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Can biochar alleviate soil compaction stress on wheat growth and mitigate soil N_2O emissions?

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A B S T R A C T

Soil compaction occurs widely in modern agriculture, leading to reduced crop yields and enhanced soil N_2O emissions. Biochar, an emerging biomass-pyrolysis product with porous structure, is hypothesized to alleviate soil compaction problems. A field mesocosm experiment involving biochar addition and soil compaction in a factorial design was conducted on a land cultivated with wheat. The results showed that biochar had little effect on wheat grain yield, but it increased wheat vegetative growth and reduced seasonal cumulative soil N_2O emissions from both compacted and non-compacted soils. Across all treatments, biochar-induced changes in individual soil N_2O fluxes mainly occurred within a couple of days after nitrogen fertilization, and were sensitive to soil moisture, with an average increase of 13% under low soil moisture conditions (<70% water holding capacity (WHC)) that was likely driven by increased abundance of ammonia-oxidizing archaea and bacteria, and an average decrease of 36% under high soil moisture conditions (>70% WHC) that was likely induced by raised abundance of N_2O-reducing bacteria. The stimulated population sizes of nitrifiers and denitrifiers in biochar-amended soils were more dependent on biochar's chemical mediation (a shift of soil pH from moderate acidity towards neutrality) than physical mediation. This study indicated that biochar could alleviate soil compaction stress on wheat growth and mitigate soil N_2O emissions, and to promote biochar's role in reducing soil N_2O emissions, the best practice for nitrogen fertilization is before precipitation or followed by irrigation.

1. Introduction

In modern agriculture, due to the massive machinery usage, no tillage management, intensive grazing, increased synthetic nitrogen (N) fertilization, and reduced organic substance addition etc., soil compaction has been created as a widespread phenomenon (Batey, 2009; Gregorich et al., 2014). It is estimated that up to 68 million hectares of cropland worldwide is subjected to compaction stress by vehicular traffic alone (Flowers and Lal, 1998). Soil compaction is considered an important driver for ecological degradation (Sitaula et al., 2000; Gregorich et al., 2014). The increased soil tensile strength inhibits crop root penetration, nutrient uptake, and subsequent grain productivity (Hamza and Anderson, 2005). The decreased soil pores, restricted gas diffusion, and elevated anaerobic micro-sites are favorable for soil denitrification process, leading to increased soil N_2O emissions (an important greenhouse gas) (Yamulki and Jarvis, 2002; Li et al., 2014). Moreover, the oxygen deficiency and space limitation may suppress a certain amount of microbial enzymatic activities, which influences the biogeochemical cycles of soil nutrients (Jordan et al., 2003; Tan et al., 2008). Therefore, to ameliorate soil compaction problems is of great importance for food security, global warming mitigation, as well as soil sustainability.

Biochar, an emerging recalcitrant carbon product derived from biomass pyrolysis under no or limited oxygen, may act as an option to alleviate soil compaction problems based on its porous structure, large surface area, and high hydrophilic characteristic (Asai et al., 2009; Lee et al., 2013). Biochar has been found to reduce

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penetration resistance and increase soil water holding capacity, which could benefit plant root elongation (Vaccari et al., 2015; Andrenelli et al., 2016). Whereas, there were also circumstances under which biochar may exacerbate soil structure by clogging soil micro-pores or dispersing the aggregates, leading to declined soil moisture and reduced plant growth (Herath et al., 2013; Mukherjee and Lal, 2014). Yanai et al. (2007) suggested that biochar-enhanced soil aeration could inhibit the microbial denitrification pathway, thereby reducing soil N_2O emissions. However, Case et al. (2012) illustrated that soil physical changes caused by biochar contributed no significant effects to soil N_2O emissions. These contradictory results highlight the need for further investigation on biochar's physically-mediated effect and its interaction with soil compaction.

In addition to the physical modification on soil, biochar may also exert chemically-mediated effect such as increasing soil pH and providing mineral nutrients. The physico-chemical changes may act in combination to regulate soil microbial populations and community structure, which are highly associated with soil N_2O production and consumption (Pietikäinen et al., 2000; Xu et al., 2014). Sánchez-García et al. (2014) reported an increase in ammonia oxidation bacteria in the presence of biochar, which was likely the cause of increased soil N_2O emissions via accelerated gross nitrification. Harter et al. (2014) observed that biochar enhanced the abundance of N_2O-reducing bacteria, promoting N_2O conversion to N_2 under denitrification conditions. In addition, toxic effects from biochar on nitrifier and denitrifier communities were also found, which could suppress soil N_2O formation (Spokas et al., 2010; Anderson et al., 2011). It is known that soil compaction likely inhibits the growth of nitrifiers, but favors the colonization of denitrifiers (Pupin et al., 2009; Beylich et al., 2010). How biochar will interact with soil compaction to influence the abundance of nitrogen transformation microbial communities and their related N_2O production remains uncertain.

In this study, a field mesocosm experiment of biochar amendment and soil compaction in a factorial design was conducted on a land cultivated with wheat. The abundance of functional marker genes involved in ammonia oxidizing (archaeal and bacterial *amoA* genes), nitrite reduction (*nirK, nirS* genes), and N_2O reduction (*nosZ* gene) were quantified. Three questions were addressed as follows: (i) Can biochar alleviate soil compaction-induced physical effects, and thus contribute to a promotion of wheat growth and reduction of N_2O emissions? (ii) How do biochar and compaction interact on wheat growth and soil N_2O emissions? (iii) Do biochar-induced changes in soil chemical properties have a greater influence on soil N_2O emissions than changes in soil physical properties?

2. Materials and methods

2.1. Biochar production

Biochar was produced from maize straw anaerobically using a patented facility of slow pyrolysis (China patent No. ZL200920232191.9). Maize straw was cut into small segments (<5 cm length) before putting into the reactor. The heating temperature was elevated to 400 °C at a rate of 8.5 °C min^{-1}, and maintained for about 8 h until no smoke released from the gas ventilation pipe. The biochar varied in size from very fine powder to small-sized chunks, and was further shred into small pieces (about 65% was less than 5 mm) before application. Detailed properties of biochar were shown in Table 1.

2.2. Field site and soil characteristics

The study site is located in Xiaoji town, Jiangdu city, Jiangsu Province of China (119°42′E, 32°35′N). Paddy-wheat rotation cultivation is the main crop management, which has lasted for more than 1000 years. The region is characterized by subtropical monsoon climate with a mean air temperature of 14.7 °C. The annual rainfall is 1140 mm, of which about 270 mm falling was at wheat season from November to June. The soil is classified as Inceptisol in US Soil Taxonomy with a silt loam texture of 20% sand (1–0.05 mm), 58% silt (0.05–0.001 mm), and 22% clay (<0.001 mm). Soil bulk density is 1.12 g cm^{-3}. More detailed properties of the soil are listed in Table 1.

Table 1
Basic properties of the soil and biochar in the experiment.

Parameter[a]	Inceptisol	Biochar
pH	6.0	9.6
Total C (g kg^{-1})	16.8	597.7
Total N (g kg^{-1})	1.9	13.4
Total P (g kg^{-1})	0.64	2.47
Total K (g kg^{-1})	15.2	29.8
DOC (mg kg^{-1})	408.3	3404.0
DON (mg kg^{-1})	8.3	16.8
Available NH_4^+ (mg kg^{-1})	16.4	6.7
Available NO_3^- (mg kg^{-1})	23.9	3.8
Available P (mg kg^{-1})	13.0	1281.0
Available K (mg kg^{-1})	48.8	12371.0
CEC (cmol kg^{-1})	12.4	17.0

[a] DOC, dissolved organic carbon; DON, dissolved organic nitrogen; CEC, cation exchange capacity.

2.3. Field mesocosm experiment setup

A field mesocosm experiment of four treatments was conducted at wheat season (November-2011 to June-2012). Treatments were: (i) CK (Soil without biochar amendment following non-compaction); (ii) BC (Soil amended with biochar following non-compaction); (iii) $\overline{CK}$ (Soil without biochar amendment following compaction); and (iv) $\overline{BC}$ (Soil amended with biochar following compaction). The experiment was performed in triplicate, with twelve mesocosms placed in a randomized block layout. Each mesocosm was formed by inserting a polyvinyl chloride collar (54 × 36 cm^2 in area and 20 cm in height) into the soil at 15 cm depth. Biochar at an application rate of 48 t ha^{-1} was mixed evenly into the plough layer (0–15 cm) on November 1st in 2011. Prior to compaction performance on November 2nd, all the soil mesocosms were watered (6L H_2O for each mesocosm, simulating 30 mm rainfall) to create a water-saturated condition (>90% WHC) that is susceptible to be compacted. Compaction was conducted by placing a fitting polyvinyl chloride panel on top of the corresponding mesocosm and adding bricks (400 kg in total) to equal a pressure of 2×10^4 Pa. Fifty six wheat seeds (*Triticum aestivum* L., cv. Ning Mai 16) were sowed in each mesocosm on November 13th (Day 0) (one week later they were thinned into 46 seedlings for all treatments), and wheat was harvested at June 10th after a growing period of 212 days. All treatments received equal fertilizers. Nitrogen (180 kg N ha^{-1}) as urea was split into three applications: 50% at seedling stage (December 10th in 2011 (Day 27)), 10% at jointing stage (March 23rd in 2012 (Day 131)), and 40% at heading stage (May 6th in 2012 (Day 175)). Calcium superphosphate (P_2O_5, 50 kg ha^{-1}) and potassium chloride (K_2O, 50 kg ha^{-1}) were applied once at seedling stage (December 10th in 2011 (Day 27)). Fertilizers for each mesocosm were dissolved into 50 mL water and sprayed evenly on the surface of soil.

2.4. Soil physical properties

Two intact soil cores of 100 cm^3 were taken from each