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RESEARCH ARTICLE

Effects of straw and biochar addition on soil nitrogen, carbon, and super rice yield in cold waterlogged paddy soils of North China

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Abstract

The additions of straw and biochar have been suggested to increase soil fertility, carbon sequestration, and crop productivity of agricultural lands. To our knowledge, there is little information on the effects of straw and biochar addition on soil nitrogen form, carbon storage, and super rice yield in cold waterlogged paddy soils. We performed field trials with four treatments including conventional fertilization system (CK), straw amendment 6 t ha^{-1} (S), biochar amendment 2 t ha^{-1} (C1), and biochar amendment 40 t ha^{-1} (C2). The super *japonica* rice variety, Shennong 265, was selected as the test crop. The results showed that the straw and biochar amendments improved total nitrogen and organic carbon content of the soil, reduced N_2O emissions, and had little influence on nitrogen retention, nitrogen density, and CO_2 emissions. The S and C1 increased NH_4^+-N content, and C2 increased NO_3^--N content. Both S and C1 had little influence on soil organic carbon density (SOCD) and C/N ratio. However, C2 greatly increased SOCD and C/N ratio. C1 and C2 significantly improved the soil carbon sequestration (SCS) by 62.9 and 214.0% ($P<0.05$), respectively, while S had no influence on SCS. C1 and C2 maintained the stability of super rice yield, and significantly reduced CH_4 emissions, global warming potential (GWP), and greenhouse gas intensity (GHGI), whereas S had the opposite and negative effects. In summary, the biochar amendments in cold waterlogged paddy soils of North China increased soil nitrogen and carbon content, improved soil carbon sequestration, and reduced GHG emission without affecting the yield of super rice.

Keywords: biochar, straw, paddy field, nitrogen form, carbon sequestration, greenhouse gas emission, rice yield

1. Introduction

Straw is usually used as animal feed, biofuel, and biomass. However, a large amount of straw is not effectively utilized. In most cases, almost all the straw is either burned or discarded, which is a great waste of raw materials. It also causes serious consequences, such as greenhouse effect and environmental pollution (Cao *et al*. 2005; Tan *et al*. 2006). Therefore, effective utilization of straw is an important issue for the sustainable development of resource,

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environment, and agriculture.

Straw is rich in organic carbon, nitrogen, phosphorus, potassium, silicon, and other mineral nutrients. Returning straw to soil can directly improve the structure as well as the physical and chemical properties of soil. It can also prevent nitrogen loss, reduce greenhouse gas emission, and increase organic carbon content, which is essential for high rice yield (Oyedele *et al*. 1999; Ma *et al*. 2007; Watanabe *et al*. 2009). However, if an inappropriate amount of straw is applied at improper timing and in an improper way, it will cause adverse effects on plant growth (Nardi *et al*. 2004; Hou *et al*. 2012). In particular, the decomposition rate of straw is reduced at low temperatures during winter in Northeast China. Therefore, it is difficult to perform large-scale straw return in cold water-logged paddy soils. Recently, the pyrolysis conversion of crop straw into biochar and using it as a soil amendment has begun to attract increasing attention in China (Fan *et al*. 2012).

Biochar is a carbon-rich substance, produced by thermal decomposition of organic compounds at a relatively low temperature (<700°C) under limited supply of oxygen (Lehmann *et al*. 2006). It contains more than 60% carbon, and is rich in various nutrients and trace elements essential for crop growth (Glaser *et al*. 2002; Demirbas 2004). Retuning biochar to the field can quickly improve soil carbon storage, nitrogen content, and soil fertility. It can also reduce the emission of greenhouse gases and improve crop yields (Lehmann *et al*. 2003; Steiner *et al*. 2007; Laird *et al*. 2009; Van *et al*. 2010a; Feng *et al*. 2012; Li *et al*. 2014). Biochar has a great, stable, and a long-term potential in carbon sequestration. However, the effects of biochar on crop yield are influenced by various factors, such as the properties and amount of biochar, soil type, and environmental conditions (Mclaughlin *et al*. 2009). To date, the effects of biochar on soil nitrogen transformation, nutrient retention, crop growth, and other aspects in different regions are still unclear due to the differences in regional climatic factors and soil properties. Thus, the application of biochar in agriculture remains controversial at present (Biederman and Harpole 2013).

With the advancement in pyrolysis and carbonization technology and the industrialization of straw biochar, an in-depth research and rational use of biochar in fields have become important for an efficient, environment friendly and sustainable development of agriculture. Currently, straw and biochar amendments are mostly performed in South China (Ma *et al*. 2010; Liu *et al*. 2012; Huang *et al*. 2013). However, the field studies on straw and biochar application to cold waterlogged paddy soils of North China are largely lacking. The waterlogged paddy soil in North China has lower soil temperature due to cold climate and immersion in cold water. The soil is relatively heavy clay, with low aeration porosity, less microbial activity, and has slow soil nutrients decomposition rate. Thus, it is important to detect the effects of straw and biochar in different irrigation and eco-climatic regions having such soil. Field trials were conducted in the cold waterlogged paddy field of North China. The aim of this study was to access the effects of straw and biochar amendments on soil nitrogen content, soil carbon storage, greenhouse gas emission, and super rice yield. The results will provide theoretical basis for the application of straw and biochar in cold waterlogged paddy fields.

2. Materials and methods

2.1. Experimental site and materials preparation

Field trials were conducted in the experimental base of Tieling Academy of Agricultural Sciences, which is located in the northern part of Liaoning Province, China (42°14´N, 123°48´E). The region has a typical semi-humid temperate continental monsoon climate with a mean annual temperature of 6.3°C. The accumulated temperature above 10°C was 3 200–3 500°C. The average temperature was 19.1°C with accumulated temperature from April to September being 3 496.9°C. The precipitation was 643.5 mm and the duration of sunshine was 1 357.6 h over the years. Rice has been continuously cultivated in this area for more than 40 years and is directly irrigated from underground cold water at a depth of 30 m. The soil type was gleyic luvisols. The basic properties of the top soil (measured from soil at 0–20 cm depth) were as follows: total nitrogen of 1.06 g kg^{-1}, total phosphorus of 0.85 g kg^{-1}, total potassium of 17.24 g kg^{-1}, available nitrogen of 93.64 mg kg^{-1}, available phosphorus of 38.28 mg kg^{-1}, available potassium of 75.06 mg kg^{-1}, organic carbon of 10.73 g kg^{-1}, and pH value of 6.4. The super rice variety Shennong 265 used in this experiment was compact plant with 15 leaves on the main stem, an erect panicle, and having a good tillering ability.

The straw was chopped into small segments of length in 0.5–1 cm. The biochar was produced by the Liaoning Biochar Engineering & Technology Research Center, China by the pyrolysis of straw at 400–500°C with a residence time of 1 h under oxygen-limited conditions. The commercial process used by the traditional furnace was corn cob carbonization (Chen 2007). With such technology, 1/3 mass of straw was expected to be converted into biochar in the form of granular particles of 1.5–2 mm diameter. The properties of straw were characterized for total organic C and N with an Elementar Vario Max CNS Analyzer (Elementar, Germany). Total oxides of P and K in the straw were dissolved in 25 mL of 1 mol L^{-1} HCl solution and measured using ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometer, Elementar, Germany). The pH of the straw was measured with a compound glass electrode from a 1:5