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Effects of application of inhibitors and biochar to fertilizer on gaseous nitrogen emissions from an intensively managed wheat field

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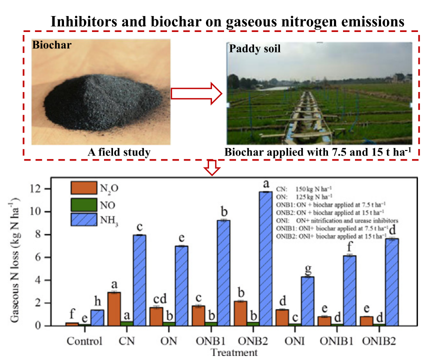
HIGHLIGHTS

- Optimal N fertilizer application rate decreased N_2O, NO and NH_3 emissions.
- Biochar application increased SOC, total N and pH, and also NH_3 and N_2O emissions.
- Addition of urease and nitrification inhibitors decreased N_2O, NO and NH_3 emissions.
- Combined application of biochar and inhibitors reduced N_2O, NO and biochar-induced NH_3 emissions.
- Wheat yield was increased by biochar; NUE was increased by biochar and inhibitors.

GRAPHICAL ABSTRACT



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ABSTRACT

The effects of biochar combined with the urease inhibitor, hydroquinone, and nitrification inhibitor, dicyandiamide, on gaseous nitrogen (N_2O, NO and NH_3) emissions and wheat yield were examined in a wheat crop cultivated in a rice-wheat rotation system in the Taihu Lake region of China. Eight treatments comprised N fertilizer at a conventional application rate of 150 kg N ha^{-1} (CN); N fertilizer at an optimal application rate of 125 kg N ha^{-1} (ON); ON + wheat-derived biochar at rates of 7.5 (ONB1) and 15 t ha^{-1} (ONB2); ON + nitrification and urease inhibitors (ONI); ONI + wheat-derived biochar at rates of 7.5 (ONIB1) and 15 t ha^{-1} (ONIB2); and, a control. The reduced N fertilizer application rate in the ON treatment decreased N_2O, NO, and NH_3 emissions by 45.7%, 17.1%, and 12.3%, respectively, compared with the CN treatment. Biochar application increased soil organic carbon, total N, and pH, and also increased NH_3 and N_2O emissions by 32.4–68.2% and 9.4–35.2%, respectively, compared with the ON treatment. In contrast, addition of urease and nitrification inhibitors decreased N_2O, NO, and NH_3 emissions by 11.3%, 37.9%, and 38.5%, respectively. The combined application of biochar and inhibitors more effectively reduced N_2O and NO emissions by 49.1–49.7% and 51.7–55.2%, respectively, compared with ON and decreased NH_3 emission by 33.4–35.2% compared with the ONB1 and ONB2 treatments. Compared with the ON treatment, biochar amendment, either alone or in combination with inhibitors, increased wheat yield and N use efficiency (NUE), while addition of inhibitors alone increased NUE but not wheat yield. We suggest that an optimal N fertilizer rate and combined application of inhibitors + biochar at a low application rate, instead of biochar application alone, could increase soil fertility and wheat yields, and mitigate gaseous N emissions.

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1. Introduction

Atmosphere nitrous oxide (N_2O) is a powerful greenhouse gas with a global warming potential (GWP) 265 times higher than carbon dioxide (CO_2) on a 100-year horizon from the latest (fifth assessment; AR5) report (IPCC, 2013). Agricultural soils are considered to be the major source of atmospheric N_2O, contributing 4.1 Tg N year^{-1} (IPCC, 2013) to the global atmospheric N_2O budget of approximately 14 Tg N year^{-1} (Fowler et al., 2009), and they are also a major source of NO emissions in rural areas, which reach 1.6 Tg N year^{-1} and account for up to 18% of global soil emissions (Bouwman et al., 2002; IPCC, 2007). Although nitric oxide (NO) does not directly affect the earth's radiative balance, it is a key precursor to the greenhouse gas, tropospheric ozone, which is linked to the atmospheric deposition of nitrogen (N) and has adverse effects on human health and vegetation dynamics (Anenberg et al., 2012). The major anthropogenic source of atmospheric ammonia (NH_3) is volatilization from agricultural systems, where 10–30% derives from fertilizer N and animal excreta N (Bouwman et al., 2002). NH_3 is not a greenhouse gas, however its emission to the atmosphere and subsequent re-deposition has been reported to result in acidification of water, biodiversity loss, and indirect emission of N_2O (Ferm, 1998; Beusen et al., 2008). Therefore, finding mitigation strategies for reducing gaseous N losses and improving fertilizer N use efficiency are urgently needed.

Many field management practices have been suggested to reduce gaseous N losses without reducing crop yields, such as optimization of N application rate (Ju et al., 2009) to improve agronomic N use efficiency (NUE) and maintain crop yield (Huang et al., 2015), double inhibitor application (Sanz-Cobena et al., 2012; Ni et al., 2014), and biochar amendment (Saarnio et al., 2013; Malińska et al., 2014). Optimal N rates were defined as the N rate which produced maximum yield where no significant yield increases were observed at higher N rates (Pittelkow et al., 2014). Liang et al. (2008) suggested that the optimal N fertilizer rates in the Taihu Lake region are 120–180 kg N ha^{-1} for wheat. In the study by Ju et al. (2009), the optimal N fertilizer rate for wheat season could be reduced to 153 kg N ha^{-1} in the same region. A large number of studies have shown that appropriate N reduction in the Taihu Lake region can sustain high yields, improve the NUE, and reduce the N loss (Liang et al., 2008; Ju et al., 2009).

It has been shown that nitrification inhibitors may delay the oxidation of ammonia to hydroxylamine, which is further oxidized into nitrite (NO_2^-) and nitrate (NO_3^-), thus limiting the substrate pools available for N_2O and NO production both directly, by reducing nitrification, and indirectly, by reducing the availability of NO_3^- for denitrification (Majumdar et al., 2000; Malla et al., 2005; Sun et al., 2015). Urease inhibitors slow the conversion of urea to NH_4^+, reducing the concentration of NH_4^+ in soil solution and the potential for NH_3 volatilization (Dawar et al., 2011). However, combined applications of nitrification and urease inhibitors have been shown to be more effective in mitigating gaseous N emissions and increasing crop yield in upland and flooded soils than single applications (Akiyama et al., 2009; Wang et al., 2015). The application of biochar to agricultural soil has been proposed as a more sustainable approach to improve soil fertility and mitigate climate change (Lehmann et al., 2006; Scheer et al., 2011), but there have been conflicting reports on its efficacy. For instance, Taghizadeh-Toosi et al. (2011) reported that biochar amendment at 30 t ha^{-1} significantly decreased N_2O emissions, but had no effect at the lower rate of 15 t ha^{-1}, whereas Sun et al. (2015, 2017) found that while lower application rates of wheat biochar (0.5–1.0% w/w) reduced soil N leaching with no effect on NH_3 volatilization, higher rates (2–4% w/w) increased NH_3 and N_2O emissions. Contrasting effects of the addition of biochar have been reported in different soil types: Sánchez-García et al. (2014) observed that the addition of biochar to Haplic Phaeozem decreased N_2O emissions by 76%, but increased emissions by 54% in Haplic Calcisol. Since the effect of biochar amendment on gaseous N emissions may be positive or negative, depending on biochar characteristics, application rates, and soil properties (Ameloot et al., 2013; Nelissen et al., 2014), predicting the likely effects of biochar amendment on N_2O, NO and NH_3 emissions at sites with contrasting soil types and land uses is not straightforward.

Up to date, many studies have focused the influence of separate applications of biochar and inhibitors on N transformation processes, gaseous N emissions, and crop yield. However, there has been little research on the combined effects of biochar and inhibitors on gaseous N emissions. The objectives of this study were to: (1) evaluate the influence of biochar application rates on gaseous N emissions, and (2) identify the optimum combination of biochar with nitrification and urease inhibitors to reduce gaseous N emissions.

2. Materials and methods

2.1. Study site

The field experiment was conducted on a rice-wheat rotation field at Linhu Town, Suzhou City, Jiangsu Province, China (31°12′N, 120°48′E). The region has a subtropical monsoon climate, with an annual mean air temperature of 16 °C and precipitation of 1139 mm. The soil is derived from alluvium deposited by the Yangtze River and is classified as a Stagnic Anthrosol. Prior to the experiment, the surface soil (0–20 cm) had a bulk density of 1.25 g cm^{-3}, pH of 5.6, organic C content of 20.26 g kg^{-1}, and total N content of 1.81 g kg^{-1}.

2.2. Field experiment

From 2013 to 2014, the field experiment in a wheat crop, comprising 4 replicates of eight treatments in 3 m × 8 m plots, was arranged in a randomized complete block design. The treatments were a none N-fertilized control; N fertilizer applied at a conventional 150 kg N ha^{-1} (CN), optimal 125 kg N ha^{-1} (ON) rates; ON + biochar applied at 7.5 (ONB1) and 15 t ha^{-1} (ONB2); ON + nitrification and urease inhibitors (ONI); and, ONI + biochar applied at 7.5 (ONIB1) and 15 t ha^{-1} (ONIB2). All plots received calcium superphosphate (40 kg P_2O_5 ha^{-1}) and potassium chloride (60 kg K_2O ha^{-1}) prior to sowing, and N was applied as urea in two applications as a basal (40%) on November 19, 2013, and supplemental (60%) fertilizer on March 9, 2014. Urease (hydroquinone, HQ) and nitrification inhibitors (dicyandiamide, DCD) were mixed thoroughly and applied at 0.3% and 5% (w/w) of the applied N, respectively, and N fertilizer and inhibitors + fertilizer were spread evenly onto the soil surface by hand and immediately incorporated into the surface soil (0–20 cm) by plowing. The wheat seeds (cultivar Yangmai 16) were sown onto the surface soil and then incorporated by tillage (at a depth of 10–15 cm). The crop was harvested by the labor on May 17, 2014. Field management practices were standardized across all plots during the experimental period.

In China, straw and straw-derived biochar have been widely used to improve soil fertility since Chinese government has forbidden crop burning in the field (Zhang et al., 2012; Zhang et al., 2016). The biochar used in this study was purchased from Sanli New Energy Ltd. (Shangqiu, China) and was produced from wheat straw. In June, biochar was incorporated into the soil by plowing to a depth of c. 20 cm. The biochar was produced at a pyrolysis temperature of 450 °C and contained 493 g C kg^{-1} and 11.6 g N kg^{-1}, with a pH (H_2O) of 10.7.

2.3. Gas flux measurement

A static chamber method was used to measure N_2O fluxes, where a PVC collar (50 cm × 50 cm × 10 cm) was installed in each plot before sowing, to allow the water-filled trough at the top edge of the collar to seal the flange of a gas-sampling chamber (50 cm × 50 cm × 50 cm). The chamber had three ports on the top surface that comprised a small, silicon-sealed vent for sampling, a port through which a thermometer was inserted for measuring chamber temperature, and a