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Annual accounting of net greenhouse gas balance response to biochar addition in a coastal saline bioenergy cropping system in China

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ABSTRACT

The potential of biochar for mitigating climatic impacts of coastal saline bioenergy production is not well established. A full accounting of net greenhouse gas balance (NGHGB) and greenhouse gas intensity (GHGI) affected by biochar amendment combined with or without nitrogen (N) fertilizer application was examined in an annual coastal reclaimed Jerusalem artichoke bioenergy cropping system. The net ecosystem exchange of CO_2 (NEE) was determined by the difference between soil heterotrophic respiration (R_H) and net primary production (NPP) using static chamber method. Biochar amendment raised the seasonal R_H but without suppressing the NPP during the Jerusalem artichoke cropping season. Soil CH_4 emissions were 72% and 80% lower in the biochar amended than unamended plots when combined with N fertilizer application during the Jerusalem artichoke cropping and non-cropping seasons, respectively. The biochar-induced soil N_2O mitigation efficiency was weakened by N fertilizer input over the annual cycle. Annual NGHGB and GHGI were negative for all the field treatments and were significantly lower in biochar amended than in unamended soils, suggesting that Jerusalem artichoke cropping system served as a net sink of GHGs due to net ecosystem CO_2 and biochar-induced C sequestration exceeding CO_2-equivalents released as CH_4 and N_2O emissions. On average, biochar amendment significantly enhanced GHGs sink capacity by resulting in almost 4–5 folds decrease in annual NGHGB or GHGI when combined with N fertilizer application or not. Therefore, higher biomass gain as potential alternative source of biofuels but lower climatic impacts of bioenergy production would be reconciled by biochar use in southeast coastal China.

1. Introduction

Atmospheric carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the most potent long-lived greenhouse gases (GHGs) contributing to climate change. The generation of biofuels from bioenergy crop biomass has been encouraged as a potential option for obtaining renewable energy instead of fossil fuels to abate global warming (Pacala and Socolow, 2004; Goldemberg, 2007; IPCC, 2013). The bioenergy crop is increasingly advocated on global scale, despite that this trend would more or less induce potential land conflicts between bioenergy production and food security (Kates et al., 2001; Fargione et al., 2008; Solomon, 2010). In addition, bioenergy crops production has been considered as an important source of GHGs, and highly needed to be addressed given its potential global warming contribution and uncertainties.

The halophyte bioenergy plant resources have been widely recommended as an alternative source of biomass material for biofuels (Khan and Qaiser, 2006; Zhao et al., 2002). Considering the potential conflicts between bioenergy and grain crops in farmland arable soils in China, non-cultivated coastal saline lands have been extensively developed for bioenergy crops cultivation (Liu et al., 2012a,b). The extreme salinity and other adverse effects enable the non-agricultural coastal lands unsuitable for growth of traditional grain crops but only for halophytes or salt-tolerant plants. For instance, Jerusalem artichoke (*Helianthus tuberosus* L.), as one of the most potential alternatives as source of biofuel, has been widely grown in coastal zones due to its strong adaptability towards stress conditions such as soil salinity and limited soil nutrients (Denoroy, 1996; Long et al., 2005; Guo et al., 2011).

Biochar has been increasingly proposed as a potential management strategy to improve crop productivity and soil quality (Glaser et al., 2002; Lehmann et al., 2011; Chan et al., 2007; Laird, 2008; Woolf et al., 2010; Case et al., 2013). Several recent controlled or field studies have suggested that biochar

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might have potentials to mitigate climate change by increasing soil carbon (C) sequestration and/or reducing a specific greenhouse gas (e.g., CH_4 or N_2O) emissions from grain crops (Lehmann, 2007; Chávez et al., 2012; Stewart et al., 2012; Zhang et al., 2013; Li et al., 2014). However, some laboratory controlled or field incubation studies showed an immediate or short-term increase in soil CO_2 emissions induced by biochar amendment (Spokas et al., 2009; Smith et al., 2010; Zimmerman, 2010; Lehmann et al., 2011). The literature on CH_4 exchange from aerobic soils following biochar addition is limited and mostly comprised of incubation studies, often suggesting a decrease in CH_4 emissions following biochar addition but with large uncertainties (Spokas and Reicosky, 2009; Zhang et al., 2010; Rogovska et al., 2011). A field study in Finland by Karhu et al. (2011) suggested a 96% increase in CH_4 uptake with a 9 t ha^{-1} biochar addition to cropping soils. Biochar to soils has been shown to decrease N_2O emissions (Yanai et al., 2007; Spokas and Reicosky, 2009; Singh et al., 2010; Zhang et al., 2010; Wang et al., 2011), and more obvious in studies when combined with N fertilizer application (Van Zwieten et al., 2010; Taghizadeh-Toosi et al., 2011). However, no or inconsistent effects of biochar amendment on N_2O emissions was recorded in other studies (Clough et al., 2010; Scheer et al., 2011). Therefore, given the uncertainty and discrepancy with regard to the biochar effect on GHGs emissions across the soils, an overall accounting of net greenhouse gas balance (NGHGB) and greenhouse gas intensity (GHGI) derived from soil CO_2, CH_4 and N_2O is needed to evaluate biochar performance on the climatic impact of coastal bioenergy production.

To our knowledge, most of the field GHG flux measurements were taken from traditional bioenergy cropping systems (e.g., sugarcane, sweet sorghum, potato, and cereal), while few studies concentrated on the halophytes bioenergy cropping systems to improve our knowledge on GHGs emissions from coastal saline bioenergy production in response to biochar amendment (Barton et al., 2010; Drewer et al., 2012; Gauder et al., 2012; Zona et al., 2012).

Annual field measurements of soil CO_2, CH_4 and N_2O fluxes as affected by biochar amendment with or without N fertilizer input in a coastal saline Jerusalem artichoke-fallow cropping system were taken in subtropical China. We hypothesized that biochar amendment would increase soil CO_2 emissions but exert no adverse effect on the NPP following an initial large amount of labile biochar-C input within an annual time basis. However, soil CH_4 and N_2O emissions would be suppressed mainly due to improved soil aeration and enhanced soil N immobilization resulting from biochar amendment. Particularly, the decreasing effect of biochar on soil N_2O emissions in initially reclaimed bioenergy cropping soils with low N availability might be subject to N fertilizer in biochar-treated soils. The objectives of this study are to gain an insight into a complete accounting of NGHGB and GHGI derived from soil CO_2, CH_4 and N_2O emissions affected by biochar addition in the presence of N fertilizer or not in an annual coastal saline bioenergy cropping system, and thereby to advance understanding the potential effects of biochar on mitigating climatic impacts of bioenergy crop production in southeast coastal China.

2. Materials and methods

2.1. Biochar and field site description

The biochar used was a by-product of hardwood charcoal production (pyrolysed at 400 °C for 24 h at a local pyrolysis plant in Nanjing, China). Subsequently, the fresh biochar was chipped to achieve a particle size of <5 mm. The top soil (0–15 cm) of the experimental site was classified as fluvoaquic, and had 65% sand, 14% silt and 21% clay. Both chemical and physical properties of the field top soil and biochar are shown in Table 1.

Table 1
Physicochemical properties of top soil (0–15 cm) and biochar used in the field experiment.

Parameters	Soil	Biochar
Texture	Sandy loam	–
pH	8.2 ± 0.2	9.6 ± 0.04
Bulk density (g cm^{-3})	1.28 ± 0.03	0.24 ± 0.02
Salinity (g kg^{-1})	3.24 ± 0.26	–
Total C (g kg^{-1})	11.8 ± 0.5	596 ± 12
Total N (g kg^{-1})	0.64 ± 0.02	6.8 ± 0.3
C/N ratio	18 ± 1	87 ± 2
Extractable NH_4^+-N (mg N kg^{-1})	9.63 ± 1.80	<1
Extractable NO_3^--N (mg N kg^{-1})	6.21 ± 0.95	<1.2
Electrical conductivity (μS cm^{-1})	520 ± 48	1258 ± 204

All values were determined on a dry weight basis (Mean ± SE, $n = 3$); "–", not determined.

A field plot experiment was performed in the coastal saline field station of Nanjing Agricultural University located in Dafeng, Jiangsu province, China (33° 19′ N, 120° 45′ E), which has an altitude of 4 m above sea level. Field plots were established in Jerusalem artichoke-fallow cropping system over the 2010–2011 annual cycle. Climate information was recorded by the local weather station. The annual mean minimum and maximum temperatures were 15.2 °C and 16.9 °C over the 2010–2011 cropping cycle, respectively. Annual rainfall amounted to 1045 mm over the 2010–2011 experimental cycle, consisting of 540 mm for the Jerusalem artichoke growing season and 505 mm for the non-cropping season.

2.2. Field experiments

Field measurements were initiated in a bioenergy Jerusalem artichoke-fallow cropping system over the period from May 10, 2010 to April 28, 2011. The site preparation was completed on May 06, 2010 and the Jerusalem artichoke (*Helianthus tuberosus L.*) was sown on May 10, 2010 with no any prior crop cultivation, and harvested on October 12, 2010. Thereafter, a fallow season followed from October 13, 2010 to April 28, 2011, during which the fields were left overgrown with natural vegetation and no field management involved. However, at the end of both Jerusalem artichoke and natural vegetation growing seasons, all above-ground biomass was harvested for potential use as bioenergy generation materials.

A completely randomized design with four field treatments, and each treatment with four replicates, was adopted in the present study. The treatment plots were: without N fertilizer or biochar amendment used as the control, plots with urea alone (U), plots with biochar alone (B), and plots treated with urea and biochar mixture (U + B). Biochar was applied on May 03, 2010 prior to crop sowing at a local recommended rate of 10 t ha^{-1} with or without urea application, and adequately mixed into the top 0–10 cm soil depth both within and between the cropping rows using hand tools prior to crop sowing. Each field plot was 6 m × 8 m, the row spacing was 60 cm × 40 cm and thus there were 200 individual plants in each field plot. All field plots were surrounded with pre-established isolation strips, which guaranteed the relative independence for each treatment.

Urea was applied at 225 kg N ha^{-1}, with 60% applied as basal fertilizer on May 10, 2010 and 40% at blossom stage on July 10, 2010 during Jerusalem artichoke growing season (Fig. 1e). Both calcium superphosphate ($Ca(H_2PO_4)_2$) and potassium chloride (KCl) were also applied at the same local rate of 135 kg ha^{-1} with the initial N fertilizer dose prior to the sowing of Jerusalem