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Response of surface albedo and soil carbon dioxide fluxes to biochar amendment in farmland

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Abstract

Purpose Understanding the effect of biochar on surface albedo and soil CO_2 fluxes is a crucial issue in evaluating the impact of biochar on carbon sequestration and greenhouse gas mitigation. In this study, we consider the following research questions: (1) Under bare soil and crop coverage conditions, do different dosages of biochar decrease the surface albedo? (2) How does the application of biochar affect soil CO_2 fluxes? (3) What are the influencing factors of surface albedo and soil CO_2 fluxes after biochar is applied?

Materials and methods We examined the influence of biochar applications on farmland on the surface albedo, soil CO_2 flux, soil temperature, soil moisture, and soil organic carbon fractions over a period of 15 months. There are six treatments (CK+, CK−, BC5+, BC5−, BC45+, and BC45−) in this study, and three biochar application rates, which are as follows: 0 t ha^{-1} $year^{-1}$ (CK), 5 t ha^{-1} $year^{-1}$ (BC5), and 45 t ha^{-1} $year^{-1}$ (BC45) of biochar, and each application is rated with two crop coverage conditions, a wheat-maize crop rotation (+) and bare soil (−).

Results and discussion We found that in the early stage of crop growth, the surface albedo of BC45+ and BC5+ were decreased significantly compared with the control treatment ($P < 0.05$). As the crop canopy structures developed, the surface albedo reduction weakened or even disappeared. Under the bare soil condition, the surface albedos of BC45− and BC5− was decreased significantly in most of the measurements ($P < 0.05$). The soil CO_2 fluxes of the biochar treatments were increased significantly ($P < 0.05$). However, the growth rates of the soil CO_2 fluxes of BC45+, BC5+, BC45−, and BC5− gradually decreased with time. The increase in the CO_2 emissions of biochar treatments may be due to mineralization of the readily oxidizable organic carbon (e.g., water-soluble organic carbon) in the biochar-soil system. Adding biochar to the soil reduced the sensitivity of the soil respiration to temperature changes.

Conclusions The leaf area index is one of the factors that affects the surface albedo. The surface albedo did not decrease proportionally with the increase in biochar application. Readily oxidizable organic carbon played an important role in the soil CO_2 emissions. The reduction of surface albedo caused by the biochar has no direct effect on soil CO_2 fluxes. The findings were helpful in evaluating the effects of adding biochar to soil and its consequences for C sequestration in agricultural soils.

Keywords Biochar · Carbon dioxide · Climate change · Q_{10} · Surface albedo

1 Introduction

Applying biochar to soils is a method used for mitigating greenhouse gas emissions by sequestering C, withdrawing CO_2 from the atmosphere, and therefore reducing global climate change. Woolf et al. (2010) estimated that a sustainable biochar application to soils might reduce global greenhouse gas emissions by 71–130 Pg CO_2-C over 100 years. Compared with other forms of organic carbon, biochar has a well-developed pore structure, and a large surface area, is negatively charged, is highly aromatic, has a strong absorption capability, and a high degree of stability (Marris 2006; Lehmann 2007; Noguera et al. 2010; Sohi et al. 2010; Tammeorg et al. 2014). Because of its unique properties, biochar has relatively high agricultural values and can potentially to improve soil properties and

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functions, including controlling the heavy metal soil pollution, improving the soil environmental quality, and improving the production potential (Ahmad et al. 2014; Darby et al. 2016; Yu et al. 2017).

Currently, research related to biochar tends to concentrate on its effect on carbon sequestration (Liu et al. 2011), soil remediation, or crop yields (Mehmood et al. 2017). Because the carbon turnover times of biochar in the soil have been estimated to be more than 1000 years (Lehmann and Sohi 2008; Liang et al. 2010; Zimmerman et al. 2011; Lehmann et al. 2011), many researchers have suggested that the application of biochar could be a suitable method for carbon sequestration. However, a problem has been discovered that needs to be addressed before the large-scale application of biochar to farmland occurs. Some studies have shown that the input of biochar to soils could affect the background color and surface albedo of the soil (Genesio et al. 2012; Zhang et al. 2013b; Bozzi et al. 2015).

Surface albedo is defined as the ratio of radiation reflected to the incoming shortwave solar radiation (Meyer et al. 2012). Surface albedo is an important parameter in the study of the surface energy balance; it directly controls the radiative energy distribution of solar radiation between the surface and the atmosphere. A decrease in surface albedo may increase the soil temperature. One study found that surface albedo decreased by 37% on charcoal-site soils, while the soil-surface temperature increased up to 4 °C on average (Oguntunde et al. 2008). Some researchers think that elevated soil temperature may increase soil respiration (Rustad et al. 2000; Jiang et al. 2013, 2015). Because biochar exhibits extremely low reflectivity, the application of biochar to farmland may induce a radiative force by decreasing the surface albedo (Bright et al. 2016).

The studies of the impact of biochar on soil surface albedo remains poorly elucidated, and only a few studies have been conducted on surface albedo variations on farmland. These valuable studies provide many important conclusions, and help us understand the range of surface albedo reductions caused by the application of biochar to soil. A case of surface albedo reduction up to 80% for biochar-treated plots at a rate of 30–60 t ha^{-1} was observed (Genesio et al. 2012). Zhang et al. (2013b) found that reflectance decreased in the infrared wavelength range with 4.5–9.0 t ha^{-1} year^{-1} of biochar addition. Another study estimated that at an application rate of 30–32 t ha^{-1}, the climate mitigation benefit of biochar systems might be reduced by 13–22% due to the albedo reduction (Meyer et al. 2012). Bozzi et al. (2015) used 12 years of moderate resolution imaging spectroradiometer (MODIS)-derived albedo data to estimate that the biochar mitigation potential might be reduced by up to 30%. These studies demonstrated that the application of biochar to agricultural soils can change the surface albedo and may counteract the mitigating greenhouse effects of biochar systems, but the effect of the surface albedo reduction on soil CO$_2$ fluxes has not yet been quantified.

Our field experiment was conducted between July 2014 and October 2015. This research addresses an urgent need to understand how biochar application affects the characterization of seasonal changes in surface albedo and soil CO$_2$ fluxes on a wheat-maize crop rotation system and on bare soil, as well as its effects on soil temperature, soil moisture, and soil organic carbon fractions.

2 Materials and methods

2.1 Experimental area

The field experiment was conducted at a planting base (30.5316° N, 114.4025° E) in Wuhan, Hubei Province, China. The experiment site has a subtropical monsoon climate, the mean air temperature from July 2014 to October 2015 was 18.9 °C, and the total rainfall was 2064 mm (Fig. 1). The soil was a sandy loam (USDA, soil classification), and the percentages of sand, silt, and clay in the top 20 cm of soil were 69.7, 28.4, and 1.9%, respectively (determined using a Bouyoucos hydrometer). The soil organic carbon content was approximately 12.5 g kg^{-1} of soil (tested by the potassium dichromate oxidation method), and the soil pH was 4.6 (analyzed with a pH meter using a 1:2.5 soil-to-water ratio). The total nitrogen content was 1.6 g kg^{-1} (tested by the micro-Kjeldahl method), and the cation exchange capacity of the soil was 9.1 cmol kg^{-1} (determined by NH$_4$OAc/HOAc at pH 7.0).

2.2 Experimental design

The biochar was obtained from Chinese chestnut wood at a pyrolysis temperature of 500 °C for approximately 5 h (heating rate 5 °C/min), pH 8.6, organic matter 566 g kg^{-1}, water soluble organic carbon 1354 mg kg^{-1}, total nitrogen 6.2 g kg^{-1}, total potassium 13.8 g kg^{-1}, total phosphorus 0.96 g kg^{-1}, surface area of biochar 31.38 m^2 g^{-1}, and pore size 1.5~5 nm.

Six treatments (CK+, CK−, BC5+, BC5−, BC45+, and BC45−) were used in this study, and the three biochar application rates employed are as follows: CK (control, biochar at a rate of 0 t ha^{-1} year^{-1}), BC5 (biochar at a rate of 5 t ha^{-1} year^{-1}), and BC45 (biochar at a rate of 45 t ha^{-1} year^{-1}). Each application rates was applied to two crop coverage conditions, which were a wheat-maize crop rotation (+) and bare soil (−). To verify if the soil surface albedo decreases with increasing biochar application rates, 5 t ha^{-1} year^{-1} is the low application rate, and 45 t ha^{-1} year^{-1} is the high application rate. The area of each treated plot was 2.25 m^2 (1.80 m × 1.25 m),

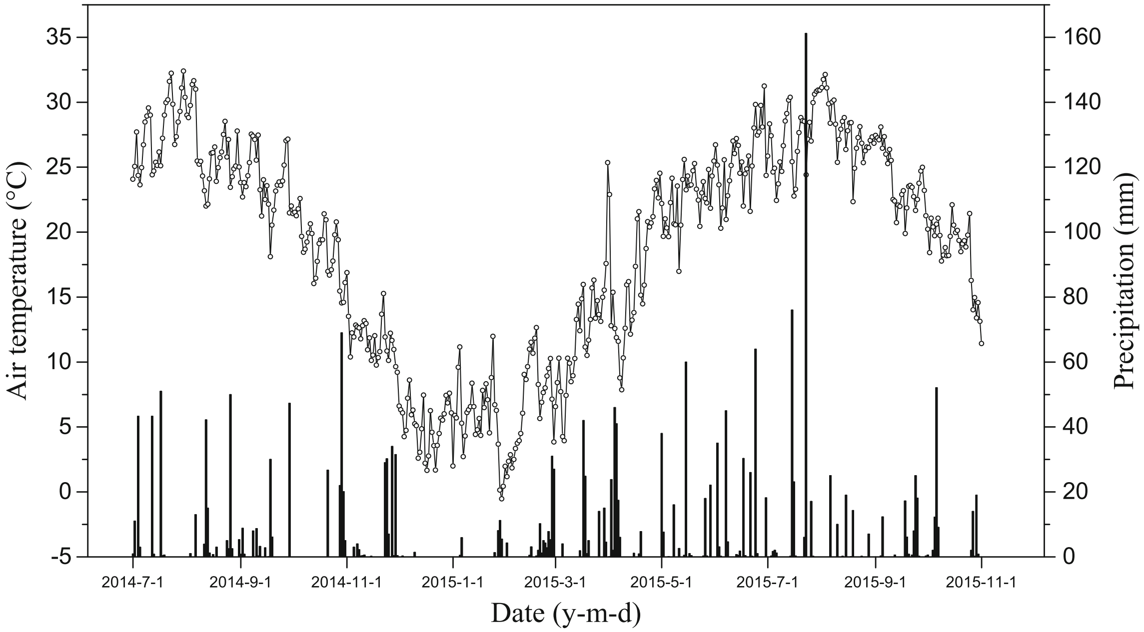

Fig. 1 Variation of precipitation and air temperature over the experimental period

and each treatment had three replications with a randomized block design.

The type of wheat and maize grown were Zhengmai 9023 and Huanuo 5 in this study. The wheat was seeded on 6 November 2014 with a density of 105 kg a^{-1}, and was reaped on 5 May 2015. The first crop of maize was planted on 24 July 2014 and was reaped on 15 October 2014, and the second crop of maize was seeded on 17 July 2015 and was reaped on 28 September 2015. The planting pattern of the maize was 40-cm row spacing, and the distance between maize plants was 30 cm. Inorganic fertilizers of 112.5 kg N ha^{-1}, 112.5 kg P_2O_5 ha^{-1}, and 112.5 kg K_2O ha^{-1} were applied in each crop season for all treatments. The dates of the biochar applications were 20 July 2014 and 12 July 2015. Biochar was applied manually and incorporated in the top 20 cm of the soil before sowing each crop; we assume that the biochar was uniformly distributed in the 0–20 cm soil layer. The average soil surface coverage of the biochar was 2.25 kg/m^2 for 45 t ha^{-1} $year^{-1}$ and 0.25 kg/m^2 for 5 t ha^{-1} $year^{-1}$.

2.3 Measurement

The surface albedo was measured with a NR01 net radiometer (Hukseflux, USA) (spectral range 305–2800 nm; accuracy ± 2.5%; sensitivity 14.9 mV kW^{-1} m^{-2}) connected to a CR1000 datalogger (Campbell Scientific, Inc., Logan, UT). To avoid the interference caused by meteorological factors such as clouds, the surface albedo measurements were taken at 3-min intervals for each plot from 11:30 to 12:30 on selected bright days. The mean surface albedo was calculated by an equation described by Zhang et al. (2014). The radiometer was mounted on the top of a tripod 16 cm from the soil to ensure that the reflected radiation flux came from the plot area (Sailor et al. 2006; Zhang et al. 2011). The surface albedo was measured 26 times from August 2014 to October 2015.

The soil temperature and soil moisture (volumetric moisture) at a depth of 10 cm were recorded hourly from 8:00 to 17:00 using a curved tube thermometer (10 cm) and soil moisture probes (TZS-1W, TOP Instrument Inc., China) and were monitored in situ for each plot. The daytime mean soil temperature and soil moisture were calculated by averaging the values of each hour. The measurements were taken during the same period as the surface albedo measurements.

The soil CO_2 fluxes measurement was taken with static chambers. The size of the chambers and the sampling method are similar to the previously published methods (Zhang et al. 2013a; Yang et al. 2017). The chambers (30 × 30 × 40 cm) and collars (30 × 30 × 10 cm) were made of polypropylene. The collars were installed in each plot without covering the plants and were buried to a depth of 5–10 cm of soil. The top edge of each collar had a groove (5 cm in depth) for filling with water to seal the rim of the chamber. Each chamber was equipped with a circulating fan to assure complete mixing of the gas. During each sampling event, the gasses were sampled with propylene syringes and injected into aluminum foil bags (gas was used to flush the bag twice before it was injected into the bag). Three samples were taken at 20-min intervals (0, 20, and 40 min) after chamber closure. The gas sampling was performed between 9:00 and 11:00. The concentration of CO_2 was analyzed using a gas chromatograph system (Agilent 6820, Agilent Technologies Inc., USA) equipped with a flame ionization detector (FID). The oven temperature was controlled at 55 °C, and the temperature of the FID was set at 200 °C. A flow rate of 25 mL min^{-1} N_2 was applied as the carrier gas for CO_2 analyses. The gas samples were collected from December 2014 to October 2015. The concentration of CO_2 was calculated by an equation described by Collier et al. (2014) and Whittaker et al. (2016).

From August 2014 to October 2015, five replicate samples of topsoil at 0–20 cm depth from each plot were collected and sealed in plastic bags. On return to the laboratory (within 2 h of collection), the small rocks and plant material in the soil samples were removed by sieving (2 mm) and the samples were used for chemical analysis within 24 h. Then, the soil samples were stored at 4 °C in the absence of light. The soil organic carbon (SOC) was determined by wet oxidation using concentrated H_2SO_4 and $K_2Cr_2O_7$, and titrating with a $Fe(NH_4)_2(SO_4)_2{\cdot}6H_2O$ solution. The easily oxidized carbon (EOC) and water-soluble organic carbon (WSOC) values were determined following the protocol described by Blair et al. (1995) and Gregorich et al. (2000), respectively.

The crop leaf area index (LAI) was measured by the length-width method (Breda 2003). From November 2014 to October 2015, the length and width of the wheat and maize leaves were measured, and the leaf area was calculated by multiplication of the empirical correction coefficients 0.83 and 0.75, respectively.

2.4 Statistical analyses

All data in this paper were expressed as the means plus or minus one standard deviation. Analysis of variance was used to evaluate the treatment effects on the surface albedo value, soil CO_2 flux, soil temperature, soil moisture, and soil organic carbon fractions using the repeated measures analysis of variance (SPSS version 22.0). The least significant difference (LSD) test at a significance level 0.05 was used as the multiple comparison test of the means.

3 Results

3.1 Surface albedo

Figure 2 shows the differences in surface albedo of the different plots with crops from August 2014 to October 2015, and Fig. 3 shows the surface albedo of the CK−, BC5−, and BC45− plots during the same period. The measurement results indicate that from 13 November 2014 (wheat seedling stage) to 6 February 2015 (wheat jointing stage), relative to CK+, the application of biochar caused a significant decrease in surface albedo ($P < 0.05$). The reduction of BC45+ on these 2 days was 21.5 and 17.9%, respectively, and 23.6%, 14.8% for BC5+. From 9 March 2015 (reviving stage) to 13 May 2015 (mature stage), with the increase in the leaf area index, there was no significant difference between BC45+, BC5+, and CK+ ($P > 0.05$). After the wheat harvest (25 May 2015), the plants were removed from the soil, and the differences in the surface albedo between the CK+, BC5+, and BC45+ were detectable again. The effects of biochar on surface albedo in maize seasons were similar to those in the wheat season. Relative to CK+, the surface albedo of BC45+ and BC5+ decreased significantly during the early growth period of the maize ($P < 0.05$). These differences were not detectable later in the season until the maize harvest. During the growth stages of the winter wheat and summer maize, no significant difference was observed between BC45+ and BC5+ in most of the measurements ($P > 0.05$). Under the bare soil condition, compared with the CK− treatment, the surface albedo of BC45− and BC5− decreased in 21 of the 26 total measurements, and the largest reductions were 44.5 and 44.9%, respectively.

3.2 Soil temperature and soil moisture

Data describing the soil temperature and soil moisture under different biochar treatments are presented in Fig. 4. The daytime mean soil temperatures at a 10-cm depth were 18.47, 18.47, 18.43, 18.77, 18.41, and 18.78 °C for CK+, BC5+, BC45+, CK−, BC5−, and BC45−, respectively; no significant differences were found between the biochar treatments and control treatment ($P > 0.05$). There were no significant differences in the soil moisture measurements of the BC45+, BC5+, and CK+ treatments ($P > 0.05$). The soil moisture of BC5− was approximately 1.1–3.0% higher than that of CK−, indicating that the biochar amendment at the rate of 5 t ha^{-1} $year^{-1}$ in the bare soil showed a slightly positive effect on the soil moisture, but no significant differences were found between BC45− and CK− ($P > 0.05$).

3.3 Soil CO_2 fluxes

The effects of biochar input on soil CO_2 fluxes are shown in Fig. 5. Compared with the control treatments, the soil CO_2 fluxes of the biochar treatments were significantly increased ($P < 0.05$) at the initial stage of application. However, with the extension of time, the growth rates of the soil CO_2 fluxes of the biochar treatments gradually decreased. The growth rate of BC45+ dropped from 276.7 to 36.1% in the winter wheat season and decreased from 90.1 to 48.1% in the summer maize season, while that of BC45− decreased from 163.5 to 39.8% in the winter wheat season and decreased from 79.5 to 36.0% in the summer maize season with the bare soil condition. Because the input of biochar was only 5 t ha^{-1} $year^{-1}$, the soil CO_2 fluxes of BC5+ and BC5− were lower than those of BC45+ and BC45−. In the winter wheat growing season,

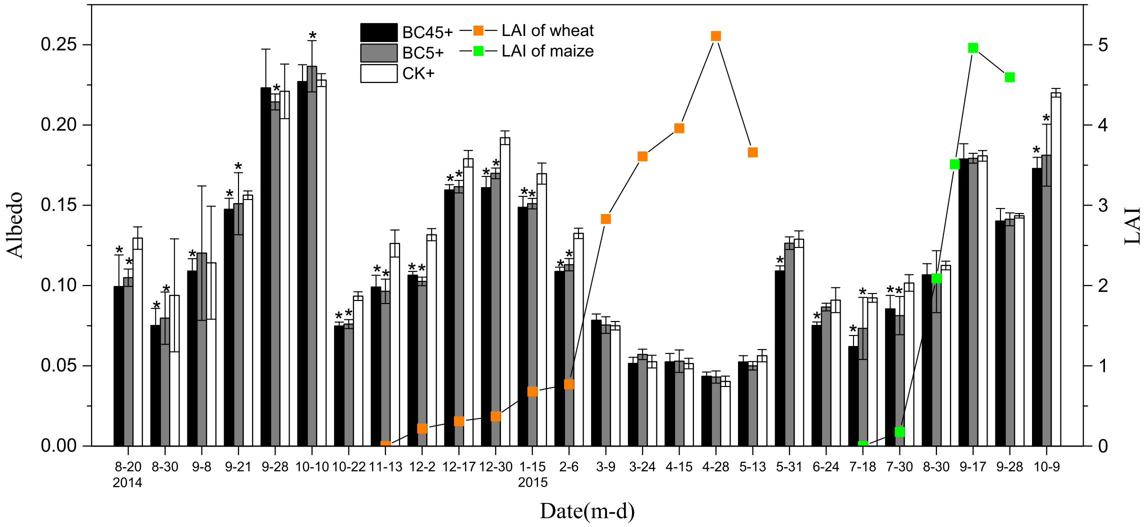

Fig. 2 Effects of biochar input on surface albedo under the condition of crop cultivation. Note: measurements with * indicate that the surface albedo values of this treatment are significantly different from the control treatment ($P < 0.05$), and are denoted similarly hereinafter

compared with CK+ or CK−, the average soil CO_2 fluxes of BC45+, BC5+, BC45−, and BC5− increased by 137.5, 13.6, 90.8, and 39.6%, respectively; the increases in the summer maize season were 45.9, 26.9, 37.3, and 27.3%, respectively. The results indicate that the high biochar application rate had a more prominent stimulating effect on the soil CO_2 fluxes.

3.4 Soil organic carbon fractions

Biochar input noticeably increased the contents of soil organic carbon, easily oxidized carbon and water-soluble organic carbon, and the growth rates increased with the greater biochar application amount. From August 2014 to October 2015, the average SOC contents of the BC45+, BC5+, BC45−, and BC5− treatments rose by 37.5, 13.6, 26.5, and 9.8%, respectively, relative to the CK+ and CK− treatments (Fig. 6). The average EOC contents increased by 55.8, 4.8, 65.1, and 26.1%, respectively (Fig. 7), while the average WSOC contents notably increased by 108.3, 69.8, 93.1, and 65.0%, respectively (Fig. 8). Compared with the SOC and EOC, the biochar input could increase the content of WSOC on a much larger scale.

After the biochar application, the changes in the SOC and EOC content were not apparent. However, the WSOC content decreased rapidly over time. Taking the data from the summer maize growing season in 2015 as an example, the WSOC content of BC45+, BC5+, BC45−, and BC5− decreased by 57.6, 16.4, 47.8, and 53.9%, respectively, from July 18 to September 28. The results indicated that the WSOC was a type of active organic carbon component in the biochar-soil system, and it could be mineralized in a short time.

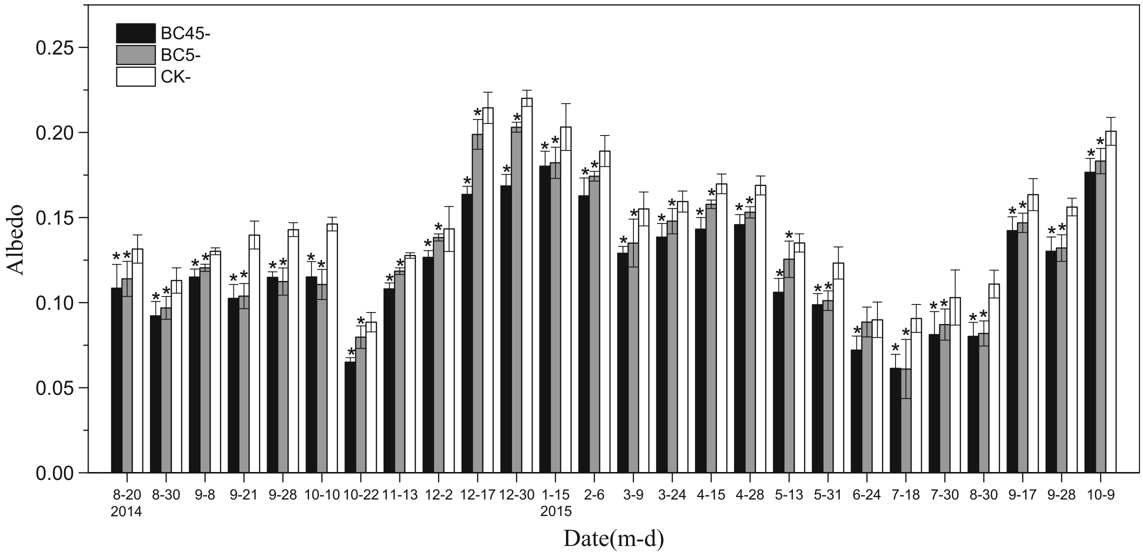

Fig. 3 Effects of biochar input on surface albedo under the condition of the bare soil

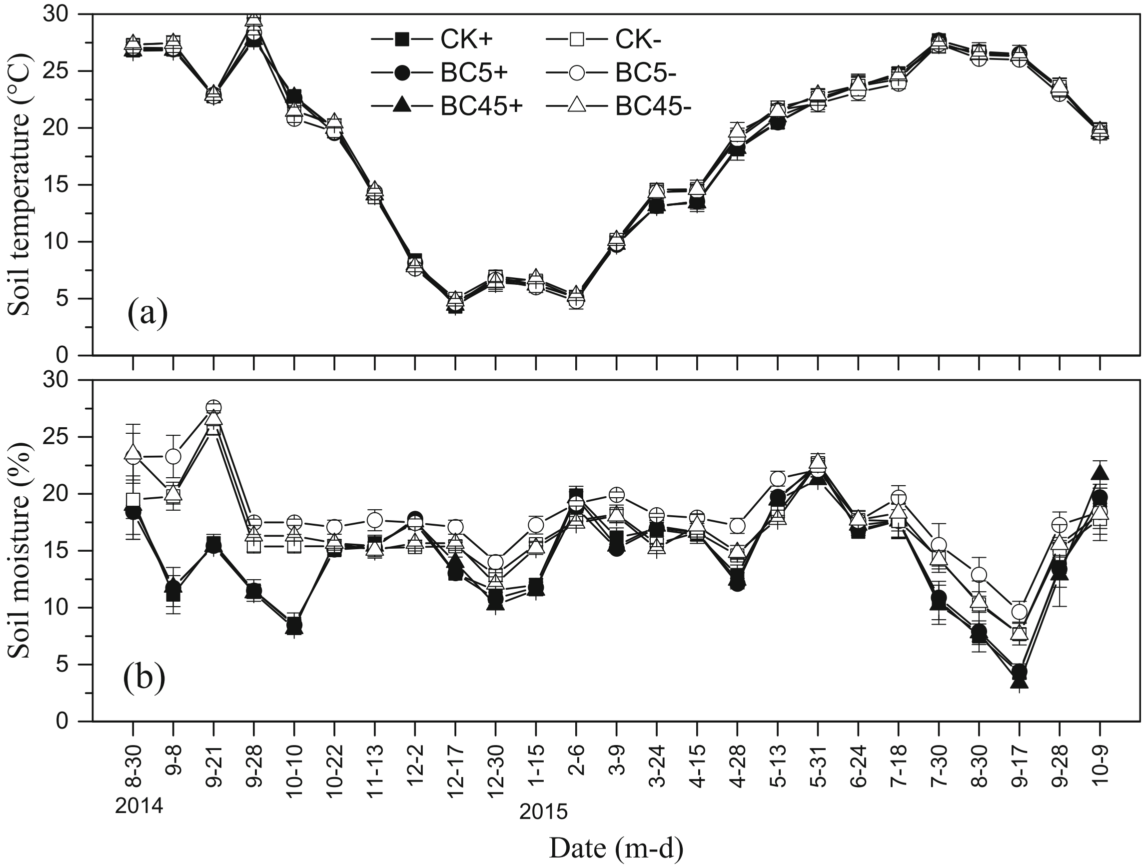

Fig. 4 Variation of soil temperature (°C) (**a**) and soil moisture (**b**) over the experimental period

4 Discussion

4.1 Effect of biochar on surface albedo

In this study, during the early growth stage of the wheat and maize, the canopy structure of the crop has not yet formed an active block to the solar radiation. With the growth of the crops, the leaf area index of the wheat and maize increased rapidly (Fig. 1), and the vegetation cover canceled out the differences in the soil albedo because of canopy development. These results are consistent with the results from Genesio et al. (2012) and Meyer et al. (2012). To study the relationship between surface albedo and crop cover, we attempted to fit the surface albedo and leaf area index with a logarithmic equation. The result shows that the leaf area indexes of CK+, BC5+ , and BC45+ were significantly correlated with the surface albedo (in the winter wheat season, $R^2 = 0.83\sim0.92$; in the summer maize season, $R^2 = 0.83\sim0.91$), and the difference in the surface albedo between the biochar treatments and control treatment gradually disappeared with the increase of the leaf area index. In addition, Table 1 shows that the mean decreasing rate of the surface albedo of the biochar treatments under the cover condition was lower than that of the biochar treatments under the bare soil condition. The surface albedo reduction caused by the input of biochar can be alleviated by the crop cover, which means that the leaf area index is one of the factors that affect the surface albedo.

In the wheat growing season, the surface albedo of the biochar treatments was lower than that of the control treatment for approximately 92 days and accounted for 46.0% of the whole growth cycle, while in the maize growing season, this proportion was only 29.1%. Compared with maize, wheat has a much longer growth period, and the leaf area index had no notable changes before the stage when the leaves turned green. The difference in the vertical distribution of the leaf area and the development speed of the crop canopy structure between two types of the crops is the main reason for this phenomenon. When the large-scale biochar application is used in farmland, it is necessary to plant crops with a faster canopy growth rate on the soil with biochar to avoid the environmental risk caused by the decrease in surface albedo.

Our study showed that there was no detectable difference in surface albedo in response to the 9 biochar application rates from 5 to 45 t ha^{-1} year^{-1} (Table 1). This suggests the existence of a certain biochar application threshold. When the biochar application rate is higher than the biochar application threshold, the surface albedo would not decrease with a greater biochar application; therefore, the change in albedo is not a function of the rate of applied biochar. This is a key for agriculture and climate change mitigation because a greater

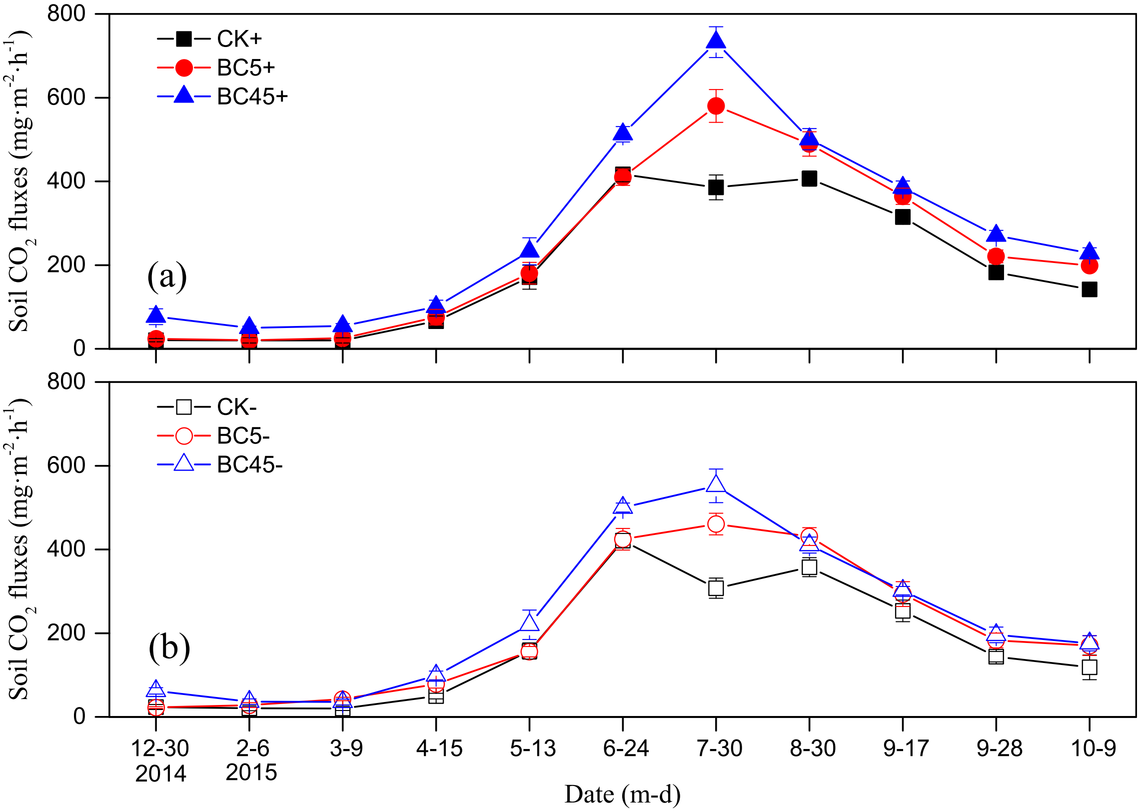

Fig. 5 Effects of biochar input on soil CO_2 fluxes under (**a**) wheat-maize crop rotation and (**b**) bare soil conditions

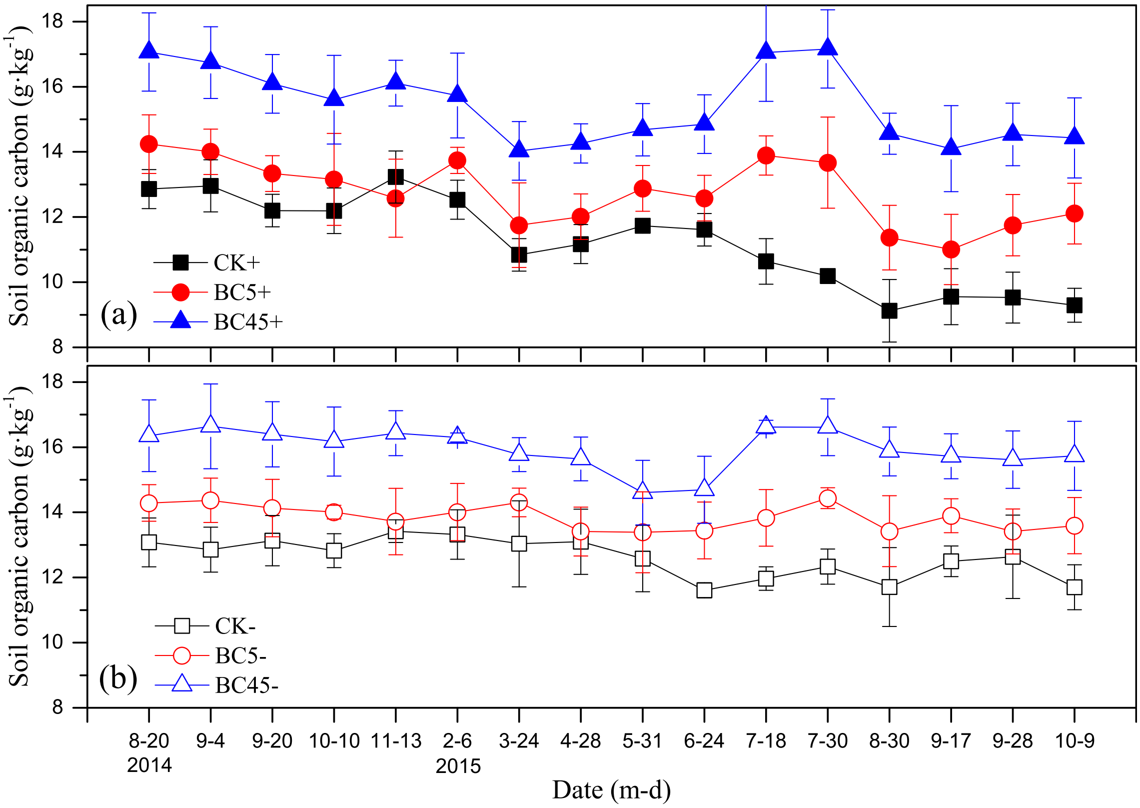

Fig. 6 Dynamics of soil organic carbon under (**a**) wheat-maize crop rotation and (**b**) bare soil conditions

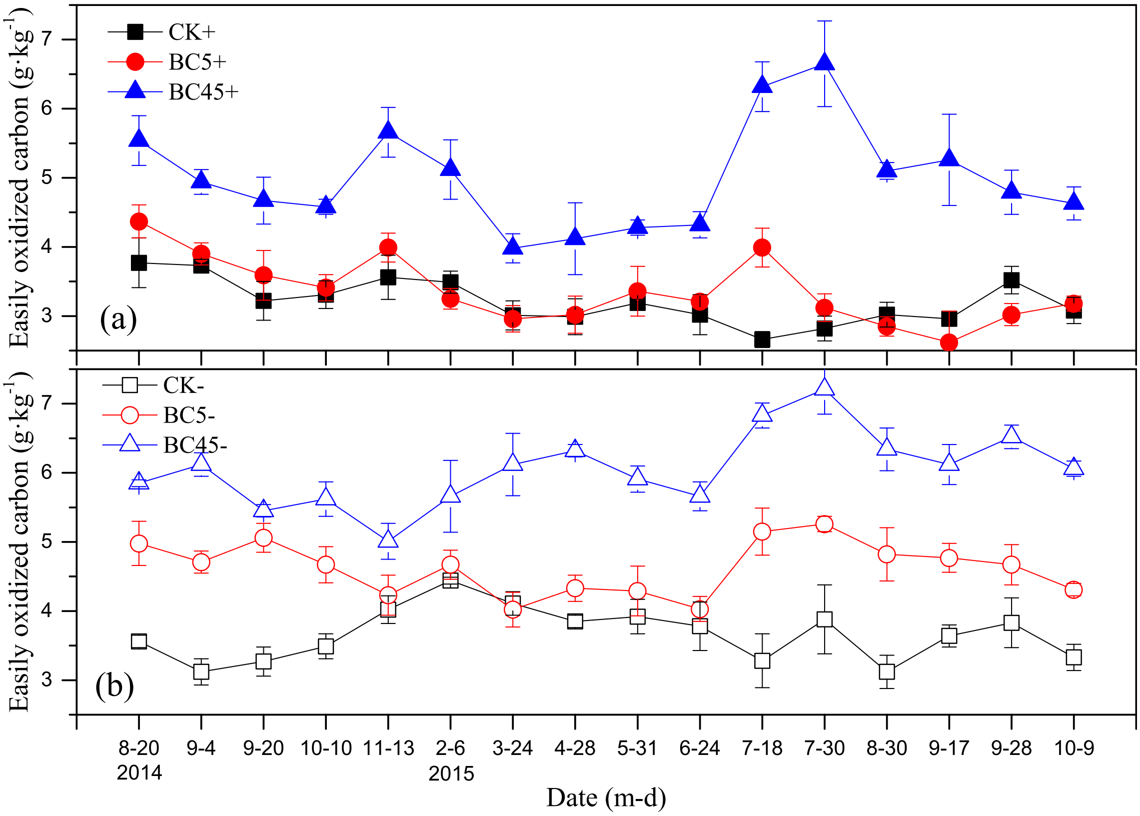

Fig. 7 Dynamics of easily oxidized carbon under (**a**) wheat-maize crop rotation and (**b**) bare soil conditions

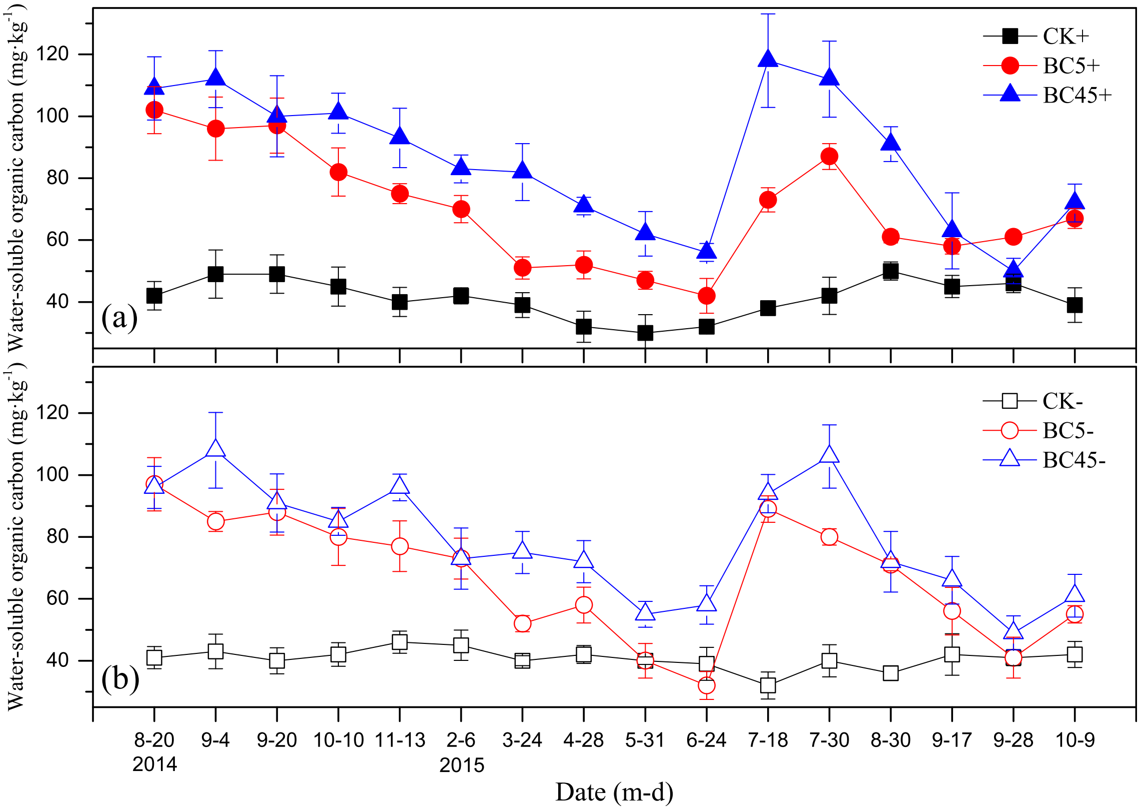

Fig. 8 Dynamics of water-soluble organic carbon under (**a**) wheat-maize crop rotation and (**b**) bare soil conditions

Table 1 Mean values of surface albedo in different time periods

Treatment	Summer maize in 2014	Winter wheat in 2014	Summer maize in 2015	Annual average (2014/8~2015/8)
BC45+	0.1366 a (7.7%)	0.0959 a (14.5%)	0.1244 a (12.3%)	0.1068 a (11.3%)
BC5+	0.1404 a (5.2%)	0.0989 a (9.9%)	0.1265 a (10.8%)	0.1098 a (8.8%)
CK+	0.1481 b	0.1097 b	0.1418 b	0.1204 b
BC45−	0.1019 c (20.1%)	0.1341 c (17.0%)	0.1120 c (18.6%)	0.1165 b (18.7%)
BC5−	0.1054 c (17.3%)	0.1480 d (8.3%)	0.1154 c (16.1%)	0.1258 b (12.2%)
CK−	0.1274 d	0.1615 e	0.1375 b	0.1433 c

Values with different letters in a row mean significant difference at $p < 0.05$; the data in brackets are the decrease of the surface albedo of the biochar treatment compared with the control treatment

amount of applied biochar may result in more carbon being sequestered per unit area. This result is consistent with Genesio's research, who found that there was no difference in surface albedo in response to the biochar application rate from 30 to 60 t ha^{-1} (Genesio et al. 2012).

4.2 Effect of biochar on soil CO_2 fluxes

The correlation analysis of surface albedo, SOC, EOC, WSOC, and soil CO_2 fluxes demonstrated that WSOC and soil CO_2 fluxes showed a distinct correlation, while the surface albedo, SOC, and EOC of each treatment were not correlated with the soil CO_2 fluxes (Table 2), our results showed that the change of surface albedo caused by biochar has no direct effect on soil CO_2 fluxes.

Many researchers found that biochar improved the living environment of microorganisms and increased the amount of easily decomposed organic matter in the soil, leading to a sharp increase in the soil respiration (Wang et al. 2012; Case et al. 2014; Deng et al. 2017). However, the results of a meta-analysis of biochar stability in the soil showed that only a small part of the biochar is bioavailable and that the remaining 97% contributes directly to long-term C sequestration in the soil (Wang et al. 2016b). Wang et al. (2016a) investigated the impact of biochar amendment on soil water soluble carbon, and the results showed that biochar addition increased the release of WSOC from native soil organic matter. In this study, mineralization of the readily decomposable organic carbon (e.g., WSOC) in the biochar-soil system may be a reason for the attenuate priming effect over time (Liu et al. 2016; He et al. 2017). The amount of WSOC in soil is small, but it is an organic carbon source that can be directly utilized by soil microorganisms, and it has a higher turnover rate than the microbial biomass carbon (Gregorich et al. 2000). Our research is helpful in understanding the emission sources of carbon dioxide after biochar input.

The soil CO_2 flux responses mainly varied with the biochar feedstock source and the pyrolysis temperature of the biochar (He et al. 2017). Liu et al. (2016) performed a meta-analysis and found that the soil CO_2 flux responses to the biochar amendment depended on the biochar feedstock materials, with the highest positive response for manure-derived biochar and a significantly negative response for biowaste sources. This result indicates that negative soil priming effects may occur if different biochars are used. Therefore, biochar characteristics should be considered to assess the effect of the biochar type on the soil CO_2 fluxes.

4.3 Effect of biochar on soil temperature and soil moisture

Our study showed that there was no detectable difference between the soil temperatures of the biochar treatments

Table 2 Pearson correlation coefficient of surface albedo, SOC, EOC, WSOC, and soil CO_2 fluxes in each treatment

Soil CO_2 fluxes	Winter wheat in 2014				Summer maize in 2015			
	Albedo	SOC	EOC	WSOC	Albedo	SOC	EOC	WSOC
BC45+	0.109	− 0.133	− 0.288	− 0.885*	− 0.183	0.642	0.941**	0.889*
BC45−	0.211	− 0.199	− 0.043	− 0.842*	− 0.166	0.891*	0.759	0.930**
BC5+	0.142	0.012	− 0.138	− 0.817*	0.125	0.439	− 0.161	0.797
BC5−	0.116	− 0.528	− 0.477	− 0.819*	0.069	0.543	0.750	0.917**
CK+	− 0.203	− 0.209	− 0.441	− 0.289	0.132	0.265	− 0.652	0.592
CK−	0.217	− 0.416	− 0.610	− 0.502	0.326	− 0.142	− 0.200	0.425

**Significant level $P < 0.01$, *significant level $P < 0.05$

and controls. Seasonal change, crop cover, rainfall, irrigation, and the interaction of these factors may explain the variations in soil temperature and soil moisture caused by the decrease in surface albedo. Soil temperature did not increase by decreasing albedo, which implies that the additional absorbed energy in the biochar-treated plots was dissipated in other ways (for instance by increased evaporation or sensible heat flux). There are a few previous reports on the effect of biochar on soil temperature and soil moisture in farmland. Zhang et al. (2013b) showed that biochar amendment reduced diurnal soil-temperature fluctuations on both daily and seasonal scales. Li et al. (2014) focused on biochar's effect on soil moisture in a tomato field, and the results showed that the soil moisture of biochar treatments (10 to 60 t ha^{-1}) is higher than that of the control treatment and decreases following an increasing trend. Because field trials are complex and field conditions change, the results from different researchers on biochar input to soil temperature and soil moisture are always different. In this study, the adherence of soil particles to the thermometer head may change by changing the soil moisture content. Additionally, the measurements were only made at a single depth during the daytime. Therefore, more scientific and comprehensive soil temperature measurements should be taken in future studies.

4.4 Effect of biochar on soil respiration temperature sensitivity

Soil respiration temperature sensitivity (Q_{10}) is regarded as an important mechanism for the possible feedback between the carbon cycle in the terrestrial ecosystem and the climate system. However, Q_{10} is not constant but is influenced by soil temperature, soil moisture, soil nutrient availability, etc. (He et al. 2016; Fang et al. 2017; Pei et al. 2017). In this study, an exponential model was constructed to explore the relationships between the soil temperature and soil CO_2 emission flux, and the Q_{10} values in each treatment were calculated (Fig. 9). There was an apparent correlation between the soil CO_2 flux and soil temperature in each treatment (in the winter wheat season, $R^2 = 0.80{\sim}0.95$; in the summer maize season, $R^2 = 0.78{\sim}0.93$), the input of biochar could decrease the sensitivity of soil respiration to temperature changes, and the decreasing amplitude increased with the growth of the biochar application amount (Fig. 9). On one hand, because of the biochar's water absorption capacity, the input of biochar into the soil could decrease the soil water availability, and these changes in soil moisture would affect the Q_{10} (He et al. 2016; Fang et al. 2017; Pei et al. 2017). On the other hand, Zhang et al. (2013b) reported that the biochar amendment in farmland could reduce the soil temperature fluctuation, which suggests that biochar may reduce the temperature sensitivity of soil respiration.

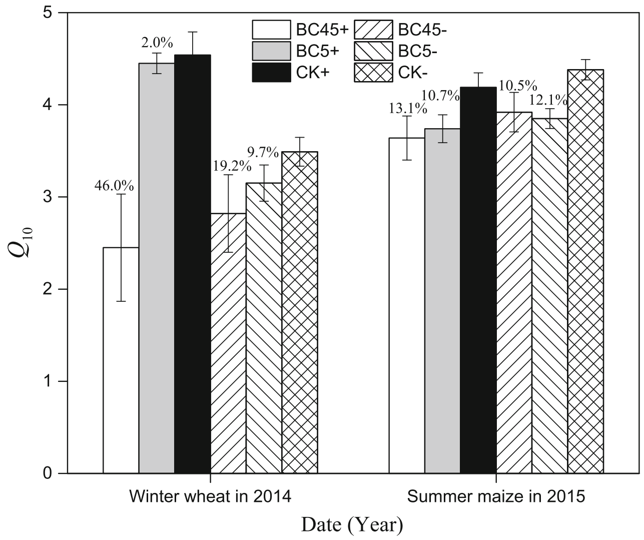

Fig. 9 Variations of Q_{10} among different biochar treatments. Note: the data above the bar are the decreases in the Q_{10} of the biochar treatments compared with the control treatment

4.5 Future work

Because the influencing factors of the field experiment are complicated and changeable, according to the results of the field observation over 15 months, it is not clear that the decrease in surface albedo has a significant effect on soil CO_2 fluxes. On one hand, the sampling frequency of CO_2 is low in this study, which may affect the test results. Therefore, the sampling frequency should be appropriately increased in future work. On the other hand, field observations with a longer time scale, multifarious crop cover conditions, and various biochar feedstock materials will be helpful to evaluate the impact of the change of surface albedo caused by biochar on soil CO_2 fluxes.

5 Conclusions

The surface albedo of biochar treatments decreased dramatically during the early crop growth period and with bare soil. However, as the crop canopy structures developed, the surface albedo reduction caused by the input of biochar weakened or even disappeared, and the leaf area index is one of the factors that affect the surface albedo. The soil surface albedo did not decrease proportionally with a greater biochar application.

The decrease in surface albedo caused by the input of biochar had no direct effect on soil CO_2 fluxes. There was no detectable difference between the soil temperature and soil moisture of the biochar treatments and controls. The enhancement of soil CO_2 fluxes in biochar treatments could be due to the mineralization of readily oxidizable carbon in the biochar-soil system and the priming effect caused by it. Meanwhile, biochar application to farmland could decrease the sensitivity of soil respiration to temperature changes.

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References

Ahmad M, Rajapaksha AU, Lim JE, Zhang M, Bolan N, Mohan D, Vithanage M, Lee SS, Ok YS (2014) Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99: 19–33. https://doi.org/10.1016/j.chemosphere.2013.10.071

Blair GJ, Lefroy R, Lise L (1995) Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. Aust J Agric Res 46(7):1459–1466. https://doi.org/10.1071/AR9951459

Bozzi E, Genesio L, Toscano P, Pieri M, Miglietta F (2015) Mimicking biochar-albedo feedback in complex Mediterranean agricultural landscapes. Environ Res Lett 10(8):084014. https://doi.org/10.1088/1748-9326/10/8/084014

Breda NJJ (2003) Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. J Exp Bot 54(392):2403–2417. https://doi.org/10.1093/jxb/erg263

Bright RM, Bogren W, Bernier P, Astrup R (2016) Carbon-equivalent metrics for albedo changes in land management contexts: relevance of the time dimension. Ecol Appl 26(6):1868–1880. https://doi.org/10.1890/15-1597.1

Case SDC, McNamara NP, Reay DS, Whitaker J (2014) Can biochar reduce soil greenhouse gas emissions from a Miscanthus bioenergy crop? GCB Bioenergy 6(1):76–89. https://doi.org/10.1111/gcbb.12052

Collier SM, Ruark MD, Oates LG, Jokela WE, Dell CJ (2014) Measurement of greenhouse gas flux from agricultural soils using static chambers. J Vis Exp 90:e52110. https://doi.org/10.3791/52110

Darby I, CY X, Wallace HM, Joseph S, Pace B, Bai SH (2016) Short-term dynamics of carbon and nitrogen using compost, compost-biochar mixture and organo-mineral biochar. Environ Sci Pollut Res 23(11): 11267–11278. https://doi.org/10.1007/s11356-016-6336-7

Deng W, Van Zwieten L, Lin Z, Liu X, Sarmah AK, Wang H (2017) Sugarcane bagasse biochars impact respiration and greenhouse gas emissions from a latosol. J Soils Sediments 17(3):632–640. https://doi.org/10.1007/s11368-015-1347-4

Fang Y, Singh BP, Matta P, Cowie AL, Van Zwieten L (2017) Temperature sensitivity and priming of organic matter with different stabilities in a Vertisol with aged biochar. Soil Biol Biochem 115: 346–356. https://doi.org/10.1016/j.soilbio.2017.09.004

Genesio L, Miglietta F, Lugato E, Baronti S, Pieri M, Vaccari FP (2012) Surface albedo following biochar application in durum wheat. Environ Res Lett 7(1):14025. https://doi.org/10.1088/1748-9326/7/1/014025

Gregorich EG, Liang BC, Drury CF, Mackenzie AF, McGill WB (2000) Elucidation of the source and turnover of water soluble and microbial biomass carbon in agricultural soils. Soil Biol Biochem 32(5): 581–587. https://doi.org/10.1016/S0038-0717(99)00146-7

He XH, ZL D, Wang YD, Lu N, Zhang QZ (2016) Sensitivity of soil respiration to soil temperature decreased under deep biochar amended soils in temperate croplands. Appl Soil Ecol 108:204–210. https://doi.org/10.1016/j.apsoil.2016.08.018

He Y, Zhou X, Jiang L, Li M, Du Z, Zhou G, Shao J, Wang X, Xu Z, Hosseini Bai S, Wallace H, Xu C (2017) Effects of biochar application on soil greenhouse gas fluxes: a meta-analysis. GCB Bioenergy 9(4):743–755. https://doi.org/10.1111/gcbb.12376

Jiang H, Deng Q, Zhou G, Hui D, Zhang D, Liu S, Chu G, Li J (2013) Responses of soil respiration and its temperature/moisture sensitivity to precipitation in three subtropical forests in southern China. Biogeosciences 10(6):3963–3982. https://doi.org/10.5194/bg-10-3963-2013

Jiang J, Guo S, Zhang Y, Liu Q, Wang R, Wang Z, Li N, Li R (2015) Changes in temperature sensitivity of soil respiration in the phases of a three-year crop rotation system. Soil Till Res 150:139–146. https://doi.org/10.1016/j.still.2015.02.002

Lehmann J (2007) A handful of carbon. Nature 447(7141):143–144. https://doi.org/10.1038/447143a

Lehmann J, Sohi S (2008) Comment on "Fire-derived charcoal causes loss of forest humus". Science 321(5894):1295. https://doi.org/10.1126/science.1160005

Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D (2011) Biochar effects on soil biota—a review. Soil Biol Biochem 43(9):1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

Li C, Qu Z, Gou M, Gao W, Sun G (2014) The research of biochar's effect on soil humidity, fertility and temperature. Ecol Environ Sci 23:1141–1147

Liang B, Lehmann J, Sohi SP, Thies JE, O'Neill B, Trujillo L, Gaunt J, Solomon D, Grossman J, Neves EG, Luizão FJ (2010) Black carbon affects the cycling of non-black carbon in soil. Org Geochem 41(2): 206–213. https://doi.org/10.1016/j.orggeochem.2009.09.007

Liu Y, Yang M, Wu Y, Wang H, Chen Y, Wu W (2011) Reducing CH_4 and CO_2 emissions from waterlogged paddy soil with biochar. J Soils Sediments 11(6):930–939. https://doi.org/10.1007/s11368-011-0376-x

Liu S, Zhang Y, Zong Y, Hu Z, Wu S, Zhou J, Jin Y, Zou J (2016) Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: a meta-analysis. GCB Bioenergy 8(2):392–406. https://doi.org/10.1111/gcbb.12265

Marris E (2006) Putting the carbon back: black is the new green. Nature 442(7103):624–626. https://doi.org/10.1038/442624a

Mehmood K, Li J, Jiang J, Masud MM, Xu R (2017) Effect of low energy-consuming biochars in combination with nitrate fertilizer on soil acidity amelioration and maize growth. J Soils Sediments 17(3):790–799. https://doi.org/10.1007/s11368-015-1219-y

Meyer S, Bright RM, Fischer D, Schulz H, Glaser B (2012) Albedo impact on the suitability of biochar systems to mitigate global warming. Environ Sci Technol 46(22):12726–12734. https://doi.org/10.1021/es302302g

Noguera D, Rondon M, Laossi KR, Hoyos V, Lavelle P, de Carvalho M, Barot S (2010) Contrasted effect of biochar and earthworms on rice growth and resource allocation in different soils. Soil Biol Biochem 42(7):1017–1027. https://doi.org/10.1016/j.soilbio.2010.03.001

Oguntunde PG, Abiodun BJ, Ajayi AE, van de Giesen N (2008) Effects of charcoal production on soil physical properties in Ghana. J Plant Nutr Soil Sci 171(4):591–596. https://doi.org/10.1002/jpln.200625185

Pei J, Zhuang S, Cui J, Li J, Li B, Wu J, Fang C (2017) Biochar decreased the temperature sensitivity of soil carbon decomposition in a paddy field. Agric Ecosyst Environ 249:156–164. https://doi.org/10.1016/j.agee.2017.08.029

Rustad LE, Huntington TG, Boone RD (2000) Controls on soil respiration: implications for climate change. Biogeochemistry 48(1):1–6. https://doi.org/10.1023/A:1006255431298

Sailor DJ, Resh K, Segura D (2006) Field measurement of albedo for limited extent test surfaces. Sol Energy 80(5):589–599. https://doi.org/10.1016/j.solener.2005.03.012

Sohi SP, Krull E, Lopez-Capel E, Bol R (2010) A review of biochar and its use and function in soil. Elsevier Science & Technology, San Diego

Tammeorg P, Simojoki A, Mäkelä P, Stoddard FL, Alakukku L, Helenius J (2014) Biochar application to a fertile sandy clay loam in boreal conditions: effects on soil properties and yield formation of wheat, turnip rape and faba bean. Plant Soil 374(1-2):89–107. https://doi.org/10.1007/s11104-013-1851-5

Wang J, Pan X, Liu Y, Zhang X, Xiong Z (2012) Effects of biochar amendment in two soils on greenhouse gas emissions and crop production. Plant Soil 360(1-2):287–298. https://doi.org/10.1007/s11104-012-1250-3

Wang D, Griffin DE, Parikh SJ, Scow KM (2016a) Impact of biochar amendment on soil water soluble carbon in the context of extreme hydrological events. Chemosphere 160:287–292. https://doi.org/10.1016/j.chemosphere.2016.06.100

Wang J, Xiong Z, Kuzyakov Y (2016b) Biochar stability in soil: meta-analysis of decomposition and priming effects. GCB Bioenergy 8(3):512–523. https://doi.org/10.1111/gcbb.12266

Whittaker C, Yates NE, Powers SJ, Donovan N, Misselbrook T (2016) Testing the use of static chamber boxes to monitor greenhouse gas emissions from wood chip storage heaps. Bioenerg Res 10:353–362. https://doi.org/10.1007/s12155-016-9800-9

Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S (2010) Sustainable biochar to mitigate global climate change. Nat Commun 1(5):1–9. https://doi.org/10.1038/ncomms1053

Yang X, Lan Y, Meng J, Chen W, Huang Y, Cheng X, He T, Cao T, Liu Z, Jiang L, Gao J (2017) Effects of maize stover and its derived biochar on greenhouse gases emissions and C-budget of brown earth in Northeast China. Environ Sci Pollut Res 24(9):8200–8209. https://doi.org/10.1007/s11356-017-8500-0

Yu L, Lu X, He Y, Brookes PC, Liao H, JM X (2017) Combined biochar and nitrogen fertilizer reduces soil acidity and promotes nutrient use efficiency by soybean crop. J Soils Sediments 17(3):599–610. https://doi.org/10.1007/s11368-016-1447-9

Zhang Y, Wang X, Pan Y, Wang Z, Hu R (2011) The dependence of surface albedo on soil moisture in an arid desert area. J Desert Res 31:1141–1148

Zhang A, Bian R, Hussain Q, Li L, Pan G, Zheng J, Zhang X, Zheng J (2013a) Change in net global warming potential of a rice-wheat cropping system with biochar soil amendment in a rice paddy from China. Agric Ecosyst Environ 173:37–45. https://doi.org/10.1016/j.agee.2013.04.001

Zhang Q, Wang Y, Wu Y, Wang X, Du Z, Liu X, Song J (2013b) Effects of biochar amendment on soil thermal conductivity, reflectance, and temperature. Soil Sci Soc Am J 77(5):1478–1487. https://doi.org/10.2136/sssaj2012.0180

Zhang Y, Wang X, Hu R, Pan Y, Zhang H (2014) Variation of albedo to soil moisture for sand dunes and biological soil crusts in arid desert ecosystems. Environ Earth Sci 71(3):1281–1288. https://doi.org/10.1007/s12665-013-2532-7

Zimmerman AR, Gao B, Ahn M (2011) Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. Soil Biol Biochem 43(6):1169–1179. https://doi.org/10.1016/j.soilbio.2011.02.005