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Effects of fertilizer management practices on yield-scaled ammonia emissions from croplands in China: A meta-analysis

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ABSTRACT

China is the world's largest emitter of gaseous ammonia (NH_3), a compound carrying severe human health and ecosystem risks. Fertilizer N application is a major source of this atmospheric NH_3. Although many studies have measured NH_3 emissions from croplands in China, the effect of fertilizer management on yield-scaled NH_3 emissions (i.e., NH_3 intensity defined as NH_3 emissions per unit crop yield) is not so clear. Thus, we performed a meta-analysis to quantify the effect of fertilizer management on NH_3 emissions and NH_3 intensity in China's croplands. Results showed that the increases in NH_3 emissions and NH_3 intensity over a control were greater at high N rates (averaging 305 kg N ha^{-1}) than at low and moderate N rates (average of 130 and 206 kg N ha^{-1}, respectively), while crop yields stayed flat over this range. Rice had greater increases in NH_3 emissions and NH_3 intensity in response to inorganic N addition than other crops. The emission factor for NH_3 was also higher for rice than other crops, and increased with increasing proportions of basal N and soil organic carbon and total N content. Relative to surface application, deep placement of fertilizer N significantly decreased NH_3 emissions and NH_3 intensity. Increasing the number of split applications of fertilizer N significantly reduced NH_3 emissions and NH_3 intensity. Organic manure amendments substituting for all or part of inorganic fertilizer N significantly mitigated NH_3 emissions and led to a reduction in NH_3 intensity but without statistical significance. The use of slow release fertilizers (SR) and urease inhibitors (UI) significantly reduced NH_3 emissions and NH_3 intensity, whereas application of nitrification inhibitors actually increased both. Overall, this meta-analysis demonstrates that appropriate fertilizer management practices such as reducing inorganic N rates, deep placement and split applications of fertilizer N, and using SR and UI can all reduce NH_3 emissions and NH_3 intensity in China's croplands.

1. Introduction

Ammonia (NH_3) is an important atmospheric pollutant, responsible for a number of deleterious impacts on human health and the environment (Behera et al., 2013). As the atmosphere's most abundant alkaline constituent, NH_3 reacts with acidic species (e.g., SO_2 and NO_x) to form ammonium-containing aerosols (Wang et al., 2015). These secondary aerosols constitute the major components of $PM_{2.5}$ (particulate matter with aerodynamic diameters less than 2.5 μm), thereby leading to the degradation of air quality and adverse impacts on human health (Wei et al., 2015). Additionally, emitted NH_3 eventually returns to the soil and surface waters through nitrogen (N) deposition, resulting in soil acidification, eutrophication, and biodiversity loss (Behera et al., 2013).

China is the world's largest emitter of NH_3, with annual emissions 3.0 and 2.7 times as much as those in the United States and European Union, respectively (Paulot et al., 2014). Agriculture activities, such as fertilizer application and livestock production, are the largest global emission source of NH_3 (Gu et al., 2012; Behera et al., 2013). With a large population and as income grows, China's food demands are shifting to a wider variety of produce with a generally larger footprint, as people substitute animal protein, fruits, and vegetables for grains (Micha et al., 2015). Accordingly,

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the nation's NH_3 emissions are expected to continue to increase (Gu et al., 2012, 2015). While mineral fertilizers are a dominant source of NH_3 emissions from agricultural soils, and China is the world's largest fertilizer consumer, considerable uncertainties remain in the national estimates of fertilizer-induced emissions (Huang et al., 2012; Paulot et al., 2014; Xu et al., 2015; Gu et al., 2015). A handful of studies have documented the effects of N fertilizer management on NH_3 emissions in China (Qi et al., 2012; Xu et al., 2012; Li et al., 2015; Liu et al., 2015), but to the best of our knowledge, very few attempts have been made to comprehensively quantify the effect of these fertilizer management practices on NH_3 emissions aside from recent syntheses examining the overall response of NH_3 emissions to N rates (Cui et al., 2013, 2014; Wang et al., 2014).

Filling this knowledge gap is critical because China seeks to achieve not only monumental increases in production but also reduced environmental degradation (Chen et al., 2014; Cui et al., 2014; West et al., 2014). Most notably, yield-oriented fertilizer management practices may actually promote NH_3 emissions (Qi et al., 2012; Sun et al., 2015). Studies so far, meanwhile, have mostly focused on the separate effect of fertilizer management on either crop yields or NH_3 emissions, leaving trade-offs and synergies between crop productivity and NH_3 losses unaddressed (Sanz-Cobena et al., 2014). To ensure food security while improving environmental quality, agricultural pollutants like greenhouse gases, are increasingly considered in relation to crop productivity, i.e., on a yield-scaled as opposed to area basis (Pittelkow et al., 2014). Still, despite several recent studies aimed at reducing areal NH_3 emissions by improving management practices such as optimizing N fertilization, screening cultivars, and water management (Sanz-Cobena et al., 2014; Chen et al., 2015; Zhao et al., 2015), little is yet known about mitigation strategies for yield-scaled NH_3 emissions (i.e., NH_3 intensity defined as NH_3 emissions per unit crop yield).

As a number of studies exist documenting the effect of fertilizer management on NH_3 emissions from croplands in China, a meta-analysis was conducted to synthesize independent experimental results and quantitatively assess the effect of fertilizer management practices on NH_3 emissions and NH_3 intensity. We focused on the following areas: N management (rate, split application, placement), application of enhanced-efficiency N fertilizers, and organic manure.

2. Materials and methods

2.1. Data

We extracted data on NH_3 emissions from peer-reviewed papers published in both Chinese and English language journals before November 2015. Papers in Chinese were collected from the China National Knowledge Infrastructure (CNKI) database and those in English from Web of Science. To be included in the present analysis, studies needed to meet several criteria. First, data collection was restricted to side-by-side field experiments in which the effects of various fertilizer management practices on NH_3 emissions were examined, with pot and lysimeter studies excluded. Second, we focused only on annual crops, and as such perennial crops and orchards were also not included. Third, NH_3 emissions over the course of the entire growing season and the number of field replications had to be reported. Fourth, the only differences between the control and treatments were management practices, while other conditions had to be identical. A minimum of two studies per category was needed to be included in the meta-analysis. In total, 78 papers were included in our analysis (see Appendix A in Supplementary material for the list of references). The geographic distribution of experimental sites and their detailed information are shown in Fig. 1 and Table A1, respectively. Most of the studies (90.0%) utilized chambers (either with or without air flow) to determine NH_3 emissions, while the remainder consisted of one wind tunnel, one dräger-tube, and four micrometeorological (integrated horizontal flux or mass balance methods) studies (Table A1). Studies were incorporated into five separate datasets according to the differences in fertilizer management practices:

(1) Inorganic N addition (dataset 1). We included studies in which a treatment without fertilizer N addition (control) was compared to treatments with inorganic N addition (treatment). To be included, exact fertilizer N rates needed to be reported. For each study in the dataset, the fertilizer-induced emission factor (EF) for NH_3 was calculated as the difference in NH_3 emissions between the N-applied treatment and the control divided by the amount of fertilizer N added. Studies were classified into three groups according to pH: <6.0, 6.0–8.0, and >8.0 (Linquist et al., 2013). Crops consisted of rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), greenhouse vegetables (GV), and open-field vegetables (OV), while other annual crops were not included due to limited numbers of observations.

(2) Split applications of fertilizer N (dataset 2). We included studies that investigated the effect of increasing the number of fertilizer N applications on NH_3 emissions using the same N rate and N source. Although extra additions of fertilizer N may lead to an increase in crop yields and a greater reduction in NH_3 emissions, all the studies included in the dataset were tests of applying fertilizer one more time during the season, for instance, a single basal dose (control) vs. two split applications (treatment) or two splits (control) vs. three splits (treatment).

(3) Nitrogen placement (dataset 3). We included studies in which a treatment with surface application of fertilizer N (control) was compared to a treatment with deep placement of fertilizer N (treatment) with the same N rate and N source.

(4) Organic manure (dataset 4). We included studies in which treatments with inorganic N fertilizer (control) were compared to treatments with full or partial substitution of inorganic N by organic manure (treatment). To be included, the organic manure treatment must have received the same total N rate as the inorganic N control, and the exact fertilizer N rate had to be reported to calculate the proportion of organic N to total N rates. Due to a limited number of observations, we did not distinguish between organic manure types.

(5) Enhanced-efficiency N fertilizers (EENF) (dataset 5). We included studies in which a treatment without EENF (control) was compared to a treatment with EENF (treatment) using the same N rate and N source. The EENF modes of action were slow release (SR), urease inhibitor (UI), and nitrification inhibitor (NI). Slow release fertilizers are either sulfur-coated urea or polymer-coated urea. Urease inhibitors include either *N*-(*n*-butyl) phosphoric triamide or *N*-(*n*-propyl) thiophosphoric triamide. Nitrification inhibitors comprised 3,4-dimethylpyrazole phosphate, dicyandiamide, and pyridine. Due to the limited number of observations, EENF was not categorized by specific products.

As only three studies examined NH_3 emissions from ammonium bicarbonate in comparison to urea and with only one of these reporting crop yields, no attempt was made to distinguish between N sources. For datasets 1 and 4, studies were classified as three groups (low, moderate, and high) according to inorganic N rates, the proportion of fertilizer N applied as a basal application, soil organic carbon (SOC) and total N (TN) content, and the proportion of N rates as organic N. First, we ranked studies according to N rate, the proportion N received as a basal application, SOC and TN concentrations, or the proportion of organic N.