Ammonia volatilization from synthetic fertilizers and its mitigation strategies: A global synthesis

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ABSTRACT

Ammonia (NH_3) volatilization is a major pathway of nitrogen (N) loss in agricultural systems worldwide, and is conducive to low fertilizer N use efficiency, environmental and health issues, and indirect nitrous oxide emission. While mitigating NH_3 volatilization is urgently needed, a quantitative synthesis is lacking to evaluate the effectiveness of mitigation strategies for NH_3 volatilization from synthetic fertilizers applied in agricultural systems. To fill this knowledge gap, we conducted a meta-analysis of 824 observations on impacts on NH_3 volatilization of '4R Nutrient Stewardship' (right source, rate, place and time), farming practices (irrigation, residue retention, amendments), and enhanced efficiency fertilizers (fertilizers with urease inhibitors, nitrification inhibitors or controlled release coatings). We found that, globally, up to 64% (an average of 18%) of applied N was lost as NH_3. The use of non-urea based fertilizers, deep placement of fertilizers, irrigation, and mixing with amendments (pyrite, zeolite and organic acids) significantly decreased NH_3 volatilization by 75, 55, 35 and 35%, respectively. In contrast, NH_3 volatilization was not affected by split application, but significantly increased with N application rate and residue retention. Among the enhanced efficiency fertilizers, urease inhibitors and controlled release fertilizers decreased NH_3 volatilization by 54 and 68% respectively whereas nitrification inhibitors increased NH_3 volatilization by 38%. These results confirm that NH_3 volatilization represents a substantial loss of N from agricultural systems, and that this N loss can be mitigated through adaption of appropriate fertilizer products and/or improved management practices.

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1. Introduction

The excessive release of reactive nitrogen (Nr) poses adverse impacts on the natural biogeochemical cycle of N, causing negative consequences on water, air and land (Fowler et al., 2013; Galloway et al., 2008). As a species of Nr, ammonia (NH_3) is lost via volatilization as one of the main pathways of N loss in agricultural systems. While >40% of the applied N is reported to be lost as NH_3 under certain environmental and edaphic conditions (Singh et al., 2013), an average of 10–14% of N is lost via volatilization from synthetic fertilizers (Bouwman et al., 2002; De Klein et al., 2006). Globally, the approximated demand for N fertilizers was 112 million tons of N in 2014 (FAO, 2015). Using the IPCC default value (10%, De Klein et al., 2006) and Bouwman et al. (2002)'s average value (14%) for volatilization from applied N, 11.2–15.7 million tons of fertilizer-N are lost as NH_3-N globally. This N loss as NH_3 represents a substantial financial cost to farmers. Furthermore, based on the 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 0.1–0.16 million tons of indirect N_2O-N emission, or 52.4–73.5 million tons of carbon dioxide equivalent (CO_2-e). However, this indirect connection between NH_3 and N_2O emissions is often neglected, and in most countries, there are no regulations or incentive programs to tackle the challenge of NH_3 volatilization (Behera et al., 2013).

Mitigation strategies for NH_3 volatilization 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. For example, when compared to urea (the most commonly used N fertilizer), alternative N source such as ammonium sulphate, diammonium phosphate and calcium ammonium nitrate decreased NH_3 volatilization by 22–55% (Bayrakli, 1990). It is widely reported that NH_3 volatilization increased with N application rate (Black et al., 1985; Bosch-Serra et al., 2014; Turner et al., 2012).

Sub-surface banding or deep placement of urea reduced NH_3 volatilization when compared to surface broadcast of urea on calcareous or well-buffered soils (Cai et al., 2002; Rao and Batra, 1983). Rochette et al. (2013) found that urea applied at depths >7.5 cm resulted in negligible NH_3 volatilization. Split, band application decreased NH_3 volatilization when compared to a single, surface application (Junejo et al., 2013). However, in Rodgers et al. (1984)'s study, NH_3 volatilization tended to increase under split application in summer.

Farming practices such as adjusting irrigation amount can mitigate NH_3 volatilization by 47–90% (He et al., 2014; Holcomb et al., 2011; Zaman et al., 2013). In contrast, compared to zero water application, NH_3 volatilization was increased by 9% when a 3 mm water was added to the soil immediately after urea application (Sanz-Cobena et al., 2011). 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 volatilization 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 volatilization from agroecosystems. For example, urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) was found to be more effective than phenyl phosphorodiamide 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 sulphur coated urea showed higher NH_3 volatilization (10%) compared to uncoated urea. Nitrification inhibitors prevent or slow the microbial conversion of ammonium (NH_4^+) to nitrate (NO_3^-) (Lee et al., 1999). Although nitrification inhibitors are designed to target N_2O emissions, the use of these inhibitors may prolong the retention of NH_4^+ in the soil resulting in NH_3 volatilization (Kim et al., 2012; Lam et al., 2016; Ni et al., 2014).

While studies on the mitigation strategies for NH_3 volatilization 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 crucial for improving global fertilizer N use efficiency, environmental quality, and climate change mitigation.

2. Materials and methods

2.1. Database compilation

This meta-analysis was conducted based on studies of the effects of mitigation strategies (the 4R nutrient stewardship, farming practices and enhanced efficiency fertilizers) on NH_3 volatilization in cropping and pasture systems published from 1971 to February 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; nitrification inhibitors; name of the inhibitors such as NBPT; DCD; DMPP; agriculture; cropping; pastures; and their combinations. Original data were extracted from tables and data values presented in figures were obtained using digitizing software (Engauge Digitizer). Studies were included if they met the following criteria. The sample sizes and means of NH_3 volatilization had to be reported for control and treatment plots. Details on experimental location; year; design and conditions must be provided to enable the cross checking of duplicate publication. Multiple observations from the same experimental site over sampling time or year of study were averaged. For fertilizer source; we treated urea (the most commonly used N fertilizer that is associated with NH_3 volatilization) as a control and the other fertilizers as treatments. Fertilizer source was sub-divided into non-urea and urea-mixed fertilizers. For fertilizer application rate (kg N ha^{-1}); we calculated the factor of application rate relative to the lowest N rate (x); and was grouped into $1 < x \leq 2$; $2 < x \leq 3$; $3 < x \leq 4$ and $x > 4$. Location of fertilizer application included deep placement of fertilizers relative to surface application of fertilizers (control). Fertilizer application time was categorized according to the splitting frequency (singe application or splitting 3 or 4 times). Application time in terms of plant growth stage was excluded in the analysis because most of the relevant studies did not have a proper control treatment for growth stages. Irrigation management included irrigation as the treatment; whereas no irrigation (rainfed) and supplementary irrigation (to keep the plants alive) were treated as the control. Materials added as amendments comprised pyrite; zeolite and organic acid; as these materials have been widely studied on their use in tackling NH_3 volatilization. Enhanced efficiency fertilizers were classified into fertilizers added with urease inhibitors; nitrification inhibitors and controlled release coatings. A total of 824 observations (145 studies) were included in the meta-analysis (references are listed in Appendix S1 in Supplementary materials). A database (see Supplementary Tables S1–S10) was compiled based on these literatures and classified into different categories.

This database encompasses the majority of studies that reported NH_3 volatilization from cropping and pasture systems. From this, we assessed the significance of NH_3 volatilization from these systems and expressed the NH_3-N volatilization as a percentage of N applied. To determine NH_3 volatilization without the effect of mitigation strategies under field conditions, we assembled field experimental data from the treatment of surface broadcast of urea fertilizers (78 observations). The results were categorized by continents viz. Asia (East Asia, South Asia, Southeast Asia), Australasia, Europe, North America and South America (Table 1).

Table 1
Nitrogen loss as NH_3 of applied urea from agricultural land worldwide.

Continent	N loss as NH_3					
	%			kg N ha^{-1}per cropping season		
	Mean	Median	Range	Mean	Median	Range
Asia						
East Asia	15.9	13.3	1.7–48.0	20.6	16	1.8–96.0
South Asia	30.7	21.9	3.0–56.7	37.5	27.2	5.6–69.7
Southeast Asia	16.1	14.5	14.4–19.5	10.7	8.7	8.6–14.6
Australasia	16	18.5	2.0–30.0	13.7	11.2	0.8–49.2
Europe	13	10.6	0.9–29.8	17	17.8	0.6–29.8
North America	17.5	15.3	0.6–64.0	22.2	20.5	0.6–89.6
South America	14.2	13.3	1.7–31.8	11.8	10.1	0.9–25.4
Average	17.6	15.3	0.9–64.0	19.1	15.9	0.6–96.0

2.1.1. Meta-analysis

The response ratio ($r=\bar{x}^T/\bar{x}^C$) is the ratio of treatment group to the control group and it can be used to estimate the effect as a proportionate change due to experimental manipulation (Lam et al., 2012; Rosenberg et al., 2000). For NH_3 volatilization, we used the natural log transformed response ratio as a metric for analyses (Hedges et al., 1999):

$$Inr = In\left(\frac{\bar{x}^T}{\bar{x}^C}\right)$$

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. Effect sizes are generally weighted by the inverse of pooled variance (Ainsworth and Long, 2005), replication (Adams et al., 1997; Lam et al., 2013) or unweighted (Wang, 2007), depending on availability of weighting parameters. Not all the literatures reviewed in our database had included variances. Moreover, extreme weights might be obtained by variance-based weighting function (van Groenigen et al., 2011). Therefore, in our analysis, effect sizes were weighted by a function of sample size by

$$Weight = (n_C \times n_T)/(n_C + n_T)$$

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). Mean effect sizes and 95% confidence intervals were generated by bootstrapping (4999 iterations) (Rosenberg et al., 2000). A fixed-effects model or a mixed-effects model is technically not applicable for non-parametric meta-analytic procedures based on weighting by replication. However, to perform a correct bootstrapping using MetaWin, a fixed-effects model had to be selected. The effects of the mitigation strategies were considered significant if the 95% confidence intervals did not overlap with zero.

3. Results

3.1. Percentage of N loss as NH_3

Globally, the average NH_3 volatilization losses ranged from 0.9 to 64% (a mean of 17.6%) of the applied N. The percentage of N loss
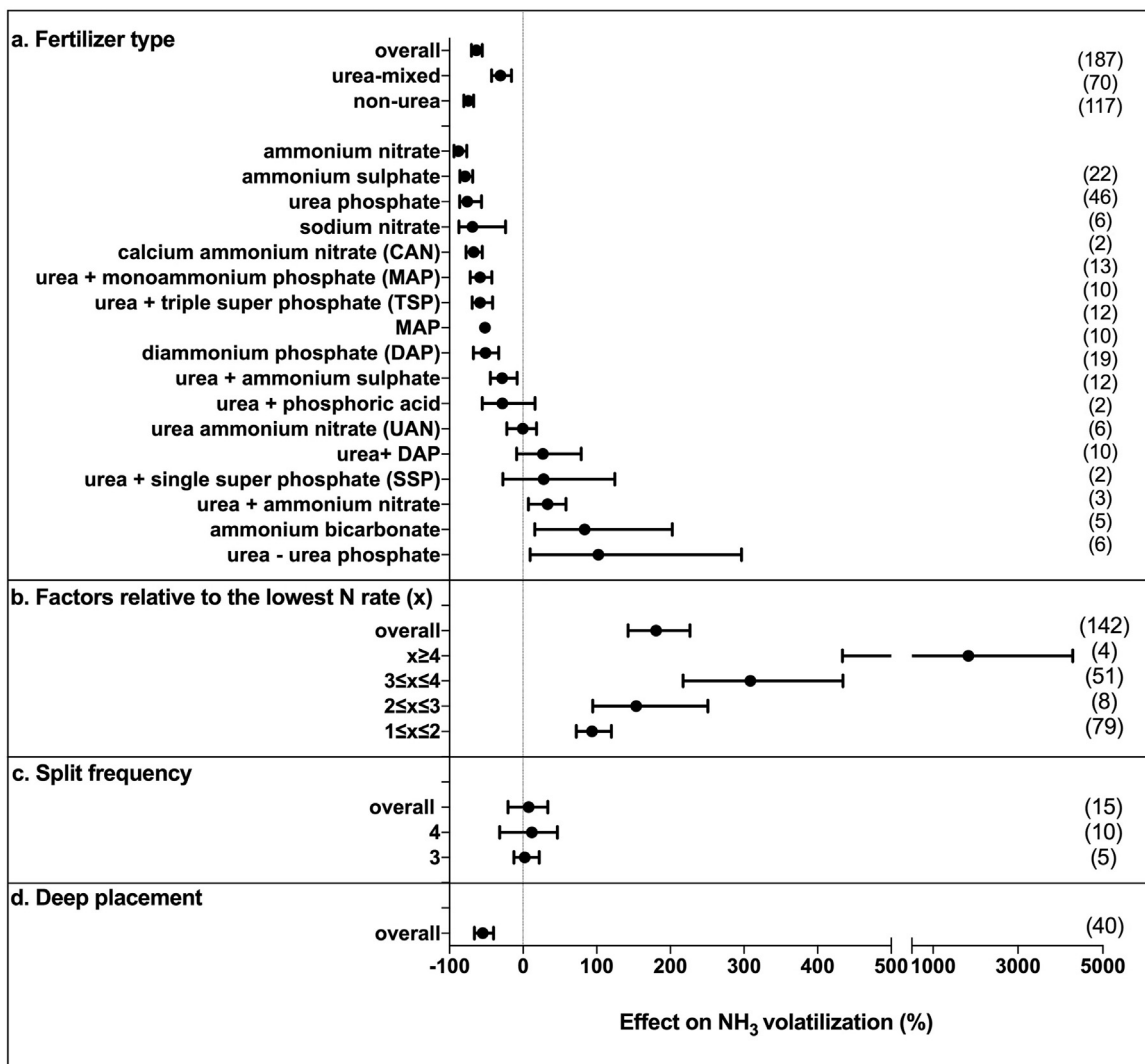

Fig. 1. Effects of (a) fertilizer source, (b) application rate, (c) split application and (d) deep placement on NH_3 volatilization. Means and 95% confidence intervals are depicted. Numbers of experimental observations are in parentheses.

as NH_3 was the highest in South Asia (30.7%), followed by North America (17.5%) and Southeast Asia (16.1%). The regions in Europe represent the lowest percentage of N loss as NH_3 (13.0%) (Table 1). In terms of amounts, NH_3 volatilization accounted for 0.6–96 (a mean of 19.1) kg N ha^{-1} per cropping season. The amount of NH_3-N volatilized per cropping season was the highest in South Asia (37.5 kg N ha^{-1}), followed by North America (22.2 kg N ha^{-1}) and East Asia (20.6 kg N ha^{-1}) (Table 1).

3.2. The 4R nutrient stewardship

When compared to urea fertilizers, the application of non-urea based fertilizers and urea-containing mixed fertilizers significantly decreased NH_3 volatilization by 74.5% and 30.8%, respectively, with an overall reduction of 63.5% (Fig. 1a). Ammonium nitrate and ammonium sulphate were the two most effective non-urea fertilizers in reducing NH_3 volatilization (by 87.9% and 78.8%, respectively) relative to urea application. Ammonia volatilization increased with N application rate (Fig. 1b). Overall, increasing N application rate resulted in up to 180.7% increase in NH_3 volatilization. Deep placement significantly decreased NH_3 volatilization through incorporation of fertilizers by 54.7% when compared to surface application (Fig. 1c). On the other hand, split applications of N fertilizer did not affect NH_3 volatilization, regardless of splitting frequency (Fig. 1d).

3.3. Farming practices

Irrigation significantly decreased NH_3 volatilization by 34.5% compared to rainfed or supplementary (minimal) irrigation (Fig. 2a). Residue retention significantly increased NH_3 volatilization by 25.5% (Fig. 2b). Amendments significantly reduced NH_3 volatilization by 31.4%. In particular, zeolite decreased NH_3 volatilization by 43.5%, followed by pyrite (20.9%) and organic acid (15.9%) when applied with fertilizers (Fig. 2c).

3.4. Enhanced efficiency fertilizers

Overall, urease inhibitors significantly reduced NH_3 volatilization by 53.7% (Fig. 3a). CHPT was the most effective urease inhibitor in decreasing NH_3 volatilization (by 86.6%). Hydroquinone, in contrast, was the only inhibitor that did not significantly reduce NH_3 volatilization (Fig. 3a). Controlled release fertilizers effectively lowered NH_3 volatilization by 68.0% (Fig. 3b). Methylene urea was the most effective in decreasing NH_3 volatilization (by 87.5%). Coated urea fertilizers such as thermoplastic resin-coated urea, sulphur-coated urea, and polyfin-coated urea significantly reduced NH_3 volatilization by 82.7%, 78.4%, and 69.4%, respectively (Fig. 3b). Nitrification inhibitors increased NH_3 volatilization by an overall of 38.0% (Fig. 3c). Apart from DMPP, which did not significantly affect NH_3 volatilization, other nitrification inhibitors increased the loss by 22.6–220.1% (Fig. 3c).

4. Discussion

4.1. Ammonia as a major N loss pathway

Ammonia volatilization from N applied in agricultural systems is a global issue that needs to be resolved. We found that the global average percentage of N loss as NH_3 was 17.6%, which is comparable to the range of 10–14% reported by the IPCC (De Klein et al., 2006) and Bouwman et al. (2002). The values for specific continents are similar to those reported by Sutton et al. (1995), Bouwman et al. (2002) and Yan et al. (2003). It is worth noting that up to 64% of N applied could be lost as NH_3 (Table 1). Based on the approximated global demand for N fertilizers of 112 million tons of N in 2014 (FAO, 2015) and an average 5-year of US $350 per ton of urea (World Bank, 2015), the global average of NH_3-N loss (17.6%, Table 1) equals a financial loss of US$15 billion. Using EF_4 of 1% (De Klein et al., 2006), we estimated that this loss of 19.7 million tons NH_3-N from fertilizers is equal to 0.2 million tons of indirect N_2O-N emission, or 92.3 million tons of CO_2-e. Ammonia volatilization represents agronomic losses and inefficient use of fertilizers; it is also associated with eutrophication of aquatic systems, formation of particulate matter, soil acidification, and indirect N_2O emission (Saggar et al., 2013). This highlights the importance of mitigating NH_3 volatilization from agricultural systems.
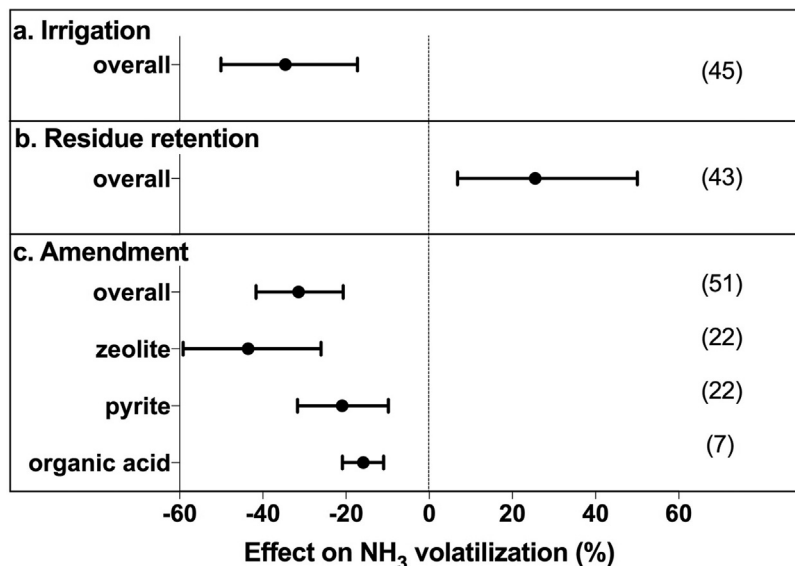

Fig. 2. Effect of (a) irrigation, (b) residue retention and (c) amendment on NH_3 volatilization. Means and 95% confidence intervals are depicted. Numbers of experimental observations are in parentheses.
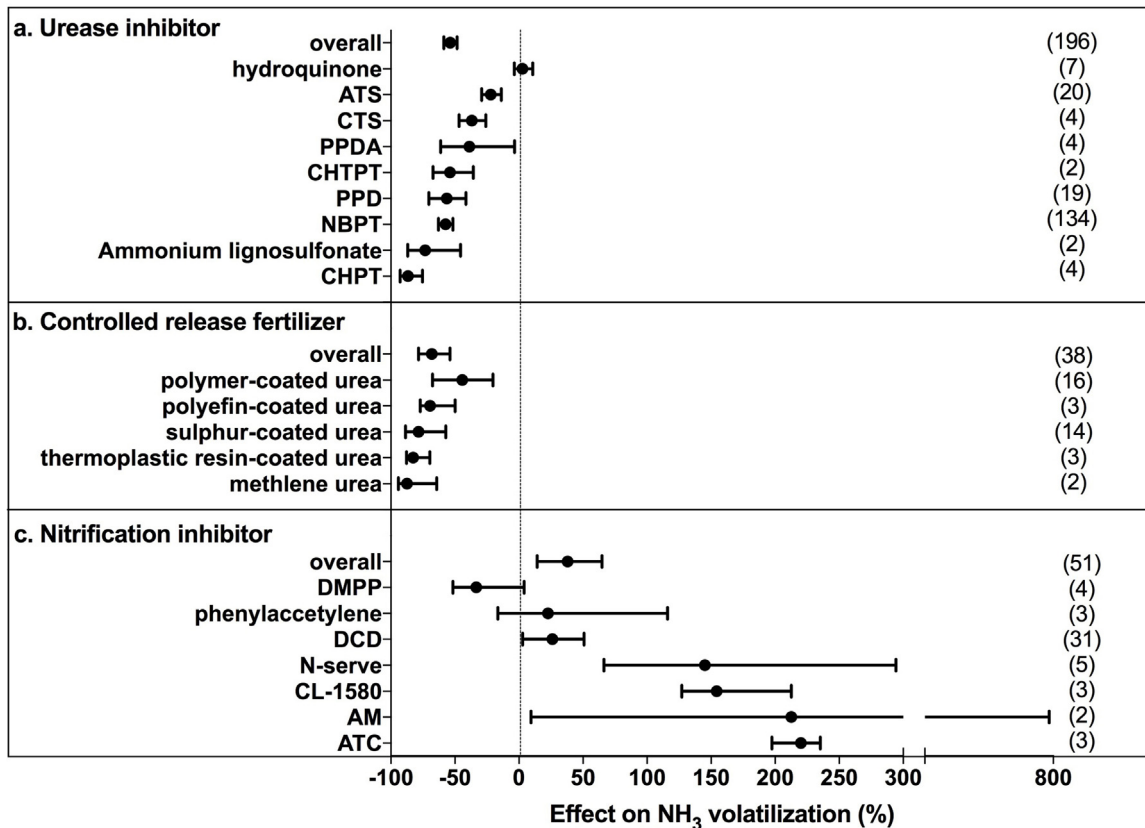
Fig. 3. Effect of (a) urease inhibitors, (b) controlled release fertilizers and (c) nitrification inhibitors on NH_3 volatilization. Means and 95% confidence intervals are depicted. Numbers of experimental observations are in parentheses. CHPT: cyclohexyl phosphoric triamide, CHTPT: cyclohexyl thiophosphoric triamide, ATS: ammonium thiosulphate, CTS: calcium thiosulphate, PPDA: phenyl phosphorodiamidate, NBPT: N-(*n*-butyl) thiophosphoric triamide, PPD: phenylphosphorodiamide, DMPP: 3,4-dimethylpyrazole phosphate, AM: 2-amino-4-chloro-6-methyl pyrimidine, ATC: 4-amino-l, 2,4-triazole, N-serve: 2-Chloro-6-trichloromethyl pyridine, DCD: dicyandiamide.

4.2. Mitigation strategy—the 4R nutrient stewardship

The 4R nutrient stewardship was proposed for achieving sustainable crop nutrition while minimizing field nutrient loss and maximizing crop uptake (Bruulsema et al., 2009). Our meta-analysis shows that three out of the four '4R's were effective in decreasing NH_3 volatilization. The first 'R'—right fertilizer: Non-urea fertilizers were effective in reducing NH_3 volatilization compared to urea fertilizers. The use of non-urea fertilizers avoids the localized pH hot spot that occurs during urea hydrolysis and drives NH_3 volatilization (Du Preez and Burger, 1988). Ammonium-based products and other non-urea based fertilizers such as sulphate and triple super phosphate, may contribute to soil acidification and subsequently decrease NH_3 volatilization (Akhtar and Naeem, 2012; Du Preez and Burger, 1988; Fan and Mackenzie, 1993). While urea is a commonly used fertilizer due to its high N content (cost-effectiveness) and ease of transport, our findings suggest that urea should be applied with appropriate measures taken (discussed in below sections) or at a lower rate blended with ammonium based fertilizers to minimize NH_3 volatilization. The second 'R'—right N application rate: Our meta-analysis indicated that NH_3 volatilization increased with N application rate. It is expected that higher N (urea or ammonium) input would increase NH_4^+ availability, and for urea, the interaction among adjacent granules on soil pH, thereby increasing NH_3 volatilization (Watson and Kilpatrick, 1991). The third 'R'—right place: Incorporating fertilizers into the soil reduces their exposure to the air and subsequent NH_3 volatilization (Al-Kanani et al., 1994; Cai et al., 2002). The fourth 'R'—right time: Split application of fertilizers did not affect NH_3 volatilization in our synthesis, regardless of the

frequency of splitting. Indeed, the effects of split application largely depend on edaphic conditions and plant growth stages. For example, when split application was applied in summer with high soil temperature and low soil moisture contents, NH_3 volatilization tended to increase compared to single application (Rodgers et al., 1984). In contrast, when split application was applied during booting or panicle initiation stages, little NH_3 was lost due to rapid plant N uptake (Sommer et al., 2004). Nonetheless, split application of fertilizers has been shown to decrease NO_3^- leaching, improving crop yield and N use efficiency of various agricultural systems (e.g. Ahmad et al., 1999; Cassman et al., 2002; Sitthaphanit et al., 2009).

4.3. Mitigation strategy—farming practices

Irrigation immediately after urea application dissolves and washes urea into the soil, and NH_4^+ can be adsorbed on cation exchange sites (Zaman et al., 2013). While urea hydrolysis usually occurs within a few days after fertilizer application (Black et al., 1985), irrigation one week after fertilizer application would have minimal mitigating effect on NH_3 volatilization (Sommer et al., 2004). In contrast, our study shows that residue retention overall increases NH_3 volatilization although contrasting impacts of residue retention on the exposure of urea to the air have been reported. On the one hand, surface residues may stimulate volatilization owing to restricted movement of urea into the soil and higher urease activity in the residues (Su et al., 2014). On the other hand, urea granules may be covered by the residue retained on the soil surface, which reduces the exposure of urea to the air (Tomar et al., 1985). In this regard, the rate and density of residue

retention is critical. Ammonia volatilization can also be decreased by adding amendments that have a high affinity for binding on NH_4^+ ions (Ndegwa et al., 2008) such as zeolite as illustrated in our meta-analysis. Zeolite with its high cation exchange capacity has been proven effective in reducing NH_3 volatilization in both acidic and alkaline soils (Ahmed et al., 2006b; He et al., 2002). Ammonia volatilization may also be attenuated by the addition of pyrite to urea fertilizers because the adsorbed sulphates and free sulphides of pyrite can retard the increase in pH around urea microsite (Blaise et al., 1996). While alkaline conditions favour NH_3 volatilization (Freney et al., 1983), amending fertilizers with organic acid e.g. fulvic acid, humic acid reduces soil pH, and subsequent NH_3 volatilization, as shown in our study.

4.4. Mitigation strategy—enhanced efficiency fertilizers

Enhanced efficiency fertilizers have been widely adopted to minimize N loss, including NH_3 volatilization from agricultural systems. Our synthesis shows that urease inhibitors significantly decreased NH_3 volatilization. This is attributed to the inhibition of urease activity by urease inhibitors, which slows down urea hydrolysis (Sommer et al., 2004). For example, compounds with thiosulphate such as ammonium thiosulphate and calcium thiosulphate, can inactivate the sulphydryl groups of urease (Saggar et al., 2013), but their effectiveness depends on edaphic and environmental conditions (Sloan and Anderson, 1995). A combination of urease inhibitors may exert positive or negative effects on their ability to mitigate NH_3 volatilization. For instance, Al-Kanani et al. (1994) found that urease inhibitors NBPT and PPD significantly decreased NH_3 volatilization, but their effectiveness was reduced when combined with ammonium lignosulphonate, a potential urease inhibitor. This interaction was attributed to a reaction between urease and lignosulphonate, which makes urease less susceptible to NBPT or PPD (Al-Kanani et al., 1994). In contrast, Phongpan et al. (1995) demonstrated that a combination of NBPT and PPD was more effective in reducing NH_3 volatilization than either of these inhibitors alone. This could be due to the lag time between the two inhibitors in inhibiting urea hydrolysis where PPD inhibited urease activity initially, followed by NBPT which became effective after its conversion to NBPTO.

We also found that controlled release fertilizers effectively decreased NH_3 volatilization. These fertilizers delay the availability of nutrients e.g. urea and ammonium for plant uptake and utilization, or extend the period during which the nutrients are available to the plant (Trenkel, 1997). Simultaneously, urea hydrolysis is minimized in particular when urea granules are covered with impermeable membrane such as a sulphur coating (Trenkel, 1997). This significantly reduces NH_3 volatilization.

In contrast, our study indicates that nitrification inhibitors increased NH_3 volatilization. This is in agreement with the meta-analysis conducted by Qiao et al. (2015), who demonstrated that nitrification inhibitors increased NH_3 volatilization from agricultural systems by 33–67%. While these inhibitors are designed for mitigating N_2O emission, their use prolongs the detention period of NH_4^+ in soil and may stimulate NH_3 volatilization (Soares et al., 2012; Zaman and Nguyen, 2012). This indicates that other climate change mitigation strategies may indirectly affect NH_3 volatilization, and subsequently N_2O emission from deposited NH_3 (Lam et al., 2016).

4.5. Potential for climate change mitigation

Our study demonstrated NH_3 volatilization could be mitigated by 16% (organic acid amendment) to 88% (the use of ammonium nitrate). As mentioned earlier, we estimated that the loss of 19.7 million tons NH_3-N from fertilizers is equal to 0.2 million tons of indirect N_2O-N emission, or 92.3 million tons of CO_2-e. Adopting various NH_3 mitigation strategies (reduction of 16–88%, Figs. 1–3) would decrease emission of 15–81 million tons CO_2-e annually from agricultural systems.

5. Conclusion

This study highlights the significance of mitigating NH_3 volatilization from agriculture and evaluates the potential of various strategies for reducing the loss. The use of non-urea based fertilizers, reduced fertilizer application rate, deep placement of fertilizers, irrigation, urease inhibitors and controlled release fertilizers are effective in reducing NH_3 volatilization. Adopting these mitigation strategies can also reduce indirect greenhouse gas emission. These strategies should be complemented by local level practicality when implemented. In contrast, split application of fertilizers did not affect NH_3 volatilization whereas residue retention and the use of nitrification inhibitors may increase the volatilization. Our results provide major implications for global N management in agricultural systems, environmental quality and climate change mitigation.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.08.019.

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