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Nitrification inhibitors mitigated reactive gaseous nitrogen intensity in intensive vegetable soils from China

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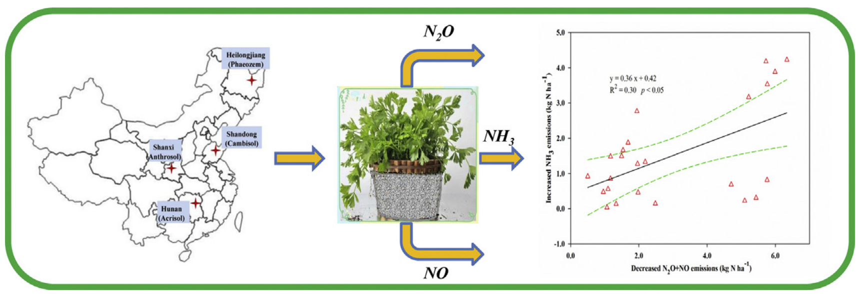
HIGHLIGHTS

- NI effects on Nr emissions and yield in 4 major vegetable soils were assessed.
- Soil type affected the performance of NIs over Nr emissions, yield and Nr intensity.
- NIs decreased NO and N_2O emissions and Nr intensity while maintaining yield.
- Significant correlations existed between inhibited N_2O + NO and stimulated NH_3.

GRAPHICAL ABSTRACT



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ABSTRACT

Nitrification inhibitors, a promising tool for reducing nitrous oxide (N_2O) losses and promoting nitrogen use efficiency by slowing nitrification, have gained extensive attention worldwide. However, there have been few attempts to explore the broad responses of multiple reactive gaseous nitrogen emissions of N_2O, nitric oxide (NO) and ammonia (NH_3) and vegetable yield to nitrification inhibitor applications across intensive vegetable soils in China. A greenhouse pot experiment with five consecutive vegetable crops was performed to assess the efficacies of two nitrification inhibitors, namely, nitrapyrin and dicyandiamide on reactive gaseous nitrogen emissions, vegetable yield and reactive gaseous nitrogen intensity in four typical vegetable soils representing the intensive vegetable cropping systems across mainland China: an Acrisol from Hunan Province, an Anthrosol from Shanxi Province, a Cambisol from Shandong Province and a Phaeozem from Heilongjiang Province. The results showed soil type had significant influences on reactive gaseous nitrogen intensity, with reactive gaseous nitrogen emissions and yield mainly driven by soil factors: pH, nitrate, C:N ratio, cation exchange capacity and microbial biomass carbon. The highest reactive gaseous nitrogen emissions and reactive gaseous nitrogen intensity were in Acrisol while the highest vegetable yield occurred in Phaeozem. Nitrification inhibitor applications decreased N_2O and NO emissions by 1.8–61.0% and 0.8–79.5%, respectively, but promoted NH_3 volatilization by 3.2–44.6% across all soils. Furthermore, significant positive correlations were observed between inhibited N_2O + NO and stimulated NH_3 emissions with nitrification inhibitor additions across all soils, indicating that reduced nitrification posed the threat of NH_3 losses. Additionally, reactive gaseous nitrogen intensity was significantly reduced in the Anthrosol and Cambisol due to the reduced reactive gaseous nitrogen emissions and increased yield, respectively. Our findings highlight the benefits of nitrification inhibitors for integrating environment and agronomy in intensive vegetable ecosystems in China.

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1. Introduction

As the major sources of reactive nitrogen, an indispensable nutrient for agriculture and human alimentation (Bodirsky et al., 2014), inorganic nitrogen (N) fertilizers have been widely applied to agriculture to supply food for feeding the increasing global population. However, a large proportion of fertilizer N applied is released into the environment as reactive nitrogen (Fowler et al., 2013; Chen, 2014; Xia et al., 2016). Liu et al. (2016) found that one third of the global N losses, approximately 15 Tg N yr^{-1}, were released to the atmosphere based on a crop growth model. Nitrous oxide (N_2O), nitric oxide (NO) and ammonia (NH_3) are the major forms of reactive gaseous nitrogen (Qiao et al., 2015) released from agricultural systems, which can cause a cascade of environmental problems, such as stratospheric ozone depletion, air pollution, acidification and eutrophication (Galloway et al., 2008; Behera et al., 2013), and also resulted in environmental economic costs in agricultural ecosystems (Van Grinsven et al., 2013). Without emission reductions, global N losses are projected to further increase and reach levels higher than 150% of the 2010 values by 2050 (Bodirsky et al., 2014).

In addition to causing environmental problems, the amounting of reactive nitrogen loss has resulted in low N use efficiency in agricultural systems (Linquist et al., 2013; Li et al., 2016). In China, vegetable production accounted for 52% of global vegetable production in 2012 (FAO, 2015). Chinese vegetable production is characterized by huge inputs of fertilizer N, high cropping indexes, and frequent management practices. To gain the maximum benefit, annual N fertilizer inputs in intensive vegetable-cropping regions are 3–6 times higher than that in cereal-cropping areas in China. On the other hand, intensive vegetable fields usually had much higher reactive gaseous nitrogen losses in the form of N_2O (Li et al., 2015b; Zhang et al., 2016; Liu et al., 2017), NO (Mei et al., 2009; Fan et al., 2017) and NH_3 (Gong et al., 2013), resulting in lower N use efficiency (Ju et al., 2009; Li et al., 2016) than other croplands. This dilemma highlights the need to abate the reactive gaseous nitrogen loss while promoting the yield in intensive vegetable cultivation systems synchronously.

Nitrification inhibitors (NIs) are recommended as a potential climate change mitigation tool (IPCC, 2014) and have been extensively investigated and widely adopted across a broad range of agroecosystems (Akiyama et al., 2010; Qiao et al., 2015; Xia et al., 2017). By temporarily retarding the microbial conversion of ammonia to nitrite, NIs can reduce substrate availability for nitrate formation and subsequent denitrification, thereby reducing N_2O and increasing crop N use efficiency (Abalos et al., 2014; Zhang et al., 2015). While many studies have reported that NI application reduces N_2O emissions (Ma et al., 2013; Li et al., 2015a), other studies have showed nonsignificant influences (Mkhabela et al., 2006; Bell et al., 2015), which were largely associated with soil and NI types (Akiyama et al., 2010; Zhang et al., 2015). On the other hand, NI application also had a significant influence on the other forms of reactive gaseous nitrogen, such as NO and NH_3. Recent studies have shown that compared with synthetic N only, the combined use of NI substantially mitigated NO emissions (Liu et al., 2017; Tian et al., 2017). Additionally, NH_3 emissions increased by an average of 20% with NI addition, and the stimulation effect varied for different NI forms and soil types (Qiao et al., 2015).

Up to now, few studies have simultaneously evaluated the responses of various reactive gaseous nitrogen emissions and vegetable yield to NI applications in intensive vegetable ecosystems. Therefore, a greenhouse pot experiment was performed to investigate the effects of two types of NI on reactive gaseous nitrogen emissions, namely, N_2O, NO, and NH_3, simultaneously in four typical intensive vegetable soils across the main vegetable production areas of mainland China. We hypothesized the following: 1) NI applications will reduce reactive gaseous nitrogen emissions, increase vegetable yield and thereby reduce reactive gaseous nitrogen intensity in vegetable soils across mainland China; and 2) these influences will vary among NI and soil types. Overall, the objectives of this study were to obtain a comprehensive insight into the influences of different species of NI on reactive gaseous nitrogen emissions, vegetable yield and reactive gaseous nitrogen intensity in intensively managed vegetable production in China.

2. Materials and methods

2.1. Experimental soil and nitrification inhibitor

As described by Fan et al. (2017), four typical greenhouse vegetable cultivation sites with a history (>10 years) of conventional cultivation were selected from Northeast, Northwest, Central and Eastern China (Fig. S1): (1) a Phaeozem from Jiamusi (46°48′ N, 130°12′ E) in Heilongjiang Province, (2) an Anthrosol from Yangling (34°18′ N, 108°2′ E) in Shanxi Province, (3) an Acrisol from Changsha (28°32′ N, 113°23′ E) in Hunan Province and (4) a Cambisol from Shouguang (36°56′ N, 118°38′ E) in Shandong Province (FAO et al., 2012). Those four types of vegetable soil represented a range of differences in physicochemical properties and regions. Details of soil types and properties are shown in Table 1. Soil samples were manually collected from the cultivated layer (0–20 cm) after the harvesting of vegetables in April 2015. The samples were air-dried, passed through a 5-mm stainless steel mesh sieve and then homogenized thoroughly. Any visible roots and organic residues were removed manually before the sample containers were packed with the necessary amount of soil to achieve the bulk density in field. Each pot received 15 kg of 105 °C dry-weight-equivalent fresh soil. Two types of NIs, namely nitrapyrin (CP) and dicyandiamide (DCD) were selected in the current study.

In accordance with Lu (2000), soil organic carbon was measured by wet digestion with H_2SO_4–$K_2Cr_2O_7$, total nitrogen was determined by semi-micro Kjeldahl digestion, and soil texture was determined with the pipette method. Soil pH was measured in deionized water at a volume ratio of 1:2.5 (soil to water) with a PHS-3C mv/pH detector (Shanghai Kangyi Inc. China). The soil nitrate and ammonium were measured following the two-wavelength ultraviolet spectrometry and indophenol blue methods, respectively, using an ultraviolet spectrophotometer (Hitachi, UV-2900, Tokyo, Japan). Electric conductivity was measured by using a Mettler-Toledo instrument (FE30-K, Shanghai, China) at a 1:5 (w:v) soil-to-water ratio. Cation exchange capacity was determined using the CH_3COONH_4 method.

2.2. Experimental setup and fertilizer management

The pot experiments were performed at the greenhouse experimental station of Nanjing Agricultural University (118.8°E, 32.1°N), China. Five vegetable crops, namely, $Amaranth_1$, $Amaranth_2$, Tung choy, Spinach and Coriander herb were grown successively in the four vegetable soils during the experimental period. For each type of soil, three treatments with three replicates were arranged in a random design: urea without NI (N), urea with nitrapyrin (N + CP), urea with dicyandiamide (N + DCD). The application rates of CP and DCD were 0.24% of the rate of urea-N (Zhang et al., 2015) and 2.3% of the rate of urea-N application (Xu et al., 2001), respectively, and mixtures of NIs were obtained by physically mixing them with urea completely. In addition, phosphate and potassium fertilizers in the form of calcium magnesium phosphate and potassium chloride, together with urea, were broadcasted and mixed with soil thoroughly prior to sowing the vegetables. No topdressing events occurred considering the frequent cultivation and short growth period for the leafy vegetables. Based on the vegetable growth, all pots received equal amounts of water and no precipitation. Detailed information on the pot management practices is provided in Table S1.

Each pot consists of a 30 cm × 30 cm (height × diameter) cylinder made of polyvinyl chloride (PVC). The top of each pot was surrounded by a special water-filled trough collar, which allowed a chamber to sit on the pot and prevented gas exchange during the gas-sampling period. Small holes (diameter of 1 cm) at the bottom of the pots were designed

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