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Different effects of biochar and a nitrification inhibitor application on paddy soil denitrification: A field experiment over two consecutive rice-growing seasons

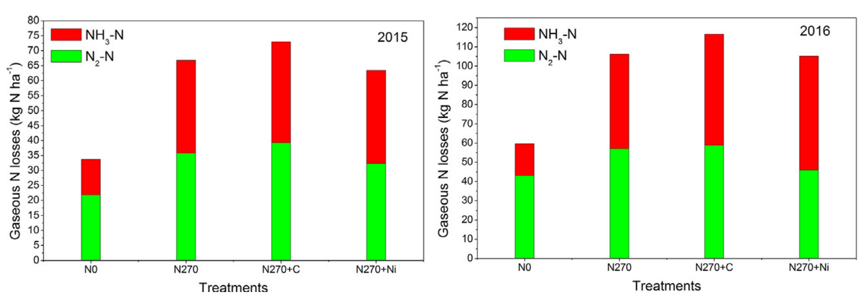
Shuwei Wang [a,b,c], Jun Shan [a,c], Yongqiu Xia [a,c], Quan Tang [a,b,c], Longlong Xia [a,b,c], Jinghui Lin [a,c], Xiaoyuan Yan [a,c,*]

[a] State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Changshu Agro-ecological Experimental Station, Chinese Academy of Sciences, Changshu 215555, China

HIGHLIGHTS

- Biochar and Ni additions increased rice yields by 4.2–5.2% and 6.2–7.3%, respectively.
- Gaseous N losses were increased by 6.2–10.6 kg N ha^{-1} for biochar application.
- Ni application decreased gaseous N losses by 0.9–3.4 kg N ha^{-1} through suppressing denitrification.
- Ni application may be a good practice to ensure food security while decreasing gaseous N loss for rice production.

GRAPHICAL ABSTRACT



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ABSTRACT

Biochar and nitrification inhibitors are increasingly being proposed as amendments to improve nitrogen use efficiency (NUE). However, their effects on soil denitrification and the major N loss in rice paddies over an entire rice-growing season are not well understood. In this study, using intact soil core incubation combined with N_2/Ar technique, the impacts of biochar and a nitrification inhibitor (Ni), 2-chloro-6-(trichloromethyl)-pyridine, on rice yield and soil denitrification, as well as ammonia (NH_3) volatilization, were investigated over two rice-growing seasons in the Taihu Lake region of China. Field experiments were designed with four treatments: N0 (no N applied), N270 (270 kg N ha^{-1} applied), N270 + C (25 t ha^{-1} biochar applied) and N270 + Ni (2-chloro-6- [trichloromethyl] -pyridine, 1.35 kg ha^{-1} N applied). Compared with single application of N fertilizer alone (N270), biochar (N270 + C) and Ni (N270 + Ni) applications increased rice yields by 4.2–5.2% and 6.2–7.3%, respectively. The cumulative N_2-N and NH_3-N losses in different treatments varied from 11.9 to 21.8% and from 11.5 to 22.0% of the applied N, respectively. Compared with the single application of N fertilizer, the Ni application increased total NH_3 emission by 4.0–20.6% and significantly decreased total N_2-N emission by 9.7–19.4% ($p < 0.05$), while the biochar application increased total NH_3 and N_2-N emissions by 8.6–17.9% and 3.3–9.7%, respectively. Overall, the biochar application resulted in an 11–15% higher net gaseous N than the Ni application. Although the biochar application may increase the rice yield and consequently the plant N uptake, it also promoted N loss more than Ni. Therefore biochar may not be good for maintaining soil fertility over a long period. Instead, applying Ni may be an optimal practice to ensure food security, while decreasing gaseous N loss, for rice production in the Taihu Lake region of China.

* Corresponding author at: State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China.
E-mail address: yanxy@issas.ac.cn (X. Yan).

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1. Introduction

Nitrogen (N) is an important nutrient element for plant growth and is often one of the most limiting nutrient in paddy fields. To encourage high grain yields, high rates, usually over 300 kg N ha^{-1}, of chemical N fertilizers have been applied in rice paddies per growing season, especially in eastern China, leading to high levels of N loss to the environment (Huang and Tang, 2010; Ju et al., 2009). Excessive N fertilizer application has resulted in a cascade of environmental problems, such as surface and ground water pollution, ammonia (NH_3) volatilization and global warming resulted from the emission of nitrous oxide (N_2O) (Chen et al., 2014). Rice paddies with seasonally alternating dry-wet conditions may have high rates of N loss from N fertilizers and low nitrogen use efficiency (NUE). The NUE of rice paddies ranges from 30 to 40% (Xia et al., 2016), or even lower in some cases (Choudhury and Khanif, 2001). During the rice growing season, N fertilizer is mainly lost through NH_3 volatilization, nitrification, and N_2 from denitrification (Xing and Zhu, 2000). Denitrification is a process that converts nitrate (NO_3^--N) into N_2, with NO and N_2O as intermediates, and is generally the most important process of N loss after N fertilizers application under flooded water conditions (Verhoeven et al., 2006). Thus, reducing the N loss by reducing the denitrification process is critical important for improving the NUE while mitigating the environmental impacts associated with N fertilizer usage in paddy fields.

For decades, biochar and nitrification inhibitors (Nis) have been used as effective amendments to reduce N losses and increase the NUE (Sohi et al., 2010; Xia et al., 2017). Biochar can alter the microbial activities in the soil (Lehmann et al., 2011), the available N and organic carbon (C) contents (González-Pérez et al., 2004; Prendergast-Miller et al., 2011), the pH (Enders et al., 2012; Van Zwieten et al., 2010) and the level of soil aeration (Kinney et al., 2012), which all exert influences on N loss from denitrification. The effects of biochar on N loss are dependent on the N content of the biochar feedstock, such as poultry manure *versus* wood (Clough et al., 2010; Singh et al., 2010; Spokas and Reicosky, 2009). Nitrification inhibitors can suppress the nitrification process in soil by delaying the oxidation of NH_4^+ to NO_3^-, which is an electron acceptor for denitrification, which then may suppresses the denitrification process in flooded soils (Di et al., 2009; Guo et al., 2013). Previously, most of the studies that investigated the effects of biochar or Nis mainly focused on N_2O emissions (Dai et al., 2013; Giltrap et al., 2010; Yanai et al., 2007). Currently, relatively little is known about their effects on denitrification in flooded rice paddies.

Various methodological approaches, such as the acetylene (C_2H_2) inhibition technique, ^{15}N tracers and mass balance approaches have been used to measure denitrification in terrestrial and aquatic environments. These available approaches are problematic for a variety of reasons, such as changing substrate concentrations, disturbing the physical setting of the process, lacking sensitivity or being prohibitively costly in time, and/or expensive (Groffman et al., 2006). Most fundamentally, it is difficult to directly measure the denitrification rate in flooded rice paddies because of the high atmospheric background level of N_2 (78%) (Groffman et al., 2006). The C_2H_2 inhibition method is easy-to-use and cheap, but it also inhibits the nitrification process (Berg et al., 1982; Wrage et al., 2004), which may lead to substrate limitations for denitrification, especially in an environment with low NO_3^- availability (Yan et al., 2011). Nitrifier denitrification generally cannot be studied with C_2H_2 because of the inhibition of NH_3 oxidation, which may cause an underestimation of denitrification rates. ^{15}Nr-tracer techniques are widely utilized for the direct measurement of denitrification following the addition of $^{15}NO_3^-$ (Cayuela et al., 2013; Dong et al., 2012; Lan et al., 2013). However, excessive $^{15}NO_3^-$ added to soils can increase the availability of N and may overestimate denitrification rates, especially in N-limited systems (Groffman et al., 2006). Detection of the end-product (N_2) is a direct measure of net denitrification, which can be determined by high-precision membrane inlet mass spectrometry (MIMS) and the nitrogen gas/argon (N_2/Ar) technique without the addition of $^{15}NO_3^-$ (Yang and Silver, 2012). The N_2/Ar technique uses an inert gas Ar as a conservative tracer. Thus, measured changes in measured N_2/Ar ratios can be attributed to changes in the abundance of N_2 (Yang and Silver, 2012). Moreover, MIMS provides rapid (<2 min) measurements on small (<7 ml) samples with no preprocessing and provides high precision (±0.03% for N_2/Ar) (Kana et al., 1994; Kana et al., 1998). However, for core incubations, there is no completely adequate control that can account for all solubility flux errors and this generally sets the lower limit of detection (Eyre et al., 2004; Groffman et al., 2006; Kana, 2004). Soil core incubation prevented the competitive consumption of dissolved inorganic N by rice, which could have promoted denitrification to some extent owing to the reduced competition for available N (Nicolaisen et al., 2004). Although this approach is not without problems, it has the advantage of measuring the direct product of denitrification (Groffman et al., 2006). Together with the intact soil/sediment core incubation method, the N_2/Ar technique has been successfully used to study *in situ* denitrification rates in water bodies and flooded paddy soils (Li et al., 2014; Li et al., 2013; Shan et al., 2016; Zhao et al., 2015). Li et al. (2014) reported that the average cumulative N_2-N loss measured by the N_2/Ar technique during the rice growth stage (21 days) was 4.7% of the applied N fertilizer.

Rice paddies as a man-managed seasonal wetland ecosystems cover ~20% of the world's total irrigated croplands (Frolking et al., 2002). The current study area is located at the Taihu Lake region, which is a major agricultural intensification region for rice production in China. Currently, rice yield in this region has already stagnated, and the NUE has been low (< 30%), due to poor agricultural practices and irrational fertilization management strategies (Ju et al., 2009; Zhao et al., 2009). In recent years, Nis and biochar have been increasingly proposed as amendments to improve grain yield and NUE (Hu et al., 2013; Major et al., 2010). However, their effects on N loss, especially for N loss as N_2-N are not well understood. In this study, we conducted a field experiment to investigate the effects of biochar and Ni on rice yield, denitrification and NH_3 volatilization over two rice-growing season in the Taihu Lake region of China. The denitrification rates of different treatments were measured using an intact soil incubation-based N_2/Ar technique. The NH_3 volatilization was measured using a dynamic chamber method. The objectives of this study were to (1) determine the potential rates of denitrification during the different phenological stages of rice growth using the intact soil incubation-based N_2/Ar technique; (2) calculate the cumulative N_2-N loss through denitrification and the NH_3-N loss under actual field experimental conditions; and (3) elucidate the impacts of biochar and Ni applications on crop yield, cumulative N loss through denitrification and NH_3 volatilization.

2. Materials and methods

2.1. Experiment site

The experimental field was located in an agro-ecological experimental station in Changshu (31°32′93″ N, 120°41′88″ E), Chinese Academy of Sciences, Jiangsu Province, China. This region in the Yangtze River Delta has a north subtropical monsoon climate, with a mean precipitation and an average temperature in 2015–2016 of 17.04 °C and 1344.8 mm, respectively. The traditional cropping system in this region is winter wheat-rice rotation system. The experimental soil is classified as Gleyi-Stagnic Anthrosol (CRGCST 2001) developed from lacustrine sediments with a silt clay loam texture (13.3% sand, 54.8% silt and 31.9% clay). The topsoil (0–20 cm) has a 6.99 pH level, containing 26.6 g kg^{-1} of organic C and 2.83 g kg^{-1} of total N, resulting in a 9.40 C:N ratio.

2.2. Field treatments and management practices

The field experiment was conducted during the rice-growing seasons of 2015 and 2016. In this experiment, four treatments were