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Effects of biochar amendment on net greenhouse gas emissions and soil fertility in a double rice cropping system: A 4-year field experiment

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ABSTRACT

A 4-year field experiment was conducted to investigate the effects of biochar amendment on the net greenhouse gas emission (NGHGE), greenhouse gas intensity (GHGI), soil fertility and crop yield in a typical double rice cropping system in the central subtropics of China, from April 2012 to April 2016. Three biochar treatments were studied in this experiment, with application rates of 0, 24 and 48 t ha^{-1} (named CK, LB and HB, respectively) using straw-derived biochar applied once at the beginning of the experiment. In each treatment, the fluxes of methane (CH_4), nitrous oxide (N_2O) and soil heterotrophic respiration (Rh) were measured using a static chamber/gas chromatography method. Major soil fertility properties were also determined throughout the experimental period. Biochar amendment was found to persistently decrease annual total CH_4 emissions by 20 to 51% in the four years, but increased the annual total N_2O emissions and Rh by 150 to 190% and 2 to 19% in the first year and the following three years, respectively. On a 4-year average, biochar addition significantly reduced annual NGHGE and GHGI by 156 to 264% and 159 to 278%, respectively ($p < 0.05$), with much higher reduction in the first year than those in the following three years (916 to 1911% vs 24 to 51%) due to soil carbon sequestration from biochar addition in the first year. The reduction of NGHGE and GHGI was mainly caused by the decrease of CH_4 emissions (71 to 74% contribution), and the increase of soil carbon sequestration (25 to 29% contribution) in biochar treatments. Biochar amendment also significantly and persistently increased soil pH, total organic carbon (TOC), total nitrogen (TSN), and total phosphorus (TSP) by 6 to 14%, 33 to 61%, 11 to 15%, and 9 to 12%, respectively ($p < 0.05$), in the four years. Significant increases ($p < 0.05$) of microbial biomass carbon and nitrogen contents were found only in the first year after biochar amendment. Soil pH was also increased significantly ($p < 0.05$) with biochar amendment, but showed a declining trend in the four years. Annual grain yields for the biochar treatments were enhanced by 1 to 13%, with an average of 4 to 7% in the four years, compared to CK ($p = 0.07$–0.26). Compared to the LB treatment, the HB treatment significantly decreased average NGHGE and GHGI, and significantly increased average soil pH value and TOC content, but there was no significantly difference in average TSN, TSP, and yield between LB and HB treatments ($p < 0.05$). The gross margin analysis by considering the profit from rice grain, gain for NGHGE, and cost for biochar indicated that the economical profit for the LB treatment might be higher than that for the CK and HB treatments. Our results suggest that addition of biochar at 24 t ha^{-1} can be regarded as a consistently effective and economic measure for greenhouse gas emission mitigation, and soil fertility improvement, in the double rice cropping system.

1. Introduction

Rice is one of the most important cereal crops, accounting for approximately 20% of global irrigated plantations, and is the main food source for more than half of the world's population (FAO, 2012; Frolking et al., 2002; Khush, 2005). On the other hand, rice paddy fields

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are one of the greatest emission sources of greenhouse gases (GHG), particularly CH_4 (Su et al., 2015; Wang et al., 2017). Annual CH_4 emissions from rice paddy account for 12% of the total CH_4 emissions in the globe (IPCC, 2013). Moreover, the total GHG emissions from paddy fields show an increasing trend of 26 (366 to 512) Tg per decade over 1961 to 2016 (FAO, 2016). In the recent decades, the long-term use of chemical fertilizers has caused soil quality degradation in croplands, and thus is harmful to food security. For example, Guo et al. (2010) found soil pH declined significantly from 1980s to 2000s in major croplands in China due to long-term overuse of nitrogen (N) fertilizer. Chen et al. (2009) found, in a 17-year field experiment, that inappropriate fertilization had caused degradation of paddy soil, which included high acidity, low nutrients, and decrease of soil aggregate stability, whilst Kumar and Yadav (2001) found that the long-term application of chemical fertilizer decreased soil fertility and rice yield in a rice-wheat system, during a 20-year field experiment. Therefore, practical approaches for decreasing GHG emissions, and increasing agricultural sustainability and production, are required for paddy rice production (Li et al., 2016; Mueller et al., 2012; Shang et al., 2011).

Biochar is produced by pyrolysis of biomass waste (Meyer et al., 2011). It is a porous and alkaline material, with high content of recalcitrant carbon (C) (Lehmann, 2007). Biochar amendment to soils has been proposed as a potential measure to mitigate GHG emissions and improve soil fertility (Cernansky, 2015; Lehmann, 2007; Woolf et al., 2010). However, a number of studies found that the environmental effects of biochar varied in soils over time, due to the ageing of biochar (Cheng and Lehmann, 2009; Fang et al., 2014; Hockaday et al., 2007).

Both incubation and field studies have showed that biochar application could decrease GHG emissions (Lehmann and Joseph, 2015; Shen et al., 2014). Feng et al. (2012) observed that biochar amendment could greatly decrease CH_4 emissions due to the decrease of the ratio of methanogens to methanotrophs in paddy soil. Likewise, a pot experiment by Khan et al. (2013) showed that sewage sludge biochar application significantly decreased N_2O emissions, and made paddy soil a CH_4 sink. In a paddy field in Tai Lake plain, China, Zhang et al. (2010) showed that straw-derived biochar amendment could decrease N_2O emissions by 40 to 51%, but increase CH_4 emissions by 31 to 49%, compared to the control. The soil heterotrophic respiration (Rh) was often increased with biochar application in short-term experiments (Farrell et al., 2013; Luo et al., 2011; Singh and Cowie, 2014). Troy et al. (2013) observed that the addition of pig manure and wood biochar increased Rh due to the increase of carbon mineralization rate in a short-term incubation experiment. In a 505-day incubation experiment in Florida soils, Zimmerman et al. (2011) found that grass biochar addition increased soil Rh in the early incubation stage, but suppressed it in the final incubation stage.

Biochar application also has the potential to improve soil fertility (Hussain et al., 2016; Lehmann and Joseph, 2015). Biochar could retain soil nutrients, by its high cation exchange capacity (CEC), pore structure, and functional groups; it could also stimulate microbial growth (Lehmann et al., 2003; Hollister et al., 2013; Nelissen et al., 2015; Xu et al., 2016). During a 150-day incubation experiment, Xu et al. (2016) reported that the 40 and 160 t ha^{-1} biochar amendment increased soil microbial biomass carbon (MBC), and nitrogen (MBN) contents, in fluvo-aquic soils. Taking Zhang et al. (2010) as an example, they reported that biochar application lowered soil bulk density (BD), and enhanced rice yields by 9 to 12%, in a paddy field in the Tai Lake plain, China. Biochar-induced increases in soil pH value were observed in most of the research (Carvalho et al., 2016; Zhang et al., 2010, 2012). The increase of soil pH value could increase nutrient availability, thus enhancing crop yields in acidic soil (Lehmann et al., 2003; Major et al., 2010). Major et al. (2010) found that maize yields were not significantly enhanced by a single addition of 20 t ha^{-1} of biochar in the first year, but that significant increases were observed during the last 3 years after biochar application. Similarly, Liang et al. (2014) found that biochar amendment could increase soil pH, and the cumulative yields of four growing seasons, although there was no significant yield increase for the first three of these growing seasons. Zhang et al. (2010, 2012) reported that soil total nitrogen (TSN), total organic carbon (TOC), and rice grain yields were increased by biochar addition in the two-year field experiment. In incubation experiments, biochar application enhanced phosphorus (P) sorption and retention capacity, by increasing soil pH values in acidic soils (Laird et al., 2010a, 2010b). Similarly, Zhai et al. (2015) found that 8% (mass ratio of biochar/soil) biochar application could substantially increase soil available P from 3 to 46 mg kg^{-1} in acid red soil through a short-term incubation experiment. Song et al. (2014) reported that application of sewage sludge biochar at 450 °C increased the rate of potassium (K) leaching, but enhanced garlic yields.

Previous studies mainly focused on the effects of biochar amendment on GHG emissions and soil fertility in short-term experiments, and have rarely measured the impact of a single biochar addition on net greenhouse gas emission (NGHGE, the net global warming effects of CH_4 and N_2O emissions, and soil carbon sequestration), and soil fertility, with ageing of biochar in soils. Considering that added biochar in soil may age, and thus may change some of its properties, e.g. physical structures, and aromatic moieties (Hockaday et al., 2006; Kuzyakov et al., 2014; Mohanty and Boehm, 2015), we hypothesize that the effects of biochar addition on GHG emissions and soil fertility may vary over time. In this study, the effects of biochar amendment on NGHGE and soil fertility were investigated in a double rice cropping system during four years in the central subtropics of China. The main objectives of this study were to evaluate the long-term effects of the biochar application on NGHGE and soil fertility in the paddy field, and to try to answer if straw biochar application could be a consistently effective strategy for the mitigation of NGHGE, while simultaneously improving soil fertility, in a double rice cropping system.

2. Materials and methods

2.1. Experimental site and biochar used

The field experiment was carried out over four annual cycles (a cycle included early rice season, late rice season, and fallow season), from April 2012 to April 2016, in typical double rice paddies (ca 50 years old) in Jinjing, Changsha County, Hunan Province, China (113°19′52″E, 28°33′04″N, elevation of 80 m). The region is featured a subtropical monsoon climate, with an annual average precipitation and air temperature of 1330 mm and 17.5 °C, respectively, and a frost-free period of about 300 days. The daily air temperature and precipitation were recorded by a weather station (Inteliment Advantage, Dynamax Inc., USA), located approximately 100 m from the sampling fields. The soil at the experimental fields is classified as Stannic Anthrosol in Chinese soil taxonomy (Gong et al., 2007) or Ultisol in USDA soil taxonomy or Hydragric Anthrosol in the World Reference Base for Soil Resources (FAO, 2015). Biochar was prepared from wheat straw, at a pyrolysis temperature of 500 °C, at Sanli New Energy Company, Henan, China. The basic properties of the soil, and the biochar composition, were described in Table 1.

2.2. Experimental design

The experiment consisted of three treatments in field plots (7 × 5 m^2), replicated three times, in a randomized block design. The treatments were as follows: (1) control treatment (no biochar amendment) (CK), (2) low biochar amendment rate treatment (24 t ha^{-1}), corresponding to 1% of the topsoil weight (0–20 cm) (LB), (3) high biochar amendment rate treatment (48 t ha^{-1}), corresponding to 2% of the topsoil weight (0–20 cm) (HB). The biochar was evenly spread on the soil surface, and thoroughly mixed with the topsoil by ploughing, on April 25, 2012. No more biochar was applied over the rest course of the experiment.