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Sustainable biochar effects for low carbon crop production: A 5-crop season field experiment on a low fertility soil from Central China

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ABSTRACT

Biochar's effects on improving soil fertility, enhancing crop productivity and reducing greenhouse gases (GHGs) emission from croplands had been well addressed in numerous short-term experiments with biochar soil amendment (BSA) mostly in a single crop season/cropping year. However, the persistence of these effects, after a single biochar application, has not yet been well known due to limited long-term field studies so far. Large scale BSA in agriculture is often commented on the high cost due to large amount of biochar in a single application. Here, we try to show the persistence of biochar effects on soil fertility and crop productivity improvement as well as GHGs emission reduction, using data from a field experiment with BSA for 5-crop seasons in central North China. A single amendment of biochar was performed at rates of 0 (C0), 20 (C20) and 40 t ha^{-1} (C40) before sowing of the first crop season. Emissions of CO_2, CH_4 and N_2O were monitored with static closed chamber method throughout the crop growing season for the 1st, 2nd and 5th cropping. Crop yield was measured and topsoil samples were collected at harvest of each crop season. BSA altered most of the soil physico-chemical properties with a significant increase over control in soil organic carbon (SOC) and available potassium (K) content. The increase in SOC and available K was consistent over the 5-crop seasons after BSA. Despite a significant yield increase in the first maize season, enhancement of crop yield was not consistent over crop seasons without corresponding to the changes in soil nutrient availability. BSA did not change seasonal total CO_2 efflux but greatly reduced N_2O emissions throughout the five seasons. This supported a stable nature of biochar carbon in soil, which played a consistent role in reducing N_2O emission, which showed inter-annual variation with changes in temperature and soil moisture conditions. The biochar effect was much more consistent under C40 than under C20 and with GHGs emission than with soil property and crop yield. Thus, our study suggested that biochar amended in dry land could sustain a low carbon production both of maize and wheat in terms of its efficient carbon sequestration, lower GHGs emission intensity and soil improvement over 5-crop seasons after a single amendment.

1. Introduction

World agriculture is challenged in a trilemma of maintaining high productivity, reducing greenhouse gases (GHGs) emission and adapting to climate change in the near future with still increasing population (Smith et al., 2013). Increasing soil organic carbon storage has been recommended as a key measure to mitigate climate change (Lal, 2004; Smith et al., 2008; Pan et al., 2009) with a couple of co-benefits (Schmidt et al., 2011; Pan et al., 2013). However, the existing practices of conservation tillage and soil amendment with manure or straw return are being questioned for the tradeoffs between carbon sequestered and GHGs emitted as well as limited long-term net mitigation potential (Lam et al., 2013; Leifeld et al., 2013). Other options of minimizing chemical inputs of fertilizer and pesticides would potentially diminish crop yield return. Nevertheless, improving soil fertility and crop productivity in croplands has been proposed as the priority option to deal with this challenge (Stocking, 2003).

Among a number of potential measures, biochar soil amendment (BSA) has been well known as a promising option to enhance soil fertility since biochar has synergic effects on building up stable

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organic carbon storage and reducing GHGs emission as well as mediating ecosystem functioning (Lehmann et al., 2006; Sohi, 2012). This role has been well depicted of the fertile soil of Terra Preta rich in stable charred organic matter in the Amazon area (Glaser et al., 2002). For the last decade, there have been increasing studies demonstrating biochar's significant potential to enhance crop productivity (Jeffery et al., 2011; Liu et al., 2013; Biederman and Harpole, 2013) and to reduce GHGs emissions (Woolf et al., 2010). Great reductions in N_2O emission but insignificant or small changes in CO_2 emission have been observed in many field studies with sustaining/enhancing crop productivity in croplands (Zhang et al., 2010; Castaldi et al., 2011; Taghizadeh-Toosi et al., 2011; Liu et al., 2012; van Zwieten et al., 2013; Cayuela et al., 2013). Particularly in rice paddies, a net carbon balance could vary with biochar application rate as well as with years following biochar application (Zhang et al., 2012a, 2013). Nevertheless, questions still exist if the biochar's effect is synergic between GHGs mitigation and crop productivity enhancement, and sustainable over years after a single application. This becomes critical for assessing biochar's role in world agriculture and for a time frame that biochar application could be rotated for avoiding excess biochar amendment in practice as well as reducing carbon cost due to high biochar price.

Therefore, the objective of this study is to address the changes in biochar's effects on soil quality, crop productivity, carbon stability and GHGs emissions over crop seasons following a single BSA treatment by revisiting measurement data of a 5-crop season field experiment with maize-wheat rotation farming in Central North China. The persistence of biochar's effect on crop yield, soil nutrient status and N_2O mitigation potential as well as the biochar-carbon stability in soil and its dependence on climate conditions are evaluated by comparing the results with different crop seasons.

2. Materials and methods

2.1. Experiment site

The study site was located at Linzhuang Village (34°32′N, 115°30′E), Shangqiu Municipality, Henan Province, China, lying in the central part of the Central Great Plain of North China. The local area is controlled by a semi-humid temperate monsoon climate. During 2003–2012, the mean annual temperature was 13.9 °C, and mean annual precipitation and potential evaporation were 780 mm and 1735 mm, respectively. The soil is a typical calcareous soil derived from paleo-deposits of Yellow River and classified as a calcic Aqui-alluvic Primisol in Chinese Soil Taxonomy (Gong, 1999) and loamy Aqufluvent in US Soil Taxonomy (Soil Survey Staff, USDA 1994). In this area, crop production has been traditionally performed under winter wheat-summer maize rotation.

2.2. Soil and Biochar properties

As described in Zhang et al. (2012b), the basic physico-chemical properties of the topsoil (0–15 cm) before BSA were: pH (H_2O) 8.38, soil organic carbon (SOC) 9.87 g kg^{-1}, total soil nitrogen 0.94 g kg^{-1}, bulk density 1.46 g cm^{-3}. Biochar used in this experiment was from wheat straw pyrolyzed in a vertical kiln at temperature of 350–550 °C (Pan et al., 2011). With this production technology, the conversion rate of straw biomass to biochar is 30%, with 800 m^3 bio-gas and 250 kg bio-liquid per ton of feedstock (Pan et al., 2011). Before use, the biochar was ground to pass through a 2 mm sieve and mix thoroughly so that the biochar would mix more uniformly with the soil. The basic properties of biochar were the following: pH (H_2O) 10.4, organic carbon 467 g kg^{-1}, total N 5.9 g kg^{-1}, K 2.6%, ash content 20.8% (Zhang et al., 2012b).

2.3. Biochar soil amendment treatment

The field experiment was designed with treatment of biochar soil amendment with or without N fertilization for crop production. Each treatment was done in triplicates with a single plot of 4 m × 5 m in area surrounded by a 0.5 m width protection row. The treatment plots were arranged in a complete-random block design (Zhang et al., 2012b).

A single soil amendment of wheat biochar was performed in June, 2010 after wheat harvest at 0, 10 and 40 t ha^{-1} (C0, C20, and C40, respectively). Biochar material was evenly broadcast on soil surface by hand and homogenized to a depth approximately of 15 cm with a tilling tractor. No more biochar amendments were applied throughout the 5-crop seasons in this study. In a single crop season, nitrogen fertilizer (urea) was applied twice with 60% as base fertilizer before sowing and another 40% as dressing at vegetation stage while super phosphate and potassium chloride were applied once as base fertilizer. Irrigation for moistening the soil was performed after seed sowing for maize and when plant turns green for wheat in dry conditions. All the other crop management practices were kept consistent over the treatment plots. Table 1 shows the information of crop cultivars and fertilization regime for the 5-crop seasons under study. The results in the first crop season with maize were published by Zhang et al. (2012b).

2.4. Crop yield measurement and GHGs emission monitoring over crop seasons

Soil sampling, GHGs emission monitoring and crop yield measurement were performed for all the crop seasons except for the third maize in 2011 (S3 in Table 1). Crop yield was estimated manually by collecting all the plants of the plot at harvest.

Over a single crop season, greenhouse gas fluxes were measured with a static closed chamber (Zou et al., 2005) at a 7-day interval except once a day for one week after N fertilizer was applied. In each plot, an aluminum flux collar (0.35 m × 0.35 m) was installed in between crop plants. Gas samples were taken manually using a gastight syringe at 0, 10, 20, 30 min after chamber closure and then injected immediately into a special boron silica glass vial (No. 5, Japan Maruemu Corporation, 2010). Concentrations of CO_2, CH_4 and N_2O of a gas sample were analyzed simultaneously with a gas chromatograph (GC, Agilent 7890D) equipped with a flame ionization detector (FID) and an electron capture detector (ECD). The performance of gas sampling in the field and gas concentration determination conditions were described in detail by Zou et al. (2005) and also by Zhang et al. (2010). Soil temperature and moisture (0–10 cm) were also measured respectively in a 7-day and a 14-day interval while gas sampling in the field. Fig. 1 shows the daily precipitation and average daily air temperature during the crop grown seasons investigated.

2.5. Soil sampling and analysis

For all the crop seasons except S3, a composite topsoil (0–15 cm) sample of random 5 subsamples was collected with an Eijkelkamp soil core sampler in each plot. Soil bulk density was measured using a 100 cm^3 cylinder while soil sampling at harvest. Soil samples were placed into sealed plastic bags and shipped to the laboratory within 2 days. The soil sample was air-dried and then ground to pass a 2 mm sieve. A small portion of a soil sample was further ground to pass a 0.15 mm sieve for SOC and total N analysis.