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Effects of biochar on spatial and temporal changes in soil temperature in cold waterlogged rice paddies

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ABSTRACT

Soil temperature is an important factor constraining plant growth, large fluctuations of which generally result in low crop yield. However, the investigation of the effect of biochar on soil temperature, especially in cold waterlogged paddies, has been limited. This study investigated the effect of bamboo biochar (BB), rice straw biochar (RB), and rice straw (RS) on temporal variations in soil temperature at different depths, compared with no exogenous organic matter amendment soil as control treatment (CK), in a cold waterlogged paddy in Zhejiang Province, China. A logger with probes was used to record soil temperatures at the depths of 5 cm, 10 cm, and 20 cm at 08:00 h, 14:00 h, and 22:00 h daily from July 1 to Oct 31, 2012. Soil physicochemical properties and rice yield were analyzed after the harvest. The results showed that the application of BB and RB significantly reduced the soil temperature at 5- and 10-cm depths by 0.11 °C–0.21 °C on average, whereas RS significantly reduced soil temperature at a 5-cm depth by 0.19 °C and increased the average temperature at a 20-cm depth by 0.06 °C. Moreover, the average soil temperature related to BB, RB, and RS treatment significantly increased at 08:00 h during the rice-growing season by 0.15 °C, 0.43 °C, and 0.52 °C and significantly decreased at 14:00 h by 0.51 °C, 0.73 °C, and 0.87 °C, respectively, as compared with that in CK. Overall, both biochar and RS reduced the differences between day and night soil temperatures by 0.66 °C–1.39 °C, thereby regulating diurnal soil-temperature fluctuations, especially at a 5-cm depth. The reduced differences were likely attributed to the relatively lower bulk density (8.87–17.1%) and higher water content (9.75–14.3%) in the biochar-amended soil as compared with that in control soil. Furthermore, RB had a significant stronger positive effect on grain yield than BB, because it regulated soil temperature more effectively. These results suggested the feasibility of applying RB to cold waterlogged paddies to improve soil properties and crop yield.

1. Introduction

A cold waterlogged paddy refers to a kind of low-yield rice paddy that results from relatively low soil temperature (generally 3–5 °C lower than normal rice paddies in summer and autumn) and long-term water accumulation on the soil surface (Xie et al., 2015). Cold waterlogged paddies typically have a low-to-average crop yield due to their high groundwater table, poor drainage, relatively low soil temperature, poor aeration, low content of available nutrients [especially soil-available phosphorous (P)], and excessive amounts of soil reducing substances (Qiu et al., 2013; Xie et al., 2015). However, cold waterlogged paddies tend to be rich in organic matter, and their soil fertility can be improved with appropriate targeted measures to increase the crop yield.

Soil temperature is an important physical property that affects the biochemical cycles of soil carbon (C), nitrogen (N), and other elements and determines the level of soil quality to some extent, thereby affecting plant growth, seed germination, and crop yields (Zhang et al., 2009). Previous research suggested that large fluctuations in soil temperature can constrain plant growth (Zhang et al., 2013). Compared with normal conditions, a much lower soil temperature might result in a slower water flow in soil, and, thus, poor contact between plant roots and soil particles, whereas much higher soil temperatures can lead to excessive evaporation of soil water (Zhang et al., 2013). Therefore, controlling soil temperature is of great importance for agricultural productivity (Ekwue et al., 2006). Generally, rice growth is inhibited, resulting in decreased grain yield via the low soil temperature and considerable accumulation of reducing substances that result from the perpetual waterlogging and hypoxic conditions in cold waterlogged paddies (Xie et al., 2015). Potential solutions to these problems in cold waterlogged paddies can be the application of soil amendments, such as biochar.

Biochar is produced through the pyrolysis of agricultural and

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Table 1
Basic physicochemical properties of biochar.

Biochar	pH	C (%)	N (%)	P (%)	K (%)	CEC ($mol_c\ kg^{-1}$)	Special surface area ($m^2\ g^{-1}$)	Total pore volume ($cm^3\ g^{-1}$)	Bulk density ($g\ cm^{-3}$)
BB	9.8	86.9	0.69	0.11	0.56	15.3	189.6	0.175	0.57
RB	10.2	42.7	0.76	0.16	1.07	44.7	81.8	0.080	0.13

BB: bamboo biochar, RB: rice straw biochar.

forestry biomass and usually has a well-developed pore structure, large surface area, high degree of stability, and good adsorption properties (Kim et al., 2011; Sohi et al., 2010). Biochar plays an important role in increasing soil C reserves, retaining soil nutrients, building soil fertility, and in most cases increasing crop yield (Chan et al., 2007; Drake et al., 2015; Liu et al., 2011; Prendergast-Miller et al., 2014; Sika and Hardie, 2014; Steinbeiss et al., 2009). Biochar characteristics are generally dependent upon biomass type and the pyrolysis process (Bruun et al., 2011; Cantrell et al., 2012; Peng et al., 2011) and can be produced from a wide range of biomass materials, such as crop residues, shrubs, greenwaste, and even livestock manures (Jeffery et al., 2011; Liu et al., 2017). In China, large quantities of crop residues, including rice straw (RS), are produced annually. With an annual increase of 10%–30% in biomass accumulation (Ding et al., 2010), bamboo can be selectively harvested and regenerated without replanting, making it an attractive feedstock for biochar production.

Although the effects of biochar as a soil amendment on certain soil properties, including pH, soil organic C, and nutrient content, are well known (Butnan et al., 2015; Huang et al., 2013; Peng et al., 2011), its influence on soil temperature in cold waterlogged paddies remains unclear. Biochar is a black material, which can darken soil color and decrease soil reflectance when applied to soils, and soil darkening has an ecologically important effect on increasing sunlight absorption, soil temperature, and evaporation rates (Briggs et al., 2005). Furthermore, the thermal conductivity of soil can be reduced by biochar amendment (Zhang et al., 2013), which in turn slows energy release from biochar-amended soil and ultimately leads to higher soil temperatures. In addition to biochar, crop straws are often incorporated into soil as natural supplements containing valuable nutrients and organic C in sustainable agriculture (Lal, 2009). Incorporating RS into topsoil has become a common practice that has increased crop yield and soil fertility in many parts of China (Wang et al., 2015). The effect of biochar and RS on soil physicochemical properties might directly or indirectly influence soil thermal conductivity, soil thermal capacity, and, thus, soil temperature. Accordingly, we hypothesized that biochar and RS addition could significantly increase soil temperature, thereby increasing rice yield in cold waterlogged paddies. Therefore, in this study, we conducted a field experiment to investigate the effect of exogenous organic matter [bamboo biochar (BB), RS biochar (RB), and RS] on soil temperature at different depths in a cold waterlogged paddy. Our findings provide a basis for agricultural-management measures that promote crop yield in cold waterlogged paddies.

2. Material and methods

2.1. Study site

This study was performed in Yiwu City, Zhejiang Province, China (120°02′11″E, 29°08′25″N), which has a subtropical humid monsoon climate with a mean annual temperature of 17.0 °C, as well as a maximum mean monthly temperature of 29.3 °C in July and a minimum mean monthly temperature of 4.2 °C in January. The mean annual precipitation ranges from 1100 mm to 1600 mm, with 2129.7 h of mean annual sunshine hours and 243 mean annual frost-free days. The altitude of the test field was 82 m above sea level. The soil type was gley paddy soil comprising 34.44% sand, 38.03% silt, and 27.53% clay. A cold waterlogged paddy field with homogeneous soil fertility was chosen near the Baifeng Reservoir. The basic physicochemical properties of the surface-layer soil (0–20 cm) were assessed before the experiment and were as follows: pH (1:2.5 H_2O), 6.16; total organic matter content, 39.2 $g\ kg^{-1}$; total N, 2.12 $g\ kg^{-1}$; available P, 8.02 $mg\ kg^{-1}$; and available potassium (K), 50.5 $mg\ kg^{-1}$.

2.2. Materials

Three types of exogenous organic matter (BB, RB, and RS) were chosen as soil-temperature conditioners. BB and RB were derived from the pyrolysis of bamboo chips and RS at 600 °C and 550 °C, respectively, in a programmable tube furnace (Hangzhou Lantian Instrument Co., Ltd., Hangzhou, China). Typically, the prepared biomass was batch pyrolyzed under anaerobic conditions at a heating rate of 25 $°C\ min^{-1}$ and a residence time of 1 h. The produced biochars were allowed to cool to room temperature. RS used as a soil temperature conditioner was cut and dried from the previous harvest. Biochar mass was ground to pass through a 2-mm sieve to obtain a fine granular consistency that would mix uniformly with the soil. The basic physicochemical properties of the biochar are shown in Table 1. The pH was measured at a solid-to-water ratio of 1:10. The C and N contents of biochar were determined using an elemental analyzer (Vario EL/micro cube, Elementar, Germany). The P and K contents were measured following the protocols described by Lu (2000). Cation exchange capacity (CEC) was determined by 1 $mol\ L^{-1}$ sodium acetate (pH 8.2) extraction, followed by flame photometry (FP6410, INESA, China). Specific surface area and total pore volume were measured using a BET surface area analyzer (ASAP2020, Micromeritics, USA).

2.3. Field-trial design

The field experiment consisted of three treatments (BB, RB, and RS) and a control (CK). Three plots of 5.4 × 7.1 m were established for each treatment and CK in a completely randomized block design. At the beginning of the experiment in June 2012, we added BB, RB, or RS to each experimental plot at a rate of 4.5 $t\ C\ ha^{-1}$, which corresponded to 5.18, 10.5, and 10.7 $t\ ha^{-1}$, respectively. Biochar was spread on the soil surface, thoroughly mixed with the soil using a wooden rake, and then ploughed to a depth of 20 cm. The CK plots were subject to the same tillage process without the addition of exogenous C. The plots were managed for rice production using conventional methods.

N fertilizer was applied at a concentration of 180 $kg\ N\ ha^{-1}$ for all treatments and CK. A local rice cultivar (Yongyou 9) was transplanted at a row-and-plant spacing of 15 × 20 cm on July 19, 2012, and manually harvested on November 1, 2012.

2.4. Sampling and measurements

A datalogger with temperature probes (CR1000, Campbell Scientific, USA) was used to record soil temperature at depths of 5 cm, 10 cm, and 20 cm in each of our experimental plots at 08:00 h, 14:00 h, and 22:00 h local time daily from July 1 to October 31, 2012. Data were recorded hourly on the 20th day of each month.

Ordinary soil samples were taken from the 0- to 15-cm soil layer of each plot after harvest. To measure bulk density, separate undisturbed soil samples were collected using cores (volume: ~100 cm^3) in the middle of the 0- to 10-cm soil layers. All samples were sealed in plastic