Field Crops Research 205 (2017) 45–54

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Contrasting effects of straw and straw–derived biochar application on net global warming potential in the Loess Plateau of China

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ARTICLE INFO

Article history:
Received 29 September 2016
Received in revised form 6 February 2017
Accepted 7 February 2017

Keywords:
Wheat straw
Wheat straw–derived biochar
Carbon sequestration
Wheat–maize rotation system
Greenhouse gas emissions
Loess Plateau

ABSTRACT

Knowledge about the impacts of the application of organic amendments such as straw and biochar to dryland agricultural soils with respect to soil properties, crop production, soil carbon sequestration and greenhouse gases emissions is limited. The objective of this study was to compare the effects of straw and straw-derived biochar amendments on soil properties, net global warming potential (NGWP) and net greenhouse gas intensity (NGHGI). A field experiment extending over two years was conducted involving simultaneous measurement of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions and soil organic carbon (SOC) content in a wheat–maize crop rotation on the Loess Plateau of China. There were five treatments: control with no amendment (CK); conventional chemical fertilizer only (F); 8 t ha^{-1} wheat straw plus fertilizer (FS); 8 t ha^{-1} straw–derived biochar plus fertilizer (FBlow); and 16 t ha^{-1} straw–derived biochar plus fertilizer (FBhigh). SOC, C:N ratio and high active organic carbon (HAC) increased by 26.4%, 30.8% and 17.1%, respectively in the FBhigh treatment relative to the FS treatment. As compared to the F treatment, addition of straw significantly increased the total soil organic carbon sequestration rate (TSOCSR) in the soil depth of 0–100 cm and CO_2 emissions, but had no significant effect on soil N_2O and CH_4 emissions or crop yield. However, straw–derived biochar amendment significantly decreased N_2O emissions while significantly increasing ($p < 0.05$) crop yield and TSOCSR, but there was no effect on soil CO_2 emissions. Over all, our result showed an overall reduction in NGWP of 37.8% and 31.5% and in NGHGI of 28.1% and 21.2% under straw–derived biochar amendment at 8 t ha^{-1} and 16 t ha^{-1}, respectively as compared to the straw amendment. Thus, amending the soil with straw–derived biochar could provide a mechanism to lower the greenhouse gas intensity while increasing the productivity of wheat and maize cropping system in the Loess Plateau of China.

1. Introduction

Agriculture is one of the major sectors contributing to the greenhouse gases emissions (GHGs), accounting for 5.1–6.1 Pg CO_2-equivalents yr^{-1} of the total global anthropogenic GHGs emissions in 2005 (IPCC, 2014). However, improved agricultural crop management practices can reduce net GHGs emissions by increasing SOC storage and decreasing CH_4 and N_2O emissions (Mosier et al., 2006; Smith et al., 2008).

Intensive summer maize (*Zea mays* L.)–winter wheat (*Triticumaestivum* L.) cropping systems are common agricultural practice in the Guanzhong Plain, which is an important food production area of China (Zhang et al., 2016; Li et al., 2016). Burning straw after the harvesting of maize and wheat is a common practice that leads to 30 days of smog in this region (Li et al., 2016). Instead of burning, incorporation of crop straw into the soil

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Abbreviations: SOC, soil organic carbon; HAC, high active organic carbon; LAC, low active organic carbon; TSOCSR, total soil organic carbon sequestration rate; NGWP, net global warming potential; NGHGI, net greenhouse gas intensity; WFPS, water–filled pore space.

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http://dx.doi.org/10.1016/j.fcr.2017.02.006
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has been widely recommended for sustaining soil organic matter and avoiding the environmental pollution in China. Incorporating the chopped crop straw (5–10 cm long) in soils through tillage accelerates SOC accumulation (Li et al., 2016) and enhances the crop productivity (Liu et al., 2014; Shadrack et al., 2014; Xiong et al., 2015). However, the effects of straw incorporation on soil C and N cycling processes and soil GHGs emissions are still unclear. In a meta−analysis study, Liu et al. (2014) reported that returned straw significantly increased soil CO_2 emissions by 27.8 ± 2.0% in upland and by 51.0 ± 2.0% in paddy soils. The increase in CO_2 emissions could be attributed to increased decomposition of native SOC, a so−called positive priming effect (Muhammad et al., 2007), and increased soil microbial or enzyme activities (Wu et al., 2013). Moreover, straw incorporation into soils has been shown to reduce (Zou et al., 2005; Wang et al., 2011; Wu et al., 2013; Shen et al., 2014; Xiong et al., 2015), have no effect (Shan and Yan, 2013), or increase (Hu et al., 2014) soil N_2O emissions. Such responses vary with crop residue quality, synthetic N fertilizer application, soil properties and other environmental parameters (Huang et al., 2004; Liu et al., 2014). Hence, it is necessary to adopt such agricultural management practices that not only increase the sustainability of intensive agricultural production, but also alleviate the environmental pollution in China (Liu et al., 2014).

The addition of biochar produced via pyrolysis of crop residues to soils has been considered to be a key environmental management option for mitigating the climate change by sequestering C and for sustaining agricultural productivity by improving soil properties and functions (Lehmann et al., 2006; Lehmann, 2007; Liu et al., 2013). Biochar addition to soil also alter soil physical and chemical properties and microbial access to carbon substrates, which in turn affect the biogeochemical cycles of C and N (Lehmann et al., 2011). However, the carbon sequestration potential of biochar has been debated due to its positive priming of native SOC mineralization, leading to a temporary increase in soil respiration (Wardle et al., 2008; Zimmerman et al., 2011; Sui et al., 2016). The positive priming effect of biochar remains for only a very short period of time after application and does not have an influence on soil C sequestration potential (Jones et al., 2011). In fact, scientists have concluded that biochar application reduces the rate of soil organic matter decomposition, suggesting that biochar has an overall negative effect on SOC mineralization. For instance, Liu et al. (2016a) conducted a meta−analysis of literature studies and found no significant priming effect on the native soil C decomposition following biochar application. Also, Weng et al. (2015) reported a short−term positive priming effect but a long-term negative priming effect on SOC mineralization following plant−biochar amendment in an annual ryegrass field system. Moreover, a comprehensive meta-analysis review by Cayuela et al. (2014) concluded that 54 ± 6% of N_2O emission was reduced following biochar application. The abiotic and biotic mechanisms of the reduction in N_2O emission were well documented by Cayuela et al. (2014, 2015). The divergent responses of GHGs emissions to biochar application are probably related to the variation in soil properties (Liu et al., 2016a; Wang et al., 2016) or inherent characteristics of biochar (Cayuela et al., 2014).

The concept of net global warming potential (NGWP) by integrating CO_2, CH_4 and N_2O emissions based on their individual global warming potential (GWP) in a given time horizon (IPCC, 2014), was used to evaluate and compare straw and straw-derived biochar amendments with respect to soil GHGs emissions following application. For the estimation of GWP, CO_2 is typically taken as the reference gas, and the increase or decrease in emissions of CH_4 and N_2O is converted into CO_2-equivalents using the radiative forcing factors (IPCC, 2014). However, there has been uncertainty to estimate of net ecosystem CO_2 fluxes since it is difficult to distinguish soil heterotrophic respiration from soil CO_2 fluxes (Shang et al., 2011; Zhang et al., 2013). In the present study, the net ecosystems CO_2 balance was assessed from the changes in total soil organic carbon sequestration rate (TSOCSR) in the soil depth of 1 m rather than ecosystem CO_2 fluxes. Thus, a net global warming potential (NGWP, kg CO_2 eq ha^{-1}) was further calculated as the sum of the emissions in CO_2-equivalents of CH_4 and N_2O subtracted TSOCSR. Another concept, net greenhouse gas intensity (NGHGI) was used to estimate the climatic impacts of agriculture in terms of per kg of yield, and calculated by dividing NGWP by crop yield (Shang et al., 2011).

Many of the aforementioned investigations have focused on the biochar or straw effects on mitigating GHG emissions from paddy soils and/or on increasing crop production and ameliorating soil physical and chemical properties (Shen et al., 2014; Sui et al., 2016). Furthermore, because of the much greater increase in CH_4 emission relative to the reduction in N_2O emission following straw or biochar incorporation into paddy soils, current studies suggest that the amendment may result in a net increase in global warming potential (Zhang et al., 2010; Sui et al., 2016; Shen et al., 2014). However, there is a knowledge gap on the effects of straw and straw−derived biochar amendment on soil GHG emissions in dryland cropping systems, especially intensively managed winter wheat–summer maize cropping systems on the Guanzhong Plain. In this study, we present field measurements to investigate SOC, CH_4 and N_2O changes following application of straw and straw−derived biochar amendments at various rates during two wheat–maize rotation cycles in the Guanzhong Plain. We tested the hypothesis that the conversion of wheat straw residues to biochar and then application to the soil would decrease the net greenhouse gas intensity while increasing the productivity of the wheat–maize rotation system in the Loess Plateau of China.

2. Materials and methods

2.1. Experimental site

A 2−year field experiment was conducted from October 2013 to October 2015 at the Experimental Station of Water Saving Irrigation of Northwest A&F University, Yangling, Shaanxi Province of China (34°20′ N, 108°24′ E). The site is located in a semi−arid to sub−humid climate zone, with an annual mean precipitation of 620 mm and a mean daily temperature of 13.0 °C. The daily maximum and minimum air temperature and precipitation during the experiment were collected from a nearby weather station, and are presented in Fig. 1. The soils in the region are Earth-cumuli-Orthic Anthrosols, derived from loess deposits with a silt clay loam texture (clay 32%, silt 52% and sand 16%). Basic properties of the topsoil (0–20 cm) are as follows: bulk density of 1.45 ± 0.05 g cm^{-3}, a pH of 8.18 ± 0.02 (soil:water ratio of 1:1), SOC content of 8.14 ± 0.08 g kg^{-1}, total soil nitrogen (TN) of 0.95 ± 0.02 g kg^{-1}, soil $NO_3{}^-$−N of 5.41 ± 0.6 mg kg^{-1}, soil $NH_4{}^+$−N of 1.35 ± 0.2 mg kg^{-1}, Olsen−P of 20.9 ± 1.6 mg kg^{-1}, and available K of 133 ± 2.5 mg kg^{-1}. These values were determined in four composite soil samples across the whole experimental field before the start of the field experiment in October 2013.

2.2. Experimental treatments and field management

Five treatments were established as follows: (1) control with no amendment (CK); (2) conventional chemical fertilizer only (F); (3) 8 t ha^{-1} wheat straw plus fertilizer (FS); (4) 8 t ha^{-1} straw−derived biochar plus fertilizer (FBlow); (5) 16 t ha^{-1} straw−derived biochar plus fertilizer (FBhigh). All treatments were arranged in a randomized complete block design with three replicates. The size of each plot was 10 m^2 (5 m × 2 m). Individual plots were separated