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Variable effects of biochar application to soils on nitrification-mediated N_2O emissions

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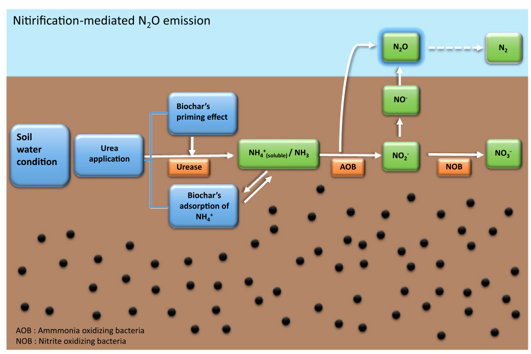
HIGHLIGHTS

- N_2O emissions were increased or not changed when both biochar and urea were applied to dry soils with low C content.
- Soil water status right after urea and biochar application was the primary determinant to predict the effect of biochar on N_2O emissions, together with soil C status and biochar's adsorptive capacity.
- Our study is unique in that we obtained the results from multiple field experiments covering the whole cropping periods.

GRAPHICAL ABSTRACT



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ABSTRACT

Although a meta-analysis on biochar's effects on N_2O emission reported an overall reduction in N_2O emission by adding biochar to the soils, there are still variations in the changes in N_2O emission, especially from field results. The objectives of this study are 1) to compare the effects of biochar addition on N_2O emission between three agricultural upland field experiments, where soil water status was dry favoring nitrification and 2) to identify main factors explaining biochar's variable effects on N_2O emission. Three field experiments were conducted: Exp A in the cultivated grassland treated with rice husk biochar at 2 ton ha^{-1} + urea (CHAR) and with urea only (CON); Exp B in the cabbage field with CHAR and CON treatments; and Exp C in the pepper field with CHAR, CON, and CHAR + DCD (dicyandiamide, nitrification inhibitor) treatments. In Exp A and C, cumulative N_2O emissions significantly increased by 82.5% and 55.8% in the CHAR than CON treatments, respectively, while in Exp B, there was no difference in cumulative N_2O emission between the CHAR and CON. Based on results from using nitrification inhibitor and soil % water filled pore space (WFPS), we assumed that the main N_2O production mechanism was nitrification. Our results suggest that soil water status right after urea application is the primary determinant of different effects of biochar on N_2O emission in addition to soil C status and biochar's adsorption. Principal component analysis using the 25 compiled data also supported our results. This study identified the specific field conditions under which biochar could have stimulating effects on N_2O emission. Mitigation potential of biochar application should be reconsidered if biochar and urea were amended to dry soils with low C contents.

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1. Introduction

Approximately 70% of anthropogenic N_2O emission originates from the agricultural sector (Bouwman et al., 2010; Smith et al., 2008), primarily from widespread use of synthetic nitrogen (N) fertilization. As N_2O is a potent greenhouse gas, this means that a management strategy is needed to cut N_2O emission, especially with regard to agricultural soils. Biochar amendment to soils has been suggested as a potential strategy for reducing N_2O emission, but the mitigation effects of biochar application have not yet been fully verified.

Cayuela et al. (2014) compiled 30 peer-reviewed literatures and collected 261 experimental treatments to investigate the impact of biochar on N_2O emission and to test whether the often proposed reductions in N_2O emissions occurred across multiple studies. They found that biochar decreased soil N_2O emissions by 54% on average but that the effects of biochar on N_2O emission varied depending on soil pH, texture, soil water status, biochar C/N ratio, and application rates. In addition, there are still many studies which reported no difference or even an increase in soil N_2O emissions after biochar amendment (Clough et al., 2010; Suddick and Six, 2013).

Inconsistent effects of biochar addition on N_2O emission might be related to different mechanisms of N_2O production in soils under various conditions. Singh et al. (2010) reported positive and negative effects of biochar addition on N_2O emission and suggested a possible mechanism of N_2O emission increase via enhanced nitrification. Sánchez-García et al. (2014) studied two soils with contrast responses to biochar amendment and reported that in the soil with reduced N_2O emission by biochar addition, the main pathway leading to N_2O was denitrification, while in the soil with increased N_2O emission, the main process of N_2O production was nitrification. Li et al. (2015) reported a slight increase in N_2O emission with the addition of wheat straw biochar and confirmed that the production of N_2O occurred via nitrification through use of a nitrification inhibitor. Lin et al. (2017) reported that the application of wheat straw biochar to rice paddy soil significantly increased N_2O emission and attributed this increase to the enhanced abundance of ammonia-oxidizing bacteria (AOB) *amoA* genes, which is the first step in the nitrification process. The abovementioned findings led us to hypothesize that biochar addition would have a stimulating effect when the main N_2O production process is nitrification. However, in prior studies, enhanced nitrification related to biochar did not always lead to increased N_2O emission. Xu et al. (2014) reported that biochar amendment stimulated both nitrification and denitrification processes, while reducing N_2O emission overall. Verhoeven et al. (2017) also reported that biochar addition reduced N_2O emission in upland systems to the same degree as rice paddy systems where denitrification is dominant. Thus, a better understanding of the main mechanism of N_2O production and influential factors is needed in order to effectively predict the effects of biochar on N_2O emission.

Meta-analyses on the effects of biochar addition on N_2O emission were recently conducted by Cayuela et al. (2014) and Verhoeven et al. (2017). These analyses were based on data collected from a wide range of water conditions from flooded to very dry soils and variable mechanisms of N_2O production. Considering that the Intergovernmental Panel on Climate Change (IPCC)'s greenhouse gas inventory includes soil N_2O emission only from agricultural upland systems, it is more practical for us to focus on the effects of biochar on N_2O emission from upland field soils (Liu et al., 2016). Under drier soil conditions where the soil % water filled pore space (WFPS) is 35–60%, N_2O was primarily produced from the microbial nitrification process (Bateman and Baggs, 2005). In the nitrification process, N_2O is formed from NH_2OH, which is oxidized from NH_4^+/NH_3 by ammonia oxidizing bacteria (AOB). Nitrite is further oxidized into nitrate by nitrite oxidizing bacteria (NOB). Considering the higher sensitivity of NOB to NH_3 toxicity compared to AOB, NO_2^- tends to be accumulated when the soil contains high levels of NH_3, resulting in high possibility of N_2O emission (He et al., 2016; Venterea et al., 2015). To understand the effects of biochar addition on nitrification-mediated N_2O emission, we need to investigate the conditions and factors for nitrification influenced by biochar.

In this study, we conducted three independent field experiments of agricultural upland systems where the soils were mostly dry. We assumed that the main N_2O production mechanism was nitrification because of the dry soil water status (Bateman et al., 2004). We considered many of the factors involved in the nitrification process, including soil pH, soil water content, soil inorganic N availability, and microbial activity (Che et al., 2015; He et al., 2016; Nelissen et al., 2012), all of which could potentially be influenced by biochar amendment. To have more generalized knowledge on the variable effects of biochar on nitrification-mediated N_2O emission, we collected data from published papers on N_2O emission and biochar addition with nitrification as the main N_2O production process. By conducting principal component analysis, we identified the main factors determining the direction and magnitude of changes in N_2O emission via biochar amendment.

The objectives of this study were 1) to compare the effects of biochar addition on N_2O emission between three agricultural field studies where soil water status of each experiment was dry favoring nitrification and 2) to identify the main factors influencing biochar's effects on N_2O emission using statistical analysis.

2. Materials and methods

2.1. Site description and biochar preparation

The field experiments were conducted in three different soils, all located in the central area of S. Korea. Annual mean temperatures ranged from 11.8 to 12.5 °C and precipitations ranged from 1227 to 1312 mm (Table 1, Korea Meterological Administration, http://www.kma.go.kr/weather/observation). Experiment A (Exp A) was set up on October 25, 2011 in a cultivated grassland planted with tall fescue (*Festuca arundiancea*), orchard grass (*Dactylis glomerata*), perennial ryegrass (*Lolium perenne*), and white clover (*Trifolium repens*). Experiment B (Exp B) was set up on September 1, 2014 and planted with cabbage (*Brassica rapa* var. glabra) and Experiment C (Exp C) was set up on May 10, 2015 and planted with pepper (*Capsicum annuum*).

Biochar used in this study was rice husk biochar, which was a commercial product sold by the Farmers' Association in Gangjin-gun, Korea. It was produced by pyrolyzing rice husks at 350 °C in a pyrolysis reactor (DCH-400) from Daewon GSI Co., Gyeongsangbuk-Do, Korea. The detailed procedures for char production are provided at www.daewonces.co.kr.

2.2. Field experiment

In Exp A, the CHAR treatment applied rice husk biochar at 2 ton ha^{-1} on October 25, 2011 together with 140 kg N ha^{-1} of urea fertilizer. The control (CON) was only applied with urea fertilizer at the same rate. The experiment lasted for 350 d because cultivated grassland was planted with perennial grass species. In Exp B, the CHAR (2 ton ha^{-1} rice husk biochar and urea application) and CON (urea application only) treatments were employed with a urea application rate of 190 kg N ha^{-1}. The duration of this experiment was 42 d (the growing period of cabbage). In Exp C, in addition to the CHAR (2 ton ha^{-1} rice husk biochar and 225 kg N ha^{-1} urea application) and CON (225 kg N ha^{-1} urea application only) treatments, a third treatment was also applied, CHAR + DCD, where we added rice husk biochar, urea and dicyandiamide (DCD). DCD is a representative nitrification inhibitor (Di and Cameron, 2002) that was applied at 10% of the urea applied by weight. The duration of this experiment was 120 d. All experiments used a completely randomized block design and had three replicates.

The biochar applied had a particle size of <3 mm and was incorporated into the soil profile to a depth of 10 cm using shovels. In Exp C, the DCD was applied in solution by dissolving 100 g of DCD powder in 1000 ml of the deioinized (D.I.) water. The non-biochar plots were