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Impacts of biochar addition on rice yield and soil properties in a cold waterlogged paddy for two crop seasons

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ABSTRACT

Cold waterlogged paddies typically have low to average yield due to their relatively low soil temperature, poorly developed plough layer, and lack of available nutrients. Despite the above, yield can be improved by targeted measures, such as supplementing with special organic materials. Past research has shown that biochar can play an important role in sequestering soil C, building soil fertility, and improving crop yield. However, the effects of biochar on crop yield and soil properties in cold waterlogged paddies have not been thoroughly investigated. We hypothesized that biochar improves soil fertility, and thus, increases rice grain yield in cold waterlogged paddies. A 2-year field experiment was conducted in 2011 and 2012 to investigate the effect of bamboo biochar (BB), rice straw biochar (RB), and rice straw (RS) on soil physical and chemical properties, grain yield, and yield components in a cold waterlogged paddy in Zhejiang Province, China. Results showed that both BB and RB significantly increased soil pH and soil organic carbon compared to control, whereas their effects on total N were either very small or non-significant. Application of RB significantly increased soil available P and K in both years, and the increases relative to control were greater in 2011 (by 33.9% and 99.1%, respectively) than in 2012 (by 15.3% and 28.6%, respectively). Moreover, RB application resulted in the greatest improvement in grain yield (8.5–10.7% greater than that from the control), and this may be attributed to increased nutrient availability (mainly P and K). Yield component analysis indicated that experimental treatments had the greatest effect on thousand-grain weight, followed by the number of productive tillers per plant and harvest index. Neither biochar nor RS significantly affected the total nutrient ($N+P_2O_5+K_2O$) content of grains, although the K content of grains from BB and RB plots was significantly higher than in those from control plots in 2012. The total nutrient content of straw under RB treatment was significantly higher than that under control and RS treatments in 2012, mainly due to increased K content (by 12.0%) of straw. The total nutrient uptake by grain was significantly (13.6–16.4%) higher under RB treatment than under control treatment. This was primarily due to the relatively high K uptake by RB grains (15.9–22.6% greater than that by the controls). Similarly, the total nutrient uptake by straw from RB plots was significantly greater than that of straw from the control plot. Further studies on biochar in cold waterlogged paddies are essential in order to evaluate the long-term effects of biochar and its behavior in soils.

1. Introduction

Cold waterlogged paddy fields are formed when the groundwater level rises due to local topographical and hydrological conditions, leading to perpetual water accumulation on the soil surface (Xie et al., 2015). These paddy fields occur mainly in mountain valleys, lake marshes, mountain ponds, and land downstream of dams. The parent materials of cold waterlogged paddies are mainly lake sediments, fluvial materials, and valley alluvial materials. Because of year-round water coverage and extensive waterlogged conditions, cold waterlogged paddies have relatively low soil temperatures, few soil aggregates, poorly developed plough layers, a lack of available nutrients (especially soil available P), and an accumulation of soil reducing substances (Jiao et al., 2012; Xie et al., 2015). This combination results in poor productivity. Such systems are common in low-lying land in eight provinces of southern China (Qiu et al., 2013). In China, there are about 3.46 million hectares of cold waterlogged paddies, accounting for 15.1% percent of the total paddy area and 44.2% of the low-yield paddy area (Chai et al., 2012). They are therefore a major obstacle to increasing rice production.

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However, cold waterlogged paddies tend to be rich in organic matter. There is great potential for soil fertility improvement in these paddies that would result in increased crop yield if appropriate and economical targeted measures are taken (Qiu et al., 2013). Therefore, exploring effective ways of improving soil properties and crop yield in cold waterlogged paddies has important practical significance.

Biochar that is produced by pyrolysis of agriculture and forestry residues typically has a well-developed pore structure, huge surface area, high degree of stability and great adsorption properties (Kei et al., 2004). Biochar can increase soil carbon reserves, hold soil nutrients, build soil fertility, and increase crop yield (Chan et al., 2007; Lehmann et al., 2003; Novak et al., 2009; Steiner et al., 2007). Generally, the characteristics of biochar depend mainly on the type of the feedstock and pyrolysis process. Biochar can be produced from a wide range of biomass sources, such as crop residues, shrubs, greenwaste, and even livestock manures. In China, large quantities of crop residues including rice straw are produced annually; with a 10–30% annual increase in biomass accumulation, bamboo can be selectively harvested and regenerated without replanting, making it an attractive feedstock for biochar production.

Studies of the effects of biochar on soil properties have yielded highly variable results that depend on the biochar type and experimental conditions. The impact of biochar on soil properties and crop production in cold waterlogged paddies is yet to be thoroughly assessed. We hypothesized that biochar addition can significantly affect soil properties, such as pH and organic carbon content, in cold waterlogged paddies and these effects will aid plant development and improve grain yield. Furthermore, as natural supplements containing valuable nutrients and organic carbon, crop straws are often incorporated into soils in sustainable agriculture. Incorporating rice straw into the topsoil has become a common practice which tended to increase crop yield and soil fertility in large parts of China (Wang et al., 2015). Therefore, a 2-year consecutive field experiment was conducted to investigate the effect of bamboo biochar (BB), rice straw biochar (RB), and rice straw (RS) on soil physical and chemical properties and rice yield in a cold waterlogged paddy. This research provides a basis for development of agricultural management measures for promoting soil quality and crop yield in cold waterlogged paddies.

2. Materials and methods

2.1. Materials

Three kinds of exogenous organic materials (BB, RB, and RS) were used as soil additives. BB was derived from pyrolysis of bamboo chips at 600 °C for 1 h. RB was derived from pyrolysis of rice straw at 550 °C for 1 h. The moisture contents of the bamboo chips and rice straw prior to pyrolysis were both 10%. RS used as soil additive was the same as the rice straw material used for pyrolysis. For the field study, particulate biochar mass was ground to pass through a 2 mm sieve, and mixed thoroughly to obtain a fine granular consistency that would mix uniformly with the soil mass. The basic physical and chemical properties of the pyrolysis materials and tested biochar were as shown in Table 1.

2.2. Field trial

The experiment was carried out in Yiwu City, Zhejiang, China (120°02′11′′E, 29°08′25′′N). The altitude of the test field was 82 m. The soil type was gley paddy soil. A cold waterlogged paddy field with smooth, homogeneous soil fertility, and consistent stubble near the Baifeng Reservoir was selected for this study. The basic physical and chemical properties of the surface layer of soil (0–20 cm) prior to the experiment were 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 K 50.5 mg kg^{-1}.

There were 4 treatments in the field experiment: BB, RB, RS, and control (CK). Three plots were established for each treatment in a randomized block design. Each treatment plot was 5.4 m × 7.1 m in area. At the beginning of the experiment in June of 2011, we added BB, RB, or RS to each experimental plot at the 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 surface, thoroughly mixed with the soil using a wooden rake, and then plowed to a depth of 20 cm. No additional biochar was added in the following year. No exogenous C was added to CK plots. The experimental plots were separated by protection rows that were 1.2 m in width, each with an irrigation and drainage outlet. Conventional farm management for rice production was consistently performed for two rice cycles.

Nitrogen fertilizer as urea was applied to all plots at a rate 150 and 180 kg N ha^{-1} in the 2011 and 2012 rice-growing cycles, respectively. Of the total applied urea, 70% was applied as a base fertilizer before transplanting, and the remaining 30% was applied at the tillering stage. Calcium biphosphate and KCl were also applied as basal fertilizers before transplanting at the rates of 54 kg P_2O_5 ha^{-1} and 75 kg K_2O ha^{-1} in 2011 and 72 kg P_2O_5 ha^{-1} and 108 kg K_2O ha^{-1} in 2012. Rice (Yong-you 9) was bred for local rice cultivation and was conventionally cultivated in the area by local farmers. Rice was transplanted at plant and row spacing of 15 cm × 20 cm on July 27, 2011 and July 19, 2012, and manually harvested on November 12 in 2011, and November 1 in 2012.

2.3. Sampling and measurements

Soil samples were taken from the 0–15 cm soil layer of each plot after rice harvest in both years. The samples were sealed in plastic bags and shipped to the laboratory within 1 day after sampling. After air-drying, the samples were sieved <0.15 mm. Soil pH was measured using a pH meter (PB-10, Sartorius, China). Soil organic carbon (SOC) was measured by $K_2Cr_2O_7$–H_2SO_4 oxidation. Total N was measured by the semimicro-Kjeldahl method (Lu, 2000). Available P was measured by treatment with 0.5 mol L^{-1} $NaHCO_3$ (pH 8.5) followed by molybdenum blue colorimetry (Lu, 2000). Available K was measured by 1 mol L^{-1} NH_4OAc extraction-flame photometry (Lu, 2000).

Biochar properties, such as pH, were measured at a solid: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 were measured following the protocols recommended by Lu (2000). Cation exchange capacity (CEC) was determined by 1 mol L^{-1} pH 8.2 sodium acetate extraction followed by flamephotometry. Special surface area and total pore volume were measured using a BET surface area analyzer (ASAP2020, Micromeritics, USA).

Before the final harvest, five plants were collected from each plot in order to determine yield components, including productive tillers per plant and thousand-grain weight. Rice plant height was measured *in situ*. Rice grain and straw yields were measured by harvesting the whole plots. Harvest index was calculated as grain mass/total above ground plant dry mass. The grain and straw samples were air-dried and ground into powder by a grinder prior to analysis. Nutrient (N, P, and K) content of grain and straw were determined according to Haefele et al. (2011) as a percentage of dry biomass. Nutrient uptake by grain and straw was then calculated by multiplying nutrient concentrations by grain and straw yields. Total nutrient content was calculated as the sum of N, P_2O_5, and K_2O contents.