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Effects of biochar on aggregate characteristics of upland red soil in subtropical China

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Abstract Soil aggregation is one of the key properties affecting the productivity of soils and the environmental side effects of agricultural soils. In this study, we aimed to identify whether biochar could be used to improve aggregate stability. A 2-year field experiment was conducted to investigate the effect of biochar application (0, 2.5, 5, 10, 20, 30 and 40 t ha^{-1}) on aggregate characteristics of upland red soil under a rapeseed–sweet potato rotation in subtropical China. Percentage of aggregate destruction (PAD$_{0.25}$), mean weight diameter (MWD), geometric mean diameter (GMD) and fractal characteristics of soil aggregates were measured using both wet and dry sieving methods. Results showed that applying biochar significantly decreased the percentage of aggregate destruction and soil fractal dimension and increased the MWD and GMD. The optimal amelioration was observed when biochar was applied at a rate of 40 t ha^{-1}. The decline of the fractal dimension of dry aggregates was 2–9 times as much as that of water-stable aggregates in the 0–15 soil layer and 1–4 times in the 15–30 cm soil layer. These results suggested that biochar could improve the resistance of aggregates to stresses and provide scientific strategies for the agricultural production.

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Introduction

The soil aggregate, the basic structural unit of soil, plays a crucial role in sustaining soil fertility. A range of factors, including soil fauna, soil microorganisms, roots, inorganic binding agents (e.g., bivalent Ca^{2+} and Mg^{2+} cations), soil organic matter (SOM) and soil moisture, affect the formation and stabilization of soil aggregates (Six et al. 2004; Horn and Smucker 2005). Soil aggregation, in turn, exerts direct and indirect influences on crop growth and yield by modulating various soil processes, such as soil aeration, water infiltration and retention, and by controlling nutrient cycling and root penetration (Bronick and Lal 2005; Denef et al. 2002). Soil aggregate stability is used as an indicator of soil structure (Six et al. 2000). From an agronomic point of view, favorable soil structure for plant growth depends predominantly on the presence of water-stable aggregates with diameters between 1 and 10 mm (Edwards 1991), on account of their beneficial mediation of soil aeration, nutrient cycling, and water infiltration and retention. Additionally, stable aggregates can reduce soil susceptibility to detachment by raindrop impact and transport by runoff, as well as the possibility of forming surface crusts and seals (Martínez-Mena et al. 1999). Usually, four indices have been used to describe soil aggregate characteristics: (1) mean weight diameter (MWD), which is the sum of the mass fraction remaining on each sieve after sieving, multiplied by the mean aperture of the adjacent sieves; (2) geometric mean diameter (GMD) can describe the size distribution of aggregates; (3) fractal dimension (D) can characterize the size and composition of soil aggregate

size, as a description of the characteristics of soil fertility; and (4) the percentage of aggregate destruction (PAD$_{0.25}$; Daniel 1988; Mandelbrot 1982; Burrongh 1983).

Biochar, a predominantly stable, recalcitrant organic carbon compound, is created by pyrolysis of biomass at temperatures between 300 and 600 °C under low or no oxygen conditions (Zhang et al. 2009). Recently, biochar has received extensive attention as a new soil amendment because of its strong alkalinity, well-developed pore structure, large specific surface area and high physico-biological stability (Sohi et al. 2009; Atkinson et al. 2010). The addition of biochar can decrease nitrous oxide and methane emissions from soils (Cayuela et al. 2014; Zhang et al. 2012). It increases crop yield through a combination of factors, including regulation of soil pH (Glaser et al. 2002), stimulation of beneficial soil microbes such as mycorrhizal fungi (Steinbeiss et al. 2009; Warnock et al. 2007), increase in moisture and nutrient retention (Lehmann et al. 2006) and enhancement of crop resistance to disease (Tang et al. 2013). Biochar incorporation into soil has been shown to effectively improve the cation exchange capacity (CEC) of the soil, in particular for calcium (Jien and Wang 2013; Lehmann et al. 2003) which, by replacing Na^+ and Mg^{2+}, can inhibit clay dispersion and the associated disruption of aggregates, thus enhancing aggregate stability (Armstrong and Tanton 1992). Under acidic conditions, the hydroxyl and carboxyl groups on the oxidized biochar surface can also adsorb soil particles and clays to form macroaggregates (Jien and Wang 2013). Natural organic matter plays an important role in soil structure formation, and a strong positive correlation between organic matter and soil aggregate stability has been reported (Tisdall and Oades 1982). However, application of biochar may result in even larger CEC than does natural organic matter due to its larger surface area, higher negative surface charge and surface charge density (Liang et al. 2006).

Investigations on the influences of biochar on agricultural soils have focused mainly on soil nutrients (Yao et al. 2012; Zheng et al. 2013), crop production (Jeffery et al. 2011) and greenhouse gas emissions (Cayuela et al. 2014). Few studies, to date, have examined the influences of biochar on aggregate stability under field conditions, and previous studies typically focused on short-term incubation experiments (Herath et al. 2013; Jien and Wang 2013; Liu et al. 2012; Peng et al. 2011; Soinne et al. 2014). In particular, results from several studies addressing the effects of biochar on soil aggregate characteristics were not consistent with each other, due to different biochar feedstocks, production technologies (e.g., charring temperature and duration) and soil types. Jien and Wang (Jien and Wang 2013) found that applying biochar at the rates of 2.5 and 5% increased MWD of clayey soils after 63-day incubation. Herath et al. (2013) reported that there was a

significant increase in MWD of two silty loam soils with biochar application after 295 days of incubation. Soinne et al. (2014) also observed an increased aggregate stability of two clayey soils with biochar additions at 15 and 30 t ha^{-1}. To the contrary, Liu et al. (2012) indicated that sawdust biochar applied at 4, 8 and 16 g kg^{-1} had no significant effect on the aggregate stability of two sandy loam soils, but increased that of silty loam soils after 11-month incubation. With a field application of an acacia green waste biochar to a loamy sand soil at a rate of 47 t ha^{-1}, Hardie et al. (2014) found no significant change in aggregate stability after 31 months. In summary, the conclusions from previous studies were not consistent with each other and were not always or fully representative of more complicated field conditions in upland red soil. Therefore, data from field experiments are needed.

Red soils (Ultisols, USDA) cover an area of nearly 2.04×10^8 ha in tropical and subtropical regions of southern China (Chen et al. 2009). The red soil regions are considered to be important bases for agricultural production due to abundant rainfall and moderate temperature. Intensive and long-term cultivation, to meet the ever-increasing food demands of booming economic growth, makes soil organic carbon (SOC) more susceptible to mineralization by disrupting larger aggregates more than smaller aggregates (Six et al. 1998). Moreover, torrential rains in summer, together with flowing irrigation water and surface runoff in this area (Ling et al. 2007; Zhang et al. 2007), lead to a decrease in macroaggregates and aggregate stability and thus poorer soil structure (Bronick and Lal 2005; Six et al. 2004). Decreased aggregate stability may decrease rates of water infiltration and increase slaking and crusting, and runoff erosion, thereby negatively affecting crop growth. Favorable soil structure and high aggregate stability are important for enhancing soil porosity, improving soil fertility, increasing agronomic productivity and decreasing soil susceptibility to runoff and erosion (Bronick and Lal 2005; Barthès et al. 2000). Consequently, it is important and urgent to improve soil aggregate stability for food security and sustainable agricultural development in the red soil regions of southern China.

Therefore, the objective of this study was to evaluate to what extent a wheat straw-derived biochar affects soil aggregate composition and aggregate stability in an upland red soil, based on field experiments.

Materials and methods

Study site

The field experiment was conducted under a rapeseed–sweet potato cropping system at the Institute of Red Soil

(28°37′N, 116°26′E), Jinxian County, Jiangxi Province, China. The experiment site is located in a flat area with an elevation of 26 m above sea level. This area belongs to a typical subtropical monsoon climate zone with distinct humid (March–June) and arid (July–September) seasons. The annual average precipitation is 1549 mm, with 61–69% of it falling between March and June. The annual average evaporation is 1100–1200 mm, of which 40–50% occurs during the arid season. The annual average temperature is 17.5 °C, with the lowest monthly average temperature at 5.1 °C in January and the highest monthly average temperature at 29.8 °C in July. The annual average sunshine duration and annual average frost-free duration are 1900–2000 h and 282 days, respectively. The soils were developed from Quaternary red clay. Basic properties of the studied soil are given in Table 1.

Biochar amendment

Biochar was produced from wheat straw pyrolyzed at 450 °C in a vertical kiln made of refractory bricks at Sanli New Energy Company, Henan Province, China. About 35% of the wheat straw dry matter would be converted to biochar during the proprietary pyrolysis process. Detailed procedures of the biochar production have been reported by Pan et al. (2011). In order to mix uniformly with the soil mass, the original biochar in a particulate form was ground to pass through a 2-mm sieve before incorporation into the soil. The basic properties of the biochar are listed in Table 1.

Field experiment

The field experiment was conducted with biochar amendment at the rates of 0, 2.5, 5, 10, 20, 30 and 40 t ha^{-1}, designated as treatment C_0, C_1, C_2, C_3, C_4, C_5 and C_6, respectively. Each treatment was carried out in triplicate. Each trial plot covered an area of 20 m^2 (4 m × 5 m), and all the 21 plots (3 × 7) were laid out in a randomized complete block design (Fig. 1). Biochar was uniformly spread on the surface of the red soil and mixed into the soil with spades to a depth of approximately 15 cm on September 22, 2011. Subsequently, we turned the soil two to three times to achieve a thorough mixture of the biochar

and soil. The mixing and turning treatments were also performed for the controls without biochar addition to maintain consistency. No more biochar was supplemented in the subsequent years.

Two crops, rapeseed and sweet potato, were then grown in rotation annually with rapeseed planted in October and harvested in mid-May, and the sweet potato planted in late May and harvested in late September.

Soil sampling and measurement

Soil samples were collected at depths of 0–15 cm (topsoil) and 15–30 cm (subsoil) after rapeseed harvesting in mid-May 2013. In each plot, undisturbed soil samples were collected from five randomly selected locations with a flat, square-cornered spade after the removal of visible plant residues. Then, the samples were mixed to form one representative sample for each soil layer. Subsequently, all the soil samples were transported to the laboratory in aluminum containers within 2 days. Much attention was paid to the soil samples to maintain their structures intact during the transportation. The large soil clods, while still moist, were gently broken along natural fracture lines by hand, passed through a 10-mm sieve (Chenu et al. 2000), and then air-dried at room temperature for measurement.

The composition of soil aggregates was determined with the routine dry and wet sieving methods (Institute of Soil Science, Chinese Academy of Science 1978). Briefly, an air-dried soil sample weighting 100 g was sieved manually on a column of four sieves: 2, 1, 0.5 and 0.25 mm. The stack was shaken horizontally by hand at a rate of 30 strokes per minute for 2 min. The weight percentage of each aggregate-size fraction was calculated. Composite soil samples for wet sieving were made by blending all fractions of dry aggregates proportionally. Exactly 50 g of soil integrated from the above steps was put on the first sieve of the same set in a water bucket containing deionized water and was gently moistened for 10 min so as to drive entrapped air from the aggregates. The >2 mm aggregates were separated by moving the sieve vertically with a speed of 30 strokes min^{-1} for 5 min. Lastly, soil fractions remaining on the sieves were separately collected, oven-dried and weighed to get a constant mass.

Table 1 Basic properties of the upland red soil and biochar

	pH	SOC (g/kg)	TN (g/kg)	CEC (cmol/kg)	Bulk density (g/cm^3)	Surface area (m^2/g)	Ash content (%)	Textural composition (%)		
								Clay	Silt	Sand
Topsoil/0–15 cm	4.54	9.45	1.06	15.2	1.23	–	–	31.60	39.12	29.28
Subsoil/15–30 cm	5.00	7.79	0.90	17.5	1.49	–	–	37.44	37.44	25.12
Biochar	10.35	467.2	5.9	21.7	0.65	8.92	20.8	–	–	–

Fig. 1 Field experiment

Calculation of soil aggregate characteristic indices

The percentage of aggregate destruction ($PAD_{0.25}$), mean weight diameter (MWD), geometric mean diameter (GMD) and fractal dimension (D) were calculated as follows (Wu et al. 2012):

$$PAD_{0.25} = \frac{m_d - m_w}{m_d} \times 100 \quad (1)$$

where m_d is the weight ratio of dry aggregates with diameter >0.25 mm, and m_w is the weight ratio of water-stable aggregates with diameter >0.25 mm.

$$MWD = \sum_i^n \overline{d_i} W_i \quad (2)$$

$$GMD = \exp\left[\sum \log \overline{d_i} W_i / W_T\right] \quad (3)$$

where $\overline{d_i}$ is the average diameter of the openings of two consecutive sieves; W_i is the weight ratio of aggregates remained on the ith sieve, and W_T is the cumulative weight of all aggregate-size fractions.

Fractal dimension was applied to assess soil aggregate stability using the weight distribution of particles instead of the size distribution of particles due to fractal characteristics of soil (Tyler and Wheatcraft 1992; Yang and Luo 1993). The smaller the fractal dimension, the higher the soil stability to resist mechanical or water dispersion. The fractal formula was defined as follows:

$$\frac{W(r < \overline{d_i})}{W_T} = \left[\frac{\overline{d_i}}{d_{max}}\right]^{3-D} \quad (4)$$

where, d_i is the diameter of the ith sieve; d_{max} is the average diameter of the largest soil particles; $W(r < \overline{d_i})$ is the cumulative weight of soil aggregates with the diameter less than d_i; and D is the fractal dimension. Logarithmic transformation was performed on both sides of Eq. (4), and then, linear approximation was conducted with $\lg\left[\frac{W(r<\overline{d_i})}{W_T}\right]$ as the abscissa and $\lg\left[\frac{\overline{d_i}}{d_{max}}\right]$ as the ordinate. D was obtained from the slope of the curve.

Statistical analysis

All statistical data analyses were performed using the SPSS software package (version 20.0), including analysis of variance (ANOVA). The results were expressed as mean ± standard error and considered significantly different at $p < 0.05$.

Results

Biochar impacts on the composition of aggregates

The composition of dry aggregates as affected by biochar amendment

The size distributions of the dry aggregates in the topsoil and subsoil under the different treatments are presented in Table 2. The results showed that the biochar amendment had a significant ($p < 0.05$) influence on the composition of dry aggregates when measured about 2 years after it was incorporated.

In the topsoil, all biochar-amended treatments except C_1 caused 22, 22, 63, 93 and 143% increases in the percentage of >2 mm dry aggregates relative to C_0 treatment. Significant differences were found among the C_4, C_5 and C_6 treatments ($p < 0.05$). The C_6 treatment significantly increased the percentage of 2–1 mm dry aggregates by 11% as compared to C_0 treatment, while no significant differences were observed among the other treatments ($p < 0.05$). The C_4, C_5 and C_6 treatments had significantly lower microaggregate (<0.25 mm) content than the other treatments, and the >2 mm fraction predominated in these treatments ($p < 0.05$). Macroaggregates (2–0.5 mm) accounted for more than 50% of whole soil weight in C_0 treatment, whereas soil was mainly composed of the >1 mm aggregates for both C_5 and C_6 treatments.

In the subsoil, biochar-amended treatments increased the >2 mm fraction by 22–83% and the 2–1 mm fraction by 10–56%. The greater the applied amount of biochar, the larger were the increases in the percentage of >2 and

Table 2 Effect of different application rates of biochar on the composition of dry aggregates

Depth (cm)	Treatment	Size of soil aggregate (%)				
		>2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm	<0.25 mm
0–15	C_0	15.40 ± 0.94e	22.75 ± 0.87b	26.25 ± 0.69a	19.47 ± 0.84ab	16.11 ± 1.52a
	C_1	17.12 ± 1.91de	22.41 ± 2.10b	27.06 ± 1.96a	19.45 ± 1.06ab	13.93 ± 0.74b
	C_2	18.80 ± 0.87d	21.05 ± 1.67b	26.25 ± 0.80a	21.08 ± 0.80a	12.78 ± 0.75bc
	C_3	18.73 ± 1.01d	22.96 ± 0.84ab	26.28 ± 0.27a	19.67 ± 0.65ab	12.36 ± 0.53c
	C_4	25.09 ± 1.59c	22.27 ± 0.72b	22.43 ± 1.08b	19.25 ± 0.52ab	10.96 ± 0.62d
	C_5	29.78 ± 0.24b	23.09 ± 0.08ab	20.12 ± 0.36c	18.01 ± 0.11b	8.98 ± 0.06e
	C_6	37.43 ± 1.37a	25.34 ± 1.40a	19.38 ± 1.11c	11.05 ± 1.81c	6.80 ± 1.01f
15–30	C_0	10.68 ± 1.13e	17.36 ± 1.17e	30.68 ± 1.18a	22.39 ± 1.86a	18.89 ± 0.57a
	C_1	13.14 ± 1.14d	19.02 ± 0.66d	29.47 ± 0.55ab	20.45 ± 1.26a	17.90 ± 0.77ab
	C_2	14.36 ± 0.96d	19.55 ± 0.50d	29.43 ± 0.71ab	20.27 ± 1.15a	16.37 ± 1.06b
	C_3	15.95 ± 0.06c	22.07 ± 0.98c	28.26 ± 0.16b	17.47 ± 0.47b	16.23 ± 0.72b
	C_4	17.98 ± 0.92b	24.86 ± 0.43b	26.82 ± 0.69c	16.38 ± 1.51bc	13.96 ± 0.43c
	C_5	19.68 ± 0.92a	27.27 ± 0.79a	25.66 ± 0.57c	14.91 ± 0.54c	12.48 ± 0.76 cd
	C_6	19.51 ± 0.74a	27.05 ± 0.49a	26.23 ± 0.99c	16.39 ± 1.03bc	10.81 ± 1.86d

Different lowercase letters in the same column indicate significant differences ($p < 0.05$) among treatments in the same soil layer

2–1 mm aggregates. However, there were no statistically significant differences in both >2 and 2–1 mm fractions between C_1 and C_2 treatments, nor between C_5 and C_6 treatments ($p < 0.05$). The soil aggregate composition was dominated by the 1–0.25 mm fractions in C_0 treatment, while the C_5 and C_6 treatments showed the largest proportion of 2–0.5 mm aggregates. So the biochar increased the percentage of dry aggregates (>2 mm) in upland red soil.

The composition of water-stable aggregates as affected by biochar amendment

The particle size distributions of the water-stable aggregates as affected by biochar amendment are shown in Table 3. The particle size distributions of the water-stable aggregates differed from those of dry aggregates. The percentages of water-stable macroaggregates (>0.25 mm) increased with the decline of particle size in both soil layers. There existed a significant increasing trend of >0.5 mm fraction and a significant decreasing trend of <0.25 mm fraction with the increase in biochar application ($p < 0.05$). Compared with C_0 treatment, the biochar application corresponding to 10, 20, 30, 40 t ha^{-1} (i.e., C_3, C_4, C_5 and C_6 treatments) resulted in significantly higher >2, 2–1 and >0.5 mm fractions in topsoil and subsoil ($p < 0.05$). The C_6 treatment significantly enhanced the three fractions by 106, 79 and 109% in topsoil, respectively, and enhanced the 2–1 and 1–0.5 mm fractions by 91 and 165% in subsoil ($p < 0.05$). The C_3, C_4, C_5 and C_6 treatments showed significantly lower contents of

<0.25 mm fraction than C_0 treatment in both soil layers. The differences were statistically significant among C_4, C_5 and C_6 treatments ($p < 0.05$).

Biochar-amended soils generally had relatively high proportions of >1 mm dry aggregates, but the disintegration of macroaggregates into microaggregates (<0.25 mm) after wet sieving led to a great reduction in the percentage of >1 mm water-stable aggregates (Tables 2, 3). Hence, the composition of water-stable aggregates was dominated by the <0.25 mm fraction in both soil layers when the biochar was applied at the rates of 0–20 t ha^{-1}. The >0.25 mm water-stable aggregates did not make up the largest percentage of whole soil weight until the amount of biochar reached 30 t ha^{-1}.

Biochar can enhance the content of water-unstable macroaggregates, but its influence on water-stable aggregates was relatively limited. Biochar application promoted the formation and stabilization of macroaggregates, and there might be a consistent relationship between the application amount and the proportion of all fractions. When biochar was applied at comparatively low rates (i.e., less than 10 t ha^{-1}), the 2–0.5 mm dry aggregates were the main fractions in topsoil. The fraction of larger macroaggregates increased with the increase in biochar application, and when the application rate was raised to 30 t ha^{-1} (C_5 treatment), the >2 and 2–1 mm fractions were more than 50% of total soil weight in the topsoil. However, macroaggregates (>1 mm) decreased substantially after wet sieving. The percentage of >1 mm water-stable aggregates was less than 10% of all aggregate-sized fractions in both soil layers in C_0 treatment. Although there existed

Table 3 Effect of different application rates of biochar on the composition of water-stable aggregates

Depth (cm)	Treatment	Size of soil aggregate (%)				
		>2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm	>0.25 mm
0–15	C_0	3.59 ± 0.52d	4.87 ± 0.54d	10.39 ± 1.10e	23.17 ± 0.25a	57.99 ± 1.88a
	C_1	4.35 ± 0.41cd	4.70 ± 0.67d	12.43 ± 1.23d	20.92 ± 0.87b	57.61 ± 1.07a
	C_2	4.42 ± 0.13cd	5.35 ± 0.87cd	14.91 ± 1.13c	18.81 ± 0.60c	56.5 ± 0.95ab
	C_3	4.62 ± 0.52c	5.99 ± 0.49c	15.95 ± 0.40c	19.23 ± 0.71c	54.21 ± 0.54b
	C_4	4.92 ± 0.64c	6.33 ± 0.07bc	17.99 ± 0.93b	19.25 ± 0.79c	51.51 ± 2.35c
	C_5	6.42 ± 0.41b	7.25 ± 0.29b	19.16 ± 0.43b	22.05 ± 0.89ab	45.11 ± 0.16d
	C_6	7.38 ± 0.42a	8.74 ± 0.69a	21.67 ± 0.41a	21.41 ± 1.09b	40.8 ± 0.59e
15–30	C_0	2.58 ± 0.63c	3.49 ± 0.51d	8.30 ± 0.88e	20.67 ± 1.29b	64.96 ± 1.72a
	C_1	2.90 ± 0.73c	4.09 ± 0.15cd	11.46 ± 0.40d	17.59 ± 1.16c	63.96 ± 0.48a
	C_2	3.04 ± 0.75c	4.18 ± 0.12c	12.92 ± 1.37d	16.18 ± 0.61c	63.68 ± 1.63a
	C_3	4.00 ± 0.16b	4.50 ± 0.51c	15.70 ± 0.41c	17.60 ± 0.33c	58.20 ± 0.82b
	C_4	4.23 ± 0.30b	5.55 ± 0.23b	17.10 ± 0.25c	19.77 ± 0.53b	53.35 ± 0.41c
	C_5	4.54 ± 0.32ab	5.57 ± 0.28b	19.38 ± 0.40b	22.88 ± 0.49a	47.62 ± 0.45d
	C_6	5.43 ± 0.43a	6.67 ± 0.61a	22.03 ± 1.66a	22.79 ± 0.72a	43.08 ± 2.26e

Different lowercase letters in the same column indicate significant differences ($p < 0.05$) among treatments in the same soil layer

significant increases of >1 mm water-stable aggregates in C_5 and C_6 treatments compared to the control ($p < 0.05$), the proportions of >1 mm water-stable aggregates were still no more than 20% of all fractions.

Biochar impacts on soil aggregate stability

Biochar impacts on the percentage of aggregate destruction ($PAD_{0.25}$)

The biochar application exerted a significant influence on $PAD_{0.25}$ ($p < 0.05$). As shown in Fig. 2, at biochar application rates of 20, 30 and 40 t ha^{-1} (C_4, C_5 and C_6 treatments), the $PAD_{0.25}$ in the topsoil was 9, 20 and 27% lower than in C_0 treatment, respectively. The C_5 and C_6 treatments had a significant lower $PAD_{0.25}$ than the other treatments ($p < 0.05$). No significant difference was found between these two treatments ($p < 0.05$). In the subsoil, the $PAD_{0.25}$ of soils amended with biochar amendment decreased by 0–36% as compared to C_0 treatment. The $PAD_{0.25}$ in C_3, C_4, C_5 and C_6 treatments was significantly lower than that in the other treatments ($p < 0.05$). The C_6 treatment showed the largest decrease in $PAD_{0.25}$ in both topsoil and subsoil, which was consistent with the lower percentage of <0.25 mm water-stable aggregates in these treatments.

Biochar impacts on mean weight diameter (MWD) and geometric mean diameter (GMD)

Biochar had significant effects on MWD and GMD of both dry aggregates and water-stable aggregates ($p < 0.05$). The MWD and GMD of different treatments after dry and wet

sieving both ranked in the order of amendment rate in the two soil layers, $C_6 > C_5 > C_4 > C_3 > C_2 > C_1 > C_0$ (Fig. 3).
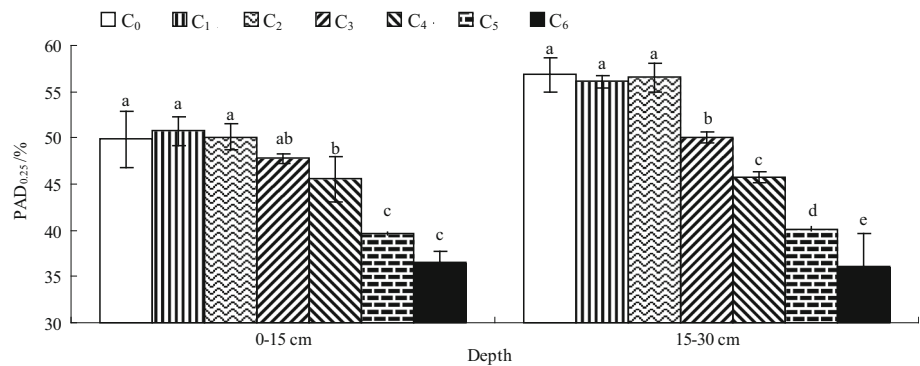
In the topsoil, the biochar-amended treatments enhanced the MWD of dry aggregates by 3, 4, 6, 15, 23 and 39%, respectively, relative to C_0 treatment. The MWD of dry aggregates in C_3, C_4, C_5 and C_6 treatments was significantly higher than in the other treatments ($p < 0.05$). There were significant differences among these four treatments ($p < 0.05$; Fig. 3a). In the subsoil, the C_3, C_4, C_5 and C_6 treatments significantly increased the MWD of dry aggregates compared with C_0 treatment, but the difference was not significant between C_5 and C_6 treatments ($p < 0.05$; Fig. 3a). The variation trend of GMD was completely consistent with that of MWD after dry sieving analysis (Fig. 3b). In contrast to C_0 treatment, the soils amended with biochar at the rates of 5, 10, 20, 30 and 40 t ha^{-1} had significantly higher MWD of water-stable aggregates with 8, 12, 17, 27 and 37% increases, respectively, in the topsoil and 8–40% increases in the subsoil ($p < 0.05$). The greatest increase occurred in C_6 treatment in both soil layers (Fig. 3c).

The MWD of dry aggregates was 1.91–2.11 times as much as that of water-stable aggregates, and GMD of dry aggregates was 1.97–2.06 times higher than that of water-stable aggregates, which can be explained by the breakdown of a proportion of water-unstable macroaggregates after immersion in water (Fig. 3d).

Biochar impacts on fractal characteristics of soil aggregates

The results of the ANOVA showed a significant influence of biochar on the fractal dimension (D) of dry aggregates

Fig. 2 Percentage of aggregate destruction ($PAD_{0.25}$) as affected by different application rates of biochar. The *error bar* above the *block* represents the standard deviation of three replicates. *Different lowercase letters* above the *blocks* indicate significant differences ($p < 0.05$) among treatments in the same soil layer

and water-stable aggregates ($p < 0.05$; Fig. 4). After dry sieving, the fractal dimension of soil amended with biochar ranged from 1.819 to 2.134 in topsoil and from 2.007 to 2.238 in subsoil. In the topsoil, fractal dimensions in all the biochar-amended soils were significantly lower than in C_0 treatment with the decrement being 3, 4, 5, 6, 10 and 17%, respectively ($p < 0.05$). The C_5 and C_6 treatments had significantly lower fractal dimensions than the other treatments, and there were significant differences among C_4, C_5 and C_6 treatments ($p < 0.05$). In the subsoil, apart from no significant difference seen between C_0 and C_1 treatments, the other biochar-amended treatments significantly lowered fractal dimensions by 3, 4, 7, 9 and 11%, respectively ($p < 0.05$). The C_4, C_5 and C_6 treatments had significantly lower fractal dimensions than the other treatments. No significant difference was detected between C_5 and C_6 treatments ($p < 0.05$).

The effect of incorporated biochar on fractal dimension of water-stable soil aggregates was slightly different from that on dry aggregates. In the topsoil, the fractal dimension was significantly reduced by 1–6% in C_2, C_3, C_4, C_5 and C_6 treatments, of which fractal dimension in C_4, C_5 and C_6 treatments was significantly lower than that of the other treatments with significant differences among those three treatments ($p < 0.05$). In the subsoil, C_3, C_4, C_5 and C_6 treatments had significantly decreased fractal dimension by 2, 3, 5 and 7%, respectively, and the differences among them were statistically significant, while no significant differences were observed among C_0, C_1 and C_2 treatments ($p < 0.05$).

The fractal dimension of water-stable aggregates was higher, compared to that of dry aggregates. This further demonstrated the breakdown of macroaggregates into microaggregates and the increase in microaggregates (<0.25 mm fraction) after soaking in water, which caused a greater fractal dimension of water-stable aggregates relative to the dry aggregates. In addition, the decrement of dry aggregate fractal dimension was 2.26–9.18 times as great as that of water-stable aggregates in topsoil and 1.68–3.86 times in subsoil, 2 years after biochar application, which

may indicate a more protective effect of biochar on the stability of soil aggregates against mechanical breakdown, than against water dispersion, in upland red soil.

Discussions

Effects of biochar amendment on the composition of dry aggregates and water-stable aggregates

In our study, the increased trend of water-stable macroaggregates (>0.5 mm) after 2-year biochar application indicated that biochar could enhance water stability of aggregates of red soil, which has also been experimentally confirmed by Wu et al. (2012), who amended granite-derived soil with biochar in a field experiment. The experiment suggests that biochar acted as a sorptive surface rather than as a source of cations, and furthermore, the increased sorption of ions supports the formation of cationic bridges. Since drying is an important factor in soil structure formation, the effect of biochar on aggregate stability was compared with that of drying-induced changes during the incubation. Our research indicated that biochar can enhance the content of water-unstable macroaggregates, but its influence on the water-stable aggregates was rather limited. These results may differ with those of Amézketa (1999) which indicated that biochar application, in particular because of its improvement of soil structure and infiltration, also can increase water viscosity, thereby increasing soil aggregation. This may be attributable partly to a low proportion of water-stable macroaggregates in red soil itself and partly to insufficient duration after biochar application. Also, when soaked in water or struck by raindrops, a range of water-unstable macroaggregates would disintegrate into microaggregates, finer and more transportable particles, thus adversely affecting the migration of soil nutrients while simultaneously exacerbating surface runoff and soil erodibility (Le Bissonnais 2016). The problem is particularly acute for the red soil region due to its rainfall intensity
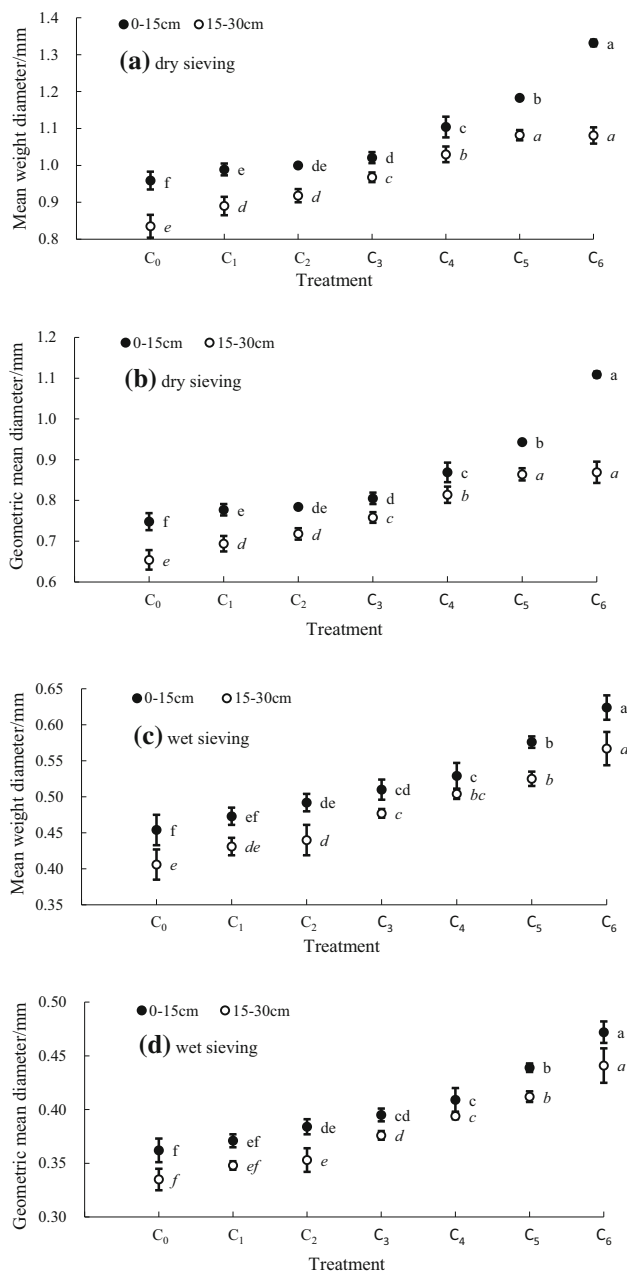
Fig. 3 Effects of different application rates of biochar on MWD and GMD of aggregates by dry and wet sieving. The *error bar* above the *filled* or *hollow dot* denotes the standard deviation of three replicates. *Different roman letters* indicate significant differences ($p < 0.05$) among treatments in the 0–15 cm soil layer; *Different italic letters* indicate significant differences ($p < 0.05$) among treatments in the 15–30 cm soil layer

during the humid season, which denotes a high susceptibility to soil erosion even after biochar application at a rate of 40 t ha^{-1}. Erosion tends to preferentially remove low-density or light particles including clay and SOC that are two of the primary bonding agents in aggregates (Bronick and Lal 2005), which, in turn, exerts a negative effect on aggregate stability. Great attention, in consequence, should

be paid when biochar is applied to the red soils which are susceptible to water erosion.

Effects of biochar amendment on soil aggregate stability and fractal characteristics of soil aggregates

Our research indicates the biochar could decrease the percentage of aggregate destruction (PAD$_{0.25}$) and fractal dimension of soil aggregates. The observed increase in the larger aggregates in the biochar-amended soils (especially in treatments C$_5$ and C$_6$) is probably attributable to the properties of biochar, binding agents and microbial activities. Previous studies indicated that biochar addition could increase the content of inorganic binding agents and microbial activity (Jien and Wang 2013; Lehmann et al. 2011), which contributed to the formation and stabilization of soil aggregates. The inorganic, organic and organo-inorganic compounds in soil act as predominant aggregates. Sesquioxides play a more important role in microaggregation (Yao et al. 1990), while organic matter has a greater effect on macroaggregation (Zhang et al. 1996). Adding biochar likely promoted the formation of humic substances (Hua et al. 2012), which interact synergistically with amorphous iron, aluminum and aluminosilicates to form persistent binding agents (Shi et al. 2002), thereby enhancing aggregation. In addition, Hua et al. (2012) reported that biochar could enhance intergranular porosity and specific surface area in the soil microenvironment, both contributing to an increased accumulation of soil organic matter, which guaranteed a long-term benefit for soil aggregation.

Soil microorganisms are the most active biological factor responsible for soil aggregation. Fungi dominate in macroaggregate formation by reorientation of clay particles, binding particles with extracellular polysaccharides and enmeshing particles with fungal hyphae (Ternan et al. 1996), while bacteria dominate in microaggregation, (Tisdall and Oades 1982) apart from the positive effects on SOM, the high specific surface area and porous characteristics of biochar provide a favorable habitat environment for soil microorganisms. The enhanced soil conditions, either in terms of an altered resource base (e.g., available C, nutrients, water), changes in abiotic factors (e.g., pH, toxic elements), all enable a stimulation of beneficial microbes and facilitation of microbial activity, especially for mycorrhizal fungi (Steinbeiss et al. 2009; Warnock et al. 2007; Lehmann et al. 2011). Moreover, red soils in subtropical China are poor in soil cations, especially in bivalent Ca^{2+} cation, due to strong eluviation. Biochar can improve the exchangeable cation status of the soil, in particular Ca^{2+} (Jien and Wang 2013) which is capable of inhibiting clay dispersion and the associated disruption of aggregates by the replacement of Na$^+$ and Mg^{2+} in clay
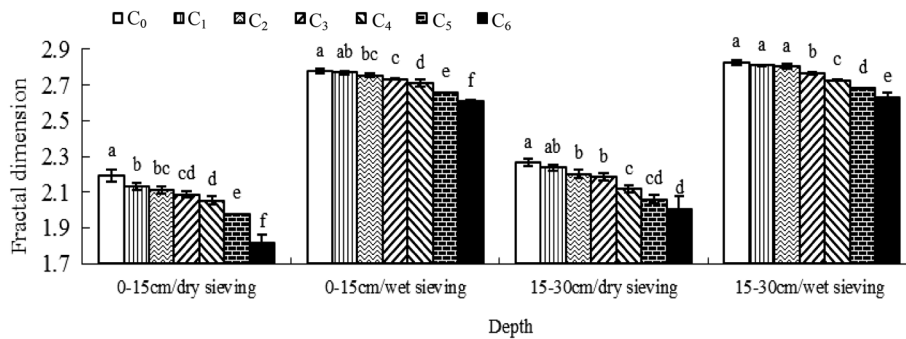
Fig. 4 Effect of different application rates of biochar on fractal dimension. The *error bar* above the *block* represents the standard deviation of three replicates. *Different lowercase letters* indicate significant differences ($p < 0.05$) among treatments in the same soil layer

and aggregates, thus improving aggregate stability (Armstrong and Tanton 1992). In acidic environments, the hydroxyl and carboxyl groups on the oxidized biochar surface could also adsorb clays to form aggregates (Jien and Wang 2013). Biochar was incorporated into the soil to a depth of less than 30 cm, but a significant effect on aggregate stability was observed not only in topsoil, but in subsoil. The observed increase in aggregate stability in subsoil may be explained by the direct and indirect effects of biochar: (1) A certain amount of biochar in topsoil was washed into subsoil by the persistent and substantial precipitation during the humid season, which then affected the aggregate stability directly. (2) The amelioration of ventilation and water infiltration in topsoil after biochar application likely increased microbial biomass and activity in subsoil which contributed to soil aggregation indirectly. Previous studies confirmed that biochar improved the saturated hydraulic conductivity (Jien and Wang 2013; Ternan et al. 1996) and total soil porosity (Oguntunde et al. 2008), contributing to a more suitable environment for the growth of microbes in subsoil. Therefore, the significant changes in soil aggregate characteristics in subsoil were presumably derived from both direct and indirect mediation of biochar.

Effects of biochar amendment on mean weight diameter (MWD) and geometric mean diameter (GMD)

The enhancement of biochar amendment at different application rates on GMD accorded with that on MWD in topsoil and subsoil except that there were significant differences in GMD among C_3, C_4, C_5 and C_6 treatments in subsoil, denoting the higher aggregate stability to resist disruption with the increase in the amount of biochar. Biochar significantly enhanced the aggregate stability of the soils mainly consisting of finer silt and clay particles, but had no effect on soils with high sand content. Typical Ultisols in southern China (occupying 1.2 M km^2) are

similar to Oxisols in the Amazon Basin, with low pH, SOC and CEC values and high clay content. The difference may be explained by the predominance of clay over sand as clay can act as an aggregant, binding organic molecules by bivalent and polyvalent cations (such as Ca^{2+}, Al^{3+} and Fe^{3+}) to make up macroaggregates and forming a protective coating to protect SOC from microbial decomposition and stabilize aggregation (Bronick and Lal 2005). Despite the high stability of biochar, incorporation into soil would change it gradually into stable humus (Topoliantz et al. 2006; Brodowski et al. 2007), which may interact synergistically with clay to improve aggregate stability. The short duration after biochar application may be responsible for the zero difference between control and biochar-amended soils, since the improvement of soil structure is a long process, not likely to occur instantly upon biochar addition. From the studies mentioned above, one may also conclude that biochar application amount contributes to the inconsistency among previous results.

Conclusions

The incorporation of wheat straw-derived biochar into upland red soil significantly influenced the size distributions of both dry aggregates and water-stable aggregates after 2 years of field experimentation. The percentage of dry aggregates (>2 mm) and water-stable aggregates (>0.5 mm) increased with the increase in biochar application rates. The most prominent improvement in aggregate stability occurred at the highest application rate (40 t ha^{-1}). Biochar improved the stability of soil aggregates against mechanical or water dispersion, and its improvement for mechanical tensile strength was more obvious than that of water stability. Since biochar affects the soil structure in a long process and might lose considerably in the long run due to the abundant water

resource in this area, the question arises whether the sustainable amelioration of soil aggregation can be achieved and when the reapplication of biochar is appropriate and essential. Both of the above questions need further study to ensure longer-term benefits for red soil.

Compliance with ethical standards

Conflict of interest The authors have declared no conflict of interest.

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