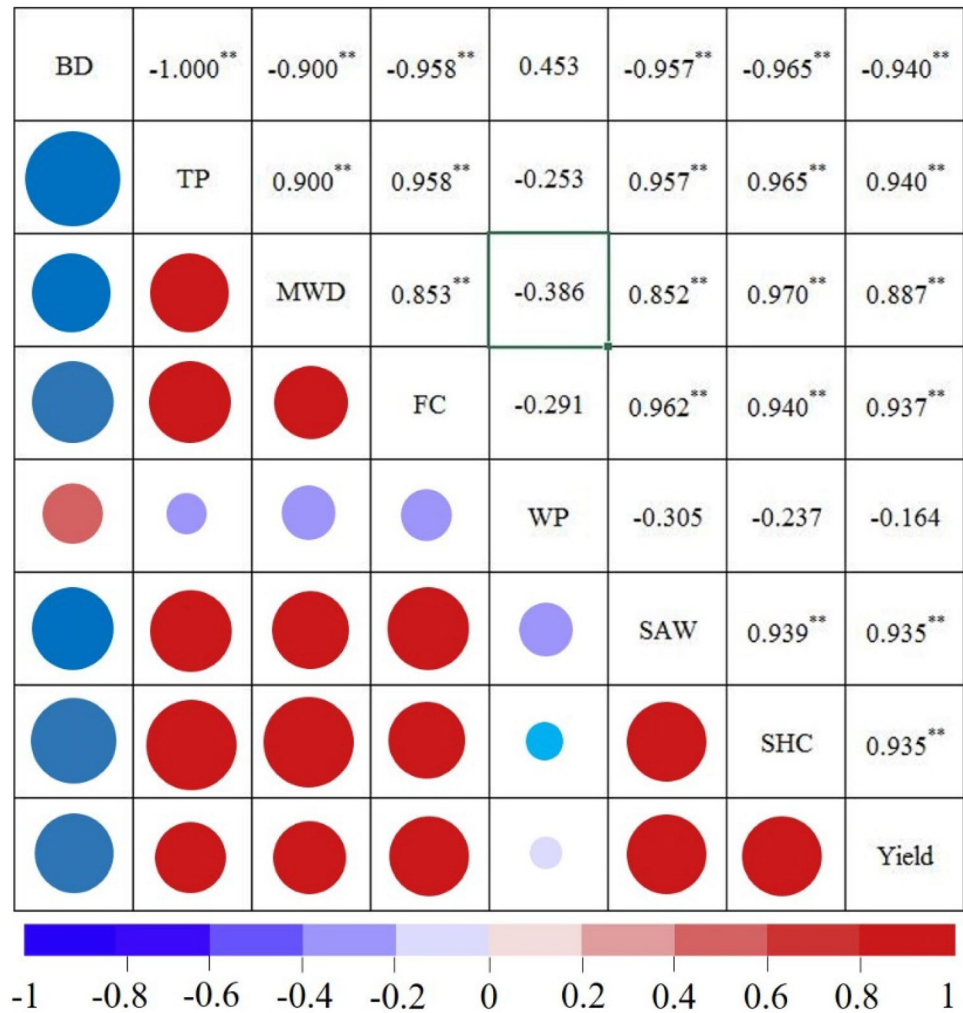
had significant positive correlation with rice yield ($P < 0.01$); BD was significantly negatively correlated with rice yield ($P < 0.01$). No significant correlation was found between rice yield and WP.

Table 3 Rice yield and rice yield components at different biochar addition rates over 3 years

		Effective spike	The number of grains per spike	Thousand seed weight/g	Yield/t/ha
2017	CK	154 ± 10.50d	143 ± 11.00a	18.45 ± 0.54d	4.06 ± 0.17d
	BC1	168 ± 9.45c	150 ± 9.50a	19.23 ± 0.50 cd	5.05 ± 0.12c
	BC2	184 ± 6.93b	143 ± 7.51a	19.74 ± 0.38bc	5.19 ± 0.30bc
	BC3	196 ± 7.77ab	140 ± 10.50a	20.67 ± 0.68ab	5.67 ± 0.26ab
	BC4	207 ± 5.77a	138 ± 7.510a	20.94 ± 0.49a	5.98 ± 0.22a
2018	CK	161 ± 9.50d	136 ± 6.51a	18.35 ± 1.10ab	4.02 ± 0.09d
	BC1	169 ± 10.50 cd	145 ± 11.37a	19.43 ± 0.91ab	4.76 ± 0.22c
	BC2	181 ± 10.59bc	142 ± 11.50a	19.49 ± 1.39b	5.01 ± 0.05bc
	BC3	192 ± 7.51b	137 ± 8.50a	20.24 ± 1.16a	5.32 ± 0.26b
2019	CK	150 ± 7.50d	140 ± 10.50a	19.46 ± 0.94a	4.08 ± 0.11c
	BC1	169 ± 9.02c	138 ± 8.08a	19.60 ± 0.75a	4.52 ± 0.34b
	BC2	173 ± 8.50bc	130 ± 6.03a	20.36 ± 1.53a	4.57 ± 0.27b
	BC3	187 ± 9.50b	142 ± 7.02a	20.88 ± 0.93a	5.54 ± 0.31a
	BC4	203 ± 9.23a	134 ± 8.50a	21.55 ± 1.06a	5.86 ± 0.14a

All data are expressed as means plus or minus one standard deviation. The different lowercase letters represent significant differences ($P < 0.05$) between biochar application treatments

Fig. 3 Correlation analysis between soil properties and rice yield



4 Discussion

4.1 Effects of biochar on soil properties in paddy soil

In this study, we found that soil BD decreased significantly and TP increased after biochar addition, which was attributed to direct and indirect effects of biochar. The direct effect is that biochar amendment reduces the soil density. Because the biochar is porous, its density is lower than the soil density, and the biochar amendment has a dilution effect on the soil (Akhtar et al. 2015). When biochar is added to the soil, the large particles of biochar and small particles of soil form pores, which causes the soil BD to decrease (Garlapalli et al. 2016). The indirect reasons for BD decrease were that biochar addition improved aeration, controlled soil moisture, and added a microbial food source, thereby enhancing microbial activity to loosen the soil (Liao et al. 2016).

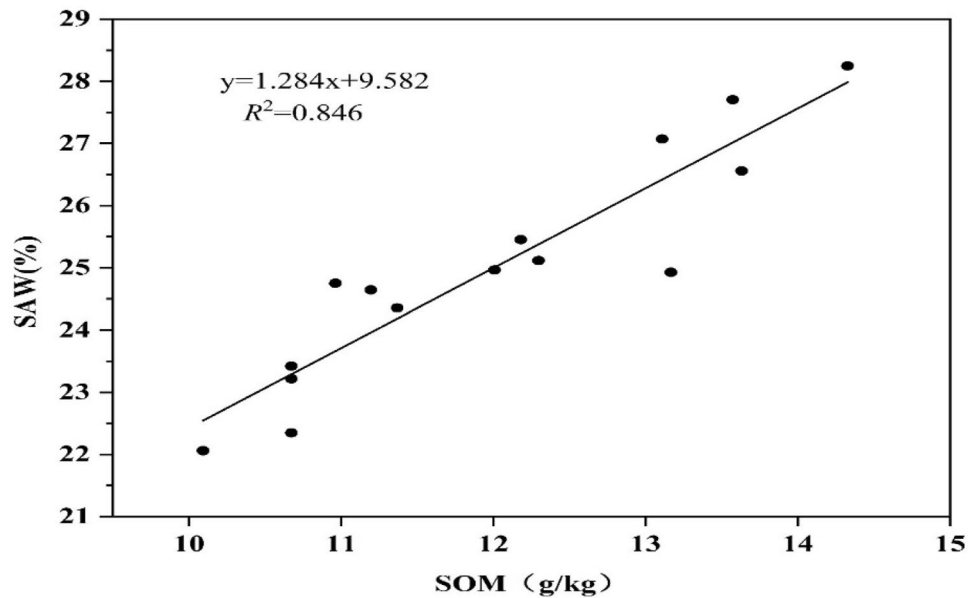
The addition of biochar changed the distribution of soil aggregate sizes significantly, mainly in the form of a significant increase in soil macro-aggregates and a significant

decrease in micro-aggregates, which caused the MWD to increase significantly with the biochar dosage. In this study, the biochar influenced the distribution of soil aggregate sizes in two ways. One was that the large specific surface area and abundant negative charge of biochar accelerated macro-aggregate formation after biochar addition. The other was that positive and negative biochar surface charges can directly bind mineral particles to form macro-aggregates (Jien et al. 2013; Enders et al. 2012). The biochar brought a lot of organic matter into the soil; organic matter is one necessary component of aggregate formation. Organic matter can promote macro-aggregate formation by condensing various tiny colloidal particles.

4.2 Effect of biochar on soil hydraulic properties in paddy soil

The effect of biochar on soil hydraulic properties depends on the soil and biochar types. Karhu et al. (2011) reported FC of loam was increased by 11% when 9 t/ha birch biochar was added in a field experiment. However, Major et al.

Fig. 4 Correlation analysis between soil properties and rice yield



(2010) found no significant change in FC of clay after 20 t/ha biochar addition. Burrell et al. (2016) found straw biochar increased SAW significantly, but woody biochar had little effect on SAW. In this study, biochar addition had a positive effect on soil hydraulic properties. The FC was significantly increased after biochar addition. There was a close relationship between FC and SOM (van Wesemael et al. 2019). Almost all biochar addition can cause a large increase in fresh SOM regardless of biochar type, which was demonstrated by Steinbeiss et al. (2009) and Wu et al. (2017). In this study, measured SAW and SOM from all samples over 3 years are shown in Fig. 4. The SOM had a significant correlation with SAW, $y = 1.284x + 9.582$, $R^2 = 0.846^{**}$ (Fig. 4). The FC increased significantly as SOM increased, but WP remained constant. Therefore, it can be inferred that biochar addition increased SAW by improving soil FC. SHC in this study increased significantly with biochar addition. This is mainly due to the relatively heavy clay soil in the study area. Biochar addition can significantly improve the aeration and permeability of soil.

4.3 The effect of biochar addition on rice yield and yield components in 3 years

In the scientific biochar literature, positive effects on rice yield were observed in approximately half of biochar amendment studies. The other half of these studies found no significant differences or even negative effects on rice yield (Dong et al. 2016; Aller et al. 2018; Liu et al. 2019). The effect of biochar on yield depends on the soil and biochar types as well as agricultural management measures (Carvalho et al. 2016; Si et al. 2018; Oladele et al. 2019). In the present field experiment, the results indicated that a

single biochar amendment could increase rice yield during 3 successive years. Thousand seed weight also increased compared with CK, but the difference was not significant ($P > 0.05$) (Table 3). Biochar addition promotes rice yield due to the increase in nitrogen and phosphorus content in the soil. The improvement effect of biochar on soil properties also played an important role. Pearson's correlation analysis showed that rice yield had close correlation with soil properties (Fig. 3). TP, MWD, FC, SAW, and SHC had significant positive correlation with rice yield ($P < 0.01$). However, soil BD had a significant negative correlation with rice yield. No significant correlation was found between rice yield and WP.

4.4 Long-term effects on soil physical and hydraulic properties over 3 years after biochar amendment

There are many studies on biochar additions to improve soil physical and hydraulic properties (Andrenelli et al. 2016; Castellini et al. 2015). However, most of these results were obtained from indoor pot experiments or short-term trials. Few studies have paid attention to sustainable effects on soil hydraulic properties. In this study, the long-term effect of biochar on soil physical and hydraulic properties was measured in the field. There were significant effects on soil properties (BD, TP, MWD, FC, SAW, and SHC) after 3 years in each biochar treatment (Fig. 5). This suggested that biochar addition had sustainable effects on soil physical and hydraulic properties. Wang et al. (2016) reported that decomposition of biochar was extremely slow under experimental conditions. Biochar could persist in soil for several hundred years, which may indicate that the effects of biochar on

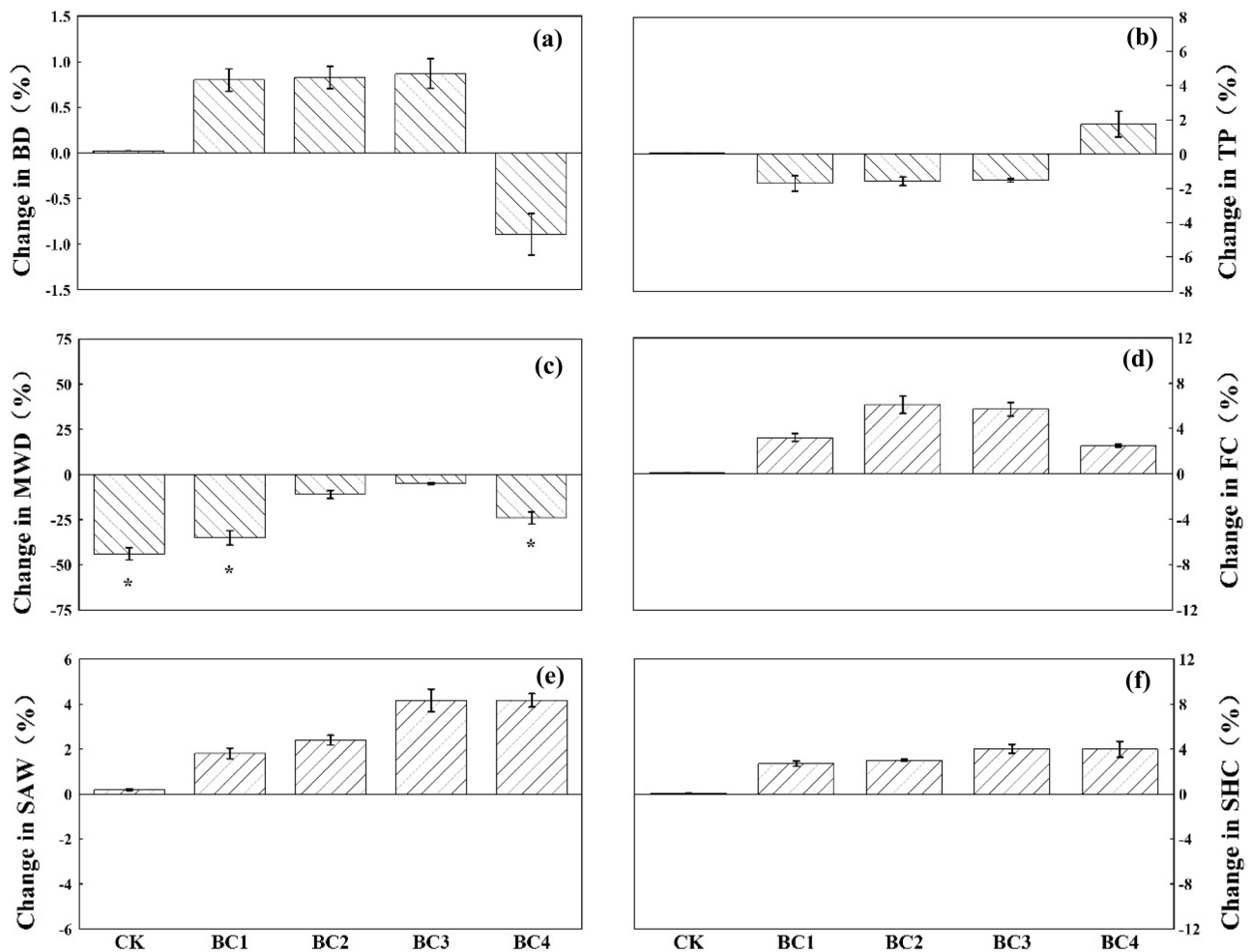


Fig. 5 Three-year changes in soil properties at the same biochar application rate

soil develop as a long-term process. Hardy et al. (2017) also confirmed long-term effect should not be ignored in evaluation of biochar on soil properties because biochar was very persistent in soil.

5 Conclusion

This study demonstrated that biochar addition had positive effect on soil physical and hydraulic properties. Biochar addition can significantly decrease soil bulk density and increase total porosity. Biochar addition also caused a profound increase in macro-aggregates and decrease in micro-aggregates, thus increasing mean weight diameter and improving soil structure. The field capacity, soil available water and saturated hydraulic conductivity were increased after biochar amendment. In addition, biochar addition increased rice yield. This is due to biochar being rich in nutrients and improving the soil physical and hydraulic properties. The results of this 3-year field experiment show that

a biochar amendment has long-term effects on soil physical and hydraulic properties, as well as increasing rice yield.

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