Strategies for mitigating ammonia emissions from agroecosystems

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Abstract
Ammonia (NH_3) volatilization is a significant pathway of nitrogen (N) loss from cropping systems. A number of studies have investigated the effects of management practices on NH_3 emission, but the findings are sometimes contradictory or inconclusive. A meta-analysis was conducted to quantitatively synthesise the global literature on the strategies for mitigating NH_3 emission from agricultural systems. Unlike qualitative reviews, a meta-analysis combines results from different studies to identify patterns among study results. The mitigation strategies included in our meta-analysis were: irrigation, N application method (deep placement), fertilizer type (ammonium-based vs. urea) and the use of urease inhibitors and controlled release fertilizers. Irrigation after fertilization and deep placement of N fertilizers decreased NH_3 emission by around 35% and 65%, respectively. Ammonium-based fertilizers decreased NH_3 loss by 31-75% when compared to urea. Both urease inhibitors and controlled release fertilisers effectively decreased NH_3 volatilization by 54-68%. The findings provide critical information on how to minimize NH_3 volatilization and increase N use efficiency and productivity in cropping systems.

Key Words
Ammonia emission, agricultural systems, mitigation, meta-analysis

Introduction
Ammonia (NH_3) volatilization is one of the main pathways of N loss in agricultural systems. IPCC estimates 10–20% of N is lost via volatilization from synthetic and organic N fertilizers (De Klein et al. 2006). Mitigation strategies for NH_3 emission from N applied in agricultural systems are widely studied. The 4R nutrient stewardship concept (right fertilizer source, rate, place and time) was introduced by Bruulsema et al. (2009) to achieve cropping system goals with economic, social and environmental benefits. Farming practices such as adjusting irrigation amount can mitigate NH_3 volatilization by 47–90% (Holcomb Iii et al. 2011; Zaman et al. 2013; He et al. 2014). The retention of crop residues on the soil surface is a common feature in conservation farming. Nevertheless, this may form a barrier which prevents urea from reaching the mineral soil, and may increase NH_3 volatilization (Su et al. 2014). Recent studies focused on mitigating NH_3 loss using inexpensive amendments such as natural mineral or industrial by-products or chemicals that have high ammonium binding capacity e.g. zeolite (Ahmed et al. 2006b; Bundan et al. 2011) or acidifying effects e.g. humic acid or fulvic acid (Ahmed et al. 2006a; Reeza et al. 2009).

In addition to farm management practices, there have been numerous studies on enhanced efficiency fertilizers in mitigating NH_3 loss from agroecosystems. For example, urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) was found to be more effective than phenyl phosphorodiamidate in retarding urea hydrolysis and more widely used because NBPT works at a low concentration and is easy to store (Chien et al. 2009; Saggar et al. 2013). Nonetheless, the effects of urease inhibitors varied with edaphic and environmental conditions (Suter et al. 2013). Controlled-release fertilizers such as polymer sulphur-coated urea and polyolefin-coated urea can improve N use efficiency, grain yield and pasture quality (Chen et al. 2008). However, Hawke and Baldock (2010) found that both sulfur coated urea and zinc-coated urea showed higher NH_3 loss (10% and 0.8%, respectively) compared to uncoated urea (Hawke & Baldock 2010). Nitrification inhibitors prevent or slow the microbial conversion of NH_4^+ to NO_3^- (Lee et al. 1999), but may prolong the retention of NH_4^+ in the soil resulting in NH_3 volatilization (Ni et al., 2014). This may outweigh the beneficial effects of the inhibitors in decreasing N2O emission (Lam et al. 2016)

While studies on the mitigation strategies for NH_3 emission are sometimes inconclusive, a systematic synthesis of these studies is lacking. To fill this knowledge gap we report the results of a quantitative synthesis of the current literature on the mitigation strategies of NH_3 volatilization to provide critical information on how to minimize N loss as NH_3 in agricultural systems. The information is critical for improving global fertilizer N use efficiency, environmental quality, and climate change mitigation.

Methods

This meta-analysis was conducted based on studies of the effects of mitigation strategies on NH_3 volatilization in cropping and pasture systems published from 1971 to April 2016. We performed extensive keyword searches of several databases (Web of Science (ISI), SCOPUS, CAB Abstracts (ISI), Academic Search complete (EBSCO) and Google Scholar), and the reference list of cited references. The keywords used in the search included ammonia/NH_3 emission, volatilization, loss and/or mitigation, management practice, fertilizer N source, rate, time, place, split application, irrigation, urease inhibitors, controlled release fertilizers, name of the inhibitors, agriculture, cropping, pastures, and their combinations. A total of 886 observations (171 studies) were included in the meta-analysis. We used the natural log transformed response ratio as a metric for analyses (Hedges et al. 1999):

$$\ln r = \ln(\frac{\bar{x}^T}{\bar{x}^C})$$

Where $\bar{x}^T$ is the mean of the treatment group, and $\bar{x}^C$ the mean of the control group. Results are reported as the percentage change of NH_3 volatilization under treatment effects ((r–1) × 100). Negative percentage changes mean the treatment decreased NH_3 volatilization when compared to control whereas positive changes indicate an increase in NH_3 volatilization due to treatment. In our analysis, effect sizes were weighted by a function of sample size by

$$\text{Weight} = (n_C \times n_T)/(n_C + n_T)$$

Where n_C and n_T are the number of replicates of the control and treatment respectively (van Groenigen et al. 2013). The meta-analysis was conducted using MetaWin version 2.1 (Rosenberg et al. 2000).

Results

The application of non-urea based fertilizers and urea-containing mixed fertilizers significantly decreased NH_3 volatilization by 75% and 31%, respectively, when compared to urea fertilizers (Fig. 1a). Ammonia loss increased with N application rate (Fig. 1b). Overall, higher application rates resulted in 186% increase in NH_3 emission. On the other hand, split applications of N fertilizer did not affect NH_3 volatilization (Fig. 1c). Deep placement significantly decreased NH_3 volatilization by 65%, when compared to surface application (Fig. 1d).

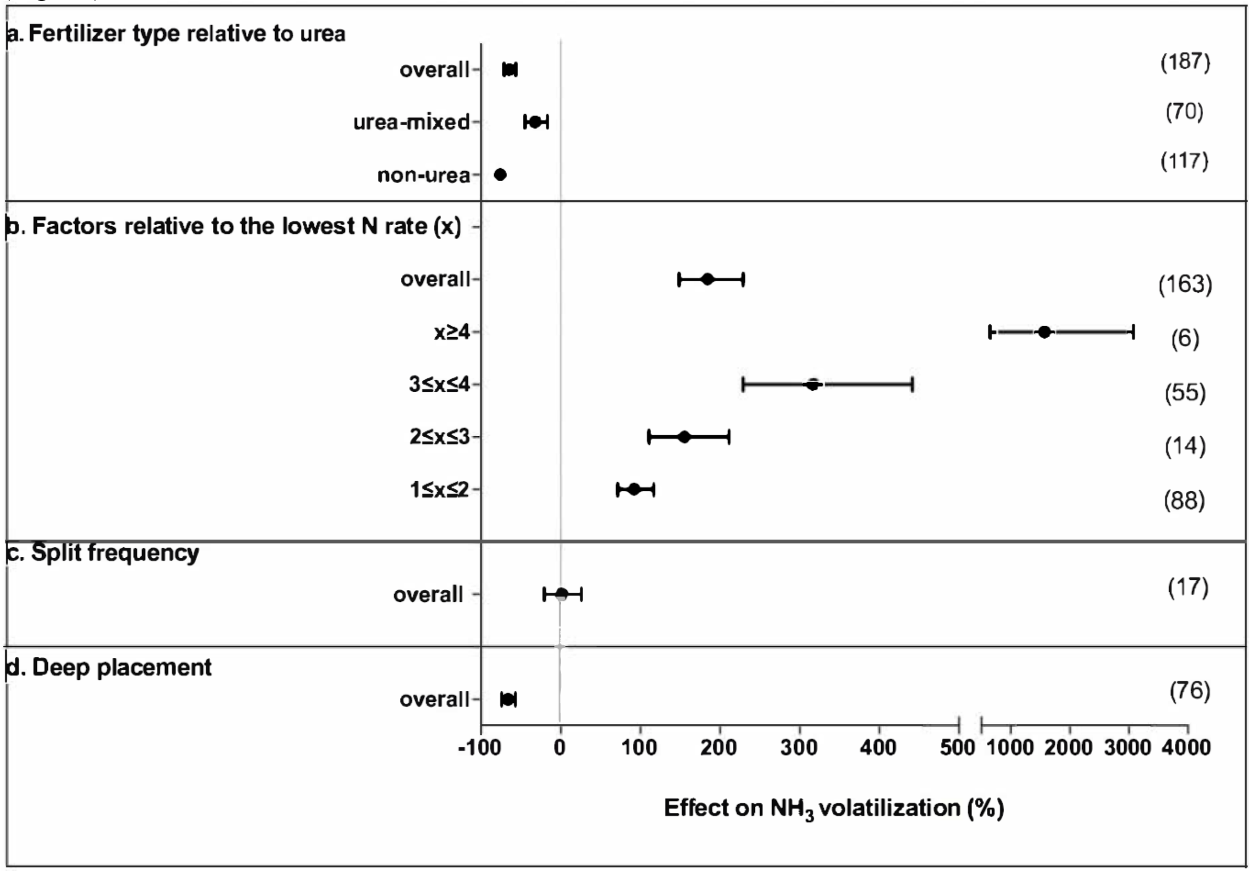

Figure 1. Effects of (a) fertilizer type, (b) factor relative to the lowest N rate, (c) split frequency and (d) deep placement on NH_3 volatilization. Means and 95% confidence intervals are depicted. Numbers of experimental observations are in parentheses.

Irrigation significantly decreased NH_3 volatilization by 35% compared to rainfed or supplementary (minimal) irrigation (Fig. 2a). Residue retention significantly increased NH_3 volatilization by 26% (Fig. 2b). Amendments significantly reduced NH_3 loss by 32% when applied with fertilizers (zeolite, 44%; pyrite, 21%; organic acid, 16%) (Fig. 2c). Urease inhibitors and controlled release fertilizers significantly reduced NH_3 volatilization by 54% and 68%, respectively (Fig. 3a).

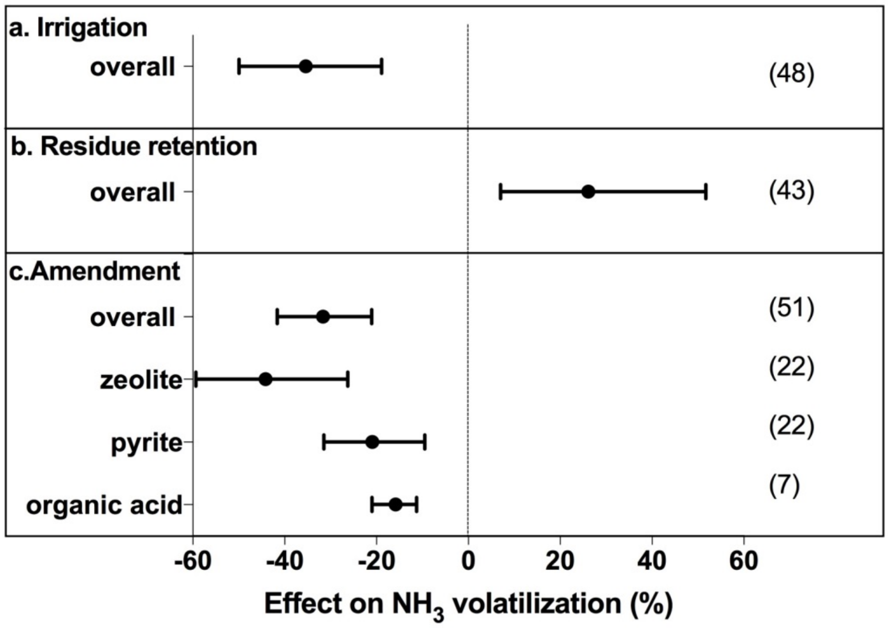

Figure 2. Effect of (a) Irrigation, (b) Residue retention and (c) Amendment on NH_3 volatilization. Means and 95% confidence intervals are depicted. Numbers of experimental observations are in parentheses.

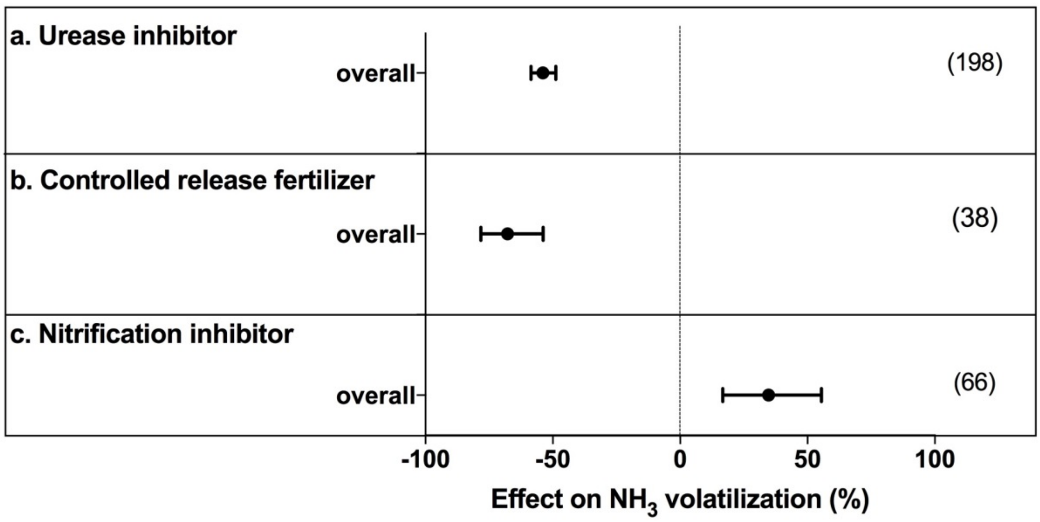

Figure 3. Effect of (a) Urease inhibitors, (b) Controlled release fertilizers and (c) Nitrification inhibitors on NH_3 volatilization. Means and 95% confidence intervals are depicted. Numbers of experimental observations are in parentheses.

Globally, the approximated demand for N fertilizers was 112 million tons of N in 2014 (FAO 2015). Using the IPCC default values (10–20%) for volatilization from applied N, 11.2 to 22.4 million tons of fertilizer-N are lost as NH_3-N globally. Furthermore, based on IPCC's default emission factor for indirect N_2O emission from N volatilization and deposition (EF_4) of 1% (De Klein et al. 2006), this loss equates 0.1–0.2 million tons of indirect N_2O-N emission, or 52.4–104.8 million tons of carbon dioxide equivalent (CO_2-e). Our study demonstrated NH_3 emission could be mitigated by 16% (organic acid amendment) to 88% (the use of ammonium nitrate). This provides substantial economic and environmental benefits.

Conclusion

Mitigating NH_3 loss from agriculture is important. Various strategies effectively decrease the loss. The use of non-urea based fertilizers, reduced fertilizer application rate, deep placement of fertilizers, irrigation, urease inhibitors and controlled release fertilizers were effective in reducing NH_3 volatilization. In contrast, split application of fertilizers did not affect NH_3 emission whereas residue incorporation may increase the emission. This information is critical for global N management in agricultural systems, environmental quality and climate change mitigation.

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