Geoderma 457 (2025) 117285

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Regionalized ammonia emission abatement by urease inhibitor treatment of urea for agro-environmental conditions of Western Central Europe

Julia Schoof[a], Roland Fuß[b], Sebastian Wulf[c], Andreas Pacholski[b,*]

[a] Group of Isotope Biogeochemistry and Gas Fluxes, Leibniz Centre for Agricultural Landscape Research (ZALF) e.V, Müncheberg, Germany
[b] Institute of Climate-Smart Agriculture, Johann Heinrich von Thünen Institute, Germany
[c] Association for Technology and Structures in Agriculture, Darmstadt, Germany

ARTICLE INFO

Handling Editor: Dr Mariluz Cayuela

Keywords:
Ammonia mitigation
Urease inhibitor
Emission factor
Ammonia emission inventory

ABSTRACT

Urea is the most widely used synthetic fertilizer worldwide, covering 16% of fertilizer consumption in Germany in 2022. It has a notable propensity to release nitrogen (N) in the form of ammonia (NH_3) when applied to soil, contributing to environmental pollution, and indirectly increasing nitrous oxide (N_2O) emissions. This loss of NH_3 from urea also represents a loss of N for crop production. Consequently, urease inhibitors (UIs) are increasingly applied in agricultural practice to mitigate N losses, and to ensure compliance with regulations recently introduced in some European countries. This development should be reflected in reported emissions at national level. Representative emission and abatement factors are, therefore, required for a precise calculation of NH_3 losses from urea application. While some *meta*-studies suggest abatement factors on a global scale, their applicability across countries is questionable, due to variable environmental and crop conditions, especially within Europe.

We conducted an analysis of the current international literature to derive a new emission factor for NH_3 losses after application of urea with UIs for Western Central Europe, that is suitable for integration into the German emission inventory and inventories of other countries with similar cropping conditions. Based on a linear mixed-effects model, we found an abatement factor of 60 %. In contrast to theoretical expectations, environmental factors, such as temperature, soil pH, soil CEC and land use had no significant influence on this abatement effect. Our findings emphasize the need for further comprehensive data sets to refine emission calculations at the national level, reflecting effects of regional weather and cropping conditions on the NH_3 abatement by use of UIs.

1. Introduction

Urea is the globally most consumed N fertilizer (>49 % of total synthetic fertilizer consumption, Fertilizers Europe 2022) and after field application a main source of ammonia (NH_3) emissions (~20 % of global NH_3 emissions, Skorupka & Nosalewicz 2021). Ammonia emissions cause considerable negative environmental effects by soil acidification, eutrophication of natural habitats and as an indirect source of the greenhouse gas nitrous oxide (N_2O) (Bremner, 1995; Canfield et al., 2010). It also causes health hazards, because it is a precursor of fine particular matter (Pozzer et al., 2017). Therefore, many countries have created policies to reduce these emissions by different regulatory and technical measures. The German fertilizer ordinance 2017 (DüV, 2017) stipulates that urea, starting from February 2020, must be either incorporated within 4 h after application or applied in combination with a urease inhibitor (UIs) to reduce NH_3 emissions concomitant with urea fertilization. In 2016, before introduction of this regulation, 25 % and 10 % of total synthetic nitrogen fertilizer were applied as urea or urea ammonium nitrogen (UAN) solution, respectively. In 2022, these values changed to 16 % urea and 9 % UAN of total synthetic nitrogen (Hu et al. 2024).

As the mode of action, UIs delay urea hydrolysis, and thus the formation of ammonium (NH_4^+) and NH_3 which exist in equilibrium in the soil solution (Byrne et al., 2020). Urea hydrolysis causes a microscale increase of soil pH in the vicinity of the fertilizer granule, which shifts the equilibrium towards NH_3 (Whitehead & Raistrick, 1990). A slower urea hydrolysis gives more time for urea distribution in soil and soil pH buffering, which reduces the potential for NH_3 emissions. It also increases the likelihood that NH_4^+ – as product of urea hydrolysis – is adsorbed to the soil matrix or that urea is translocated into deeper soil

---

* Corresponding author.
E-mail address: andreas.pacholski@thuenen.de (A. Pacholski).

https://doi.org/10.1016/j.geoderma.2025.117285
Received 9 October 2024; Received in revised form 2 April 2025; Accepted 3 April 2025

layers after precipitation events.

All these effects of UIs can significantly reduce gaseous NH_3 losses (Li et al., 2018; Ni et al., 2014; Sommer et al., 2004). According to the Guidance from the UNECE Task Force on Reactive Nitrogen (Bittman et al., 2014), NH_3 emissions from urea application are reduced by 70 % using UIs. This reduction factor has also been included in the calculations of the German Emission Inventory since the 2022 submissions (Vos et al., 2022) under the United Nations Framework Convention on Climate Change (UNFCCC) and under the Geneva Convention on Long-range Transboundary Air Pollution (CLRTAP). Prior to 2020 and for unmitigated NH_3 emissions from urea, it was assumed that urea was applied without UIs, whereby the default EF from EMEP/EEA (2019) was adopted for the emission calculation, which amounts to 0.155 kg NH_3 per kg urea N.

However, current literature studies on the effect of UIs on NH_3 emission with the application of urea determined an average emission reduction effect between 52.0 % and 63.4 % and are, thus, rather below the level of Bittman et al. (2014) (Table 1). Apart of the biochemical mechanism of inhibition itself, the emission reduction by UIs can be affected by site characteristics as well as the prevailing environmental conditions and can, therefore, vary considerably (Fan et al., 2022). As NH_3 emissions from fertilizers are to be considered a key category (according to amount) of NH_3 emissions in Germany (UBA, 2023), higher Tier levels of emission reporting should be applied, e.g. country-specific estimation of fertilizer derived NH_3 emissions. The use of UIs on urea fertilizers has been subject of several global *meta*-studies (Fan et al., 2022; Li et al., 2018; Pan et al., 2016) and showed considerable emission reduction. Effects of temperature, soil pH and carbon exchange capacity were shown to influence the NH_3 emission from urea solution (Ohnemus et al., 2021). In addition, the influence of soil pH on NH_3 emissions from synthetic fertilizers has already been considered in the recent EMEP guidebook on emission reporting within the framework of the Gothenborg protocol, providing different emission factors for low ($\text{pH} \leq 7$) and high soil pH regions ($\text{pH} > 7$). Interaction of rainfall and temperature were also shown to affect NH_3 emissions but the effect is not yet included in EF calculation (EMEP/EEA, 2023). For a better understanding and reporting, the determination of the regionalized effect size of UIs on NH_3 emissions is, therefore, indispensable.

The aim of this study was to analyse the efficacy of UIs on NH_3 emission abatement under conditions of Western Central Europe and to derive modified emission factors reflecting the effect of UIs on NH_3 emissions after surface spreading of urea, based on currently available scientific literature. Additionally, the existing gaps in research data should be identified in this context.

Table 1
Overview of previous literature studies, investigating the efficacy of urease inhibitors in mitigating NH_3 volatilization.

Reference	Reduction by UIs in NH_3 compared to urea [%]	Temporal scale	Number of studies	Number of observations
Fan et al. (2022) $^{+}$	51.0 (36–55)	1996–2022	NA	76
Li et al. (2018)	63.4 (57.5 – 68.9) *(NBPT: 64.3)*	1980–2016	30	100
Pan et al. (2016)	53.7 *(NBPT: 60.0)*	1971–2016	35	196
Silva et al. (2017) $^{+}$	52.0	1990–2014	35	121
Ti et al. (2019)	53.1 *(NBPT: 53.9)*	1980–2017	NA	66

$^{+}$ authors only considered the urease inhibitor N-(n-Butyl)-thiophosphortriamid (NBPT) in their *meta*-analysis.

2. Materials and methods

2.1. Data collection

Instead of applying a model based on a globally sourced dataset to regional conditions, we have decided to select, analyze and model data for the conditions (soil, weather, canopy) for our target geographic region of Western Central Europe (Germany and regions close to it). Thereby, uncertainties stemming from emission data which are affected by a wide range of interacting factors are avoided. This is because establishing satisfactory relationships is difficult or even impossible when using data from experiments conducted by different teams under agronomic and environmental conditions that differ significantly from those of the geographical area under study.

The statistical analysis considered field studies on the effect of UIs on NH_3 volatilization from agricultural soils that had been published by 2021. We collected the international literature from the *Web of Science* and *google.scholar.de* databases (keywords: *mineral fertilizer; NH_3 volatilization; NH_3 emission; NH_3 loss; agriculture; application; inhibitor*). Previously published literature reviews (Li et al., 2018; Pan et al., 2016) were also used to compile the data set. We did not include unpublished data, as this would have contradicted the recommendations of the EMEP/EEA (2023) for deriving national Tier 2 emission factors for key emission sources. However, we included published non-peer reviewed data (e.g. Chadwick et al., 2005), containing all relevant information and, therefore, considered to be reliable. Data only provided in charts was extracted using *WebPlotDigitizer* (https://automeris.io/WebPlotDigitizer/).

All studies with data on NH_3 losses had to have (i) applied urea (control) and urea with UIs (treatment) at the same time, in the same location and in the same crop, and (ii) investigated crops that are important in German agriculture (Table S 2). Further selection criteria were based on environmental properties that should represent Western Central Europe, and, therefore, Central European crop production conditions. We excluded studies from soils with $\text{pH} > 7.8$ for arable land and $\text{pH} > 7.6$ for grassland. Such soils are not found in Germany, as parent material and climatic conditions do not allow the formation of strongly alkaline soils (Poeplau et al 2020). The pH dynamics after fertilization affect the level of NH_3 volatilization even more than the pH value of the soil before the fertilizer application (Sommer et al., 2004; Whitehead & Raistrick, 1990). However, as such data is usually not available and information on initial soil pH was provided in almost all studies conducting field experiments on NH_3 losses, studies were selected based on the pH value of the soil. In this context, the initial soil pH is the pH level before fertilizer application.

Soils which significantly differ from German soils in their mineral composition were also excluded from the data set. This includes (a) tropical soils with low-activity clays, such as Ferralsols and Nitisols, (ii) paddy soils, disrupted by deep ploughing under waterlogged conditions, thereby, changing soil structure, sorption behavior and water conductivity; (iii) saline soils characterized by a high Na^{+} saturation and a soapy texture, which are predominately found in arid climates (WRB, 2015). Furthermore, we only included studies with application rates ≤ 150 kg N ha^{-1} per fertilization event. This threshold value was chosen in accordance with German fertilizer application ordinance DüV 2017, which is the basis for fertilization according to good practice. This regulation defines yield-dependent maximum N amounts for different crops. The N application rate is adjusted by the farmer and remains an individual management decision. In practice, also due to splitting of N doses, single N application rates rarely exceed 120 kg N/ha per fertilization event for both arable land and grassland (Lütke Entrup & Schäfer, 2011). The effect of application rate on relative NH_3 emissions, expressed as a percentage of applied N, is small compared to other influencing factors such as application technique or environmental conditions (Du Preez and Burger, 1987, Rochette et al. 2013).

We also excluded studies with a mean air temperature of >20 °C over the entire measurement period, following the maximum of the long-term mean air temperature during the growing season in Germany. Even in the last warmest years (2003, 2018) average monthly air temperatures were close to 20 °C in the summer months (DWD, 2025). Urea application is not a common agricultural practice for grasslands in Western Central Europe, due to a predominant use of organic fertilizers, and farmers are advised to use calcium ammonium nitrate under such conditions. Urea is recommended to be used only in colder spring months to avoid NH_3 emissions and preserve fertilizer efficiency. The use of urea in vegetable production, where fertilization is also practiced in summer, is not common due to the use of specialty products (NPKs) and there is very limited data available for such crops.

Studies that did not fulfill the criteria or in which the required information was missing, were not included in the analysis. In addition, only studies in which data on NH_3 losses were available for a single fertilization event were considered. Studies summarizing emissions from multiple applications were excluded from the analysis, as it is not possible to assess environmental effects on NH_3 emissions in the analysis of UIs efficacy using such data.

Few studies reported negative NH_3 losses, indicating uncertainties in the applied measurement technique, or NH_3 influxes from other sources close to the experimental site, which are not related to the fertilizer applied (Chadwick et al., 2005; Drury et al., 2017; Velthof et al., 1990). Although negative fluxes after urea fertilization are not occurring in nature, these values were neither set to zero, nor were they removed from the data set, as long as NH_3 did not stem from an external source. We therefore considered that measurement uncertainties could have occurred in all recorded experiments, leading to both underestimation and overestimation of the calculated abatement factors.

The market for UIs treated fertilizers is growing rapidly with many different products, most of which containing the active ingredient N-(n-butyl)thiophosphoric triamide (NBPT) (Cantarella et al., 2018). In this study, we did not distinguish between different industry products with NBPT formulations, as there is sparse information on specific formulations of UIs coating. Due to a lack of data and chemical similarity of active ingredients to NBPT, other UIs compounds as 2 NPT and NPPT/NBPT mixture (Matse et al., 2024) are analyzed together with NBPT.

Currently, various methods are implemented to measure NH_3 losses in the field, such as static chamber, dynamic chamber, or micrometeorological techniques (Table S1). An international standardized measurement protocol does not exist. Therefore, we did not exclude any study due to its measurement technique. However, individual methods were grouped following Scotto di Perta et al. (2020).

2.2. Statistical evaluation

The data analysis was performed using the software R, version 4.3.1 (R Core Team, 2023). We derived a new Tier 2 abatement factor for the German Emission Inventory by applying a linear mixed effects model, using the *nlme()* package (Pinheiro & Bates, 2023). The NH_3 losses from the treatment with the inhibited urea was, thereby, modelled as a function of the NH_3 losses from the non-inhibited urea. The fixed term in the model describes the population effect over all recorded observations. The main objective was to describe the relation between the NH_3 losses from the inhibited and the non-inhibited urea. The data base was not composed to derive a regional EF for Western Central Europe as it comprised also data from chamber and wind tunnel methods, which are not considered as giving reliable quantitative NH_3 flux readings, but can account for relative differences between treatments (Kamp et al. 2024). Furthermore, we tested different environmental factors that may influence the mitigation effect in the model. This included soil pH, soil cation exchange capacity (CEC), land use (grassland vs arable land) and air temperature. Data on soil CEC was not available in most of the studies and, therefore, the data set was further reduced for this analysis. If an intercept was included in the models, it was very small and slightly negative. The final models were fitted without an intercept because, for inventory reporting purposes, a non-existing (0) activity (here urea fertilization) is per definition not connected to NH_3 emissions and zero NH_3 emissions are assumed to only occur without urea fertilization.

As the data originates from experiments that differ e.g. in terms of site characteristics, weather or measurement methods, and were carried out by different working groups, the assumption of independence for a simple regression analysis is not met (Zuur et al., 2009). This is shown by a lower variance within a group (here described by the author of the study) than between measured values from different authors (Figure S1). Therefore, we included the first author as a random effect in the model, to account for study- and institute specific variance in the data (Eq. 1). Large institutional effects were also observed for NH_3 emissions from organic fertilizers (Hafner et al. 2018).

$$\begin{aligned} urea_{UIi,j} = {} & 0 + \beta_1 \times urea_{ij} + \beta_2 \times urea_{ij} \times temp_{ij} + \beta_3 \times urea_{ij} \\ & \times land_{ij} + \beta_4 \times urea_{ij} \times PH_{ij} + \beta_5 \times urea_{ij} \times CEC_{ij} + u_i \\ & \times urea_{ij} + \varepsilon_i \; with \; \varepsilon_i \quad N\left(0,\ \sigma^2 \times \left(\delta_1 + \left|REF_{ij}\right|^{\delta_2}\right)^2\right) \end{aligned} \tag{1}$$

where $urea_{UIi,j}$ describes the NH_3 loss from the application of the inhibited urea of measurement j and author i, $urea_{ij}$ the NH_3 loss from the non-inhibited urea, β_1 the strength of the relationship between $urea_{UI}$ and urea (*fixed slope*). The interaction between $urea_{ij}$ and air temperature ($temp_{ij}$), land use ($land_{ij}$), soil pH (PH_{ij}), and soil CEC (CEC_{ij}) is described by β_2, β_3, β_4 and β_5, respectively. The author-specific variation in the data (*random slope*) is described by u_i and is assumed to be normally distributed with expected value of zero. ε_i are the model residuals, and heteroscedasticity was accounted for by modelling the variance of the residuals as a function of $REF_{ij.}$ with the square root of the variance parameter $\sigma = 0.47$, $\delta_1 = -21.30$ and $\delta_2 = 0.81$. The model parameters were estimated using the restricted maximum likelihood (REML) method. We used diagnostic plots for assessing normality and homogeneity of the residuals (Zuur et al., 2010). To test the significance of the different environmental factors in the model, likelihood ratio tests were performed (significance level $p < 0.05$). The optimal model was selected using the *Akaike Information Criterion (AIC)*. The model results were used to derive a new Tier 2 abatement factor for UIs treated urea.

3. Results

3.1. Data description

A total of 133 paired observations of NH_3 losses from urea and urea + UIs on arable land and 53 on grassland were extracted from studies published between 1990 and 2020 (Table S1). These studies were selected based on criteria reflecting conditions of German crop production. Therefore, mean temperatures ranged between −4.5 and 20.0°C, soil pH between pH 4.6 and 7.8, and soil CEC between 3.8 and 34.8 cmol kg^{-1}. Overall, 41 % of the observations were from experiments conducted in Germany, 20 % from the USA, 16 % from Great Britain and 13 % from Canada. As no information on the formulation of the different products was available, we did not distinguish between different UIs. However, due to the selection criteria, we included 4 different inhibitors in the statistical analysis (Table S1), which are all authorized in Germany and the EU. One exception was the UI N-(isopropoxycarbonyl)-phosphoric acid triamide (IPAT), which we included in the analysis, but which is not available on the European market.

Across all studies, reported NH_3 losses varied between 0.00 and 58.00 kg N ha^{-1} (mean: 10.97 kg N ha^{-1},16.3 % N applied) for non-inhibited, and −2.00 and 27.00 kg N ha^{-1} (mean: 4.01 kg N ha^{-1}, 5.2 % N applied) for inhibited urea (Table S1). The NH_3 fluxes cannot be considered as quantitatively representative for Western Central Europe due to the inclusion of wind tunnel and chamber measurements. The mitigation effect of the UIs, calculated by dividing the difference between NH_3 losses of the non-inhibited and the inhibited urea treatments by the losses of the non-inhibited urea (Pan et al., 2016), reached values of up to 100 % in some studies, meaning that NH_3 losses were completely avoided by the application of the inhibitor. However, few observations (n = 9) showed higher NH_3 losses when treated with the inhibitor compared to the control. In these cases, NH_3 losses were generally low, regardless of whether urea was treated with a UIs or not, or the measured losses of the control and the treatment were quite similar.

3.2. *Model results and calculation of a EF_{NH3} for urea with urease inhibitor*

Our model result yielded no significant covariates, we found a significant positive linear relationship between the NH_3 losses from urea alone and from inhibited urea (Fig. 1, Table 2). The mixed-effects model had a fixed component, describing the mitigation effect of the UIs over all studies with $\beta_1 = 0.40 \pm 0.03$, corresponding to an emission abatement compared to untreated urea by 60 %, that was significantly different from zero ($p < 0.001$). The standard deviation of the random value u_i describes the variation of the mean effect of UIs on NH_3 volatilization between different studies (Eq. 1) and is 0.24.

Following the revision of the EMEP/EEA Guidebook, the Tier 2 default EF_{NH3} was set to 0.195 kg NH_3 (kg N applied)$^{-1}$ in 2023 (EMEP/EEA, 2023). Using this value, we calculated an EF_{NH3} for urea applied with UIs by a simple linear relationship (Eq. (2)

$$EF_{NH3,ureaUI} = EF_{NH3,urea} \bullet \beta_1 \tag{2}$$

where $EF_{NH3,\ urea}$ is the latest Tier 2 EF_{NH3} for urea provided by EMEP/EEA, (2023) and β_1 is the relation between urea and inhibited urea, deriving from our model results (Eq. 1).

Based on the data, describing German crop conditions, we calculated an EF_{NH3} for urea applied with UIs of 0.078 kg NH_3 (kg N)$^{-1}$. This value is 0.019 kg NH_3 (kg N)$^{-1}$ above the EF_{NH3}, assuming a 70 % reduction in NH_3 losses, as currently provided in Bittman et al. (2014), and used for the emission calculation in countries like Germany.

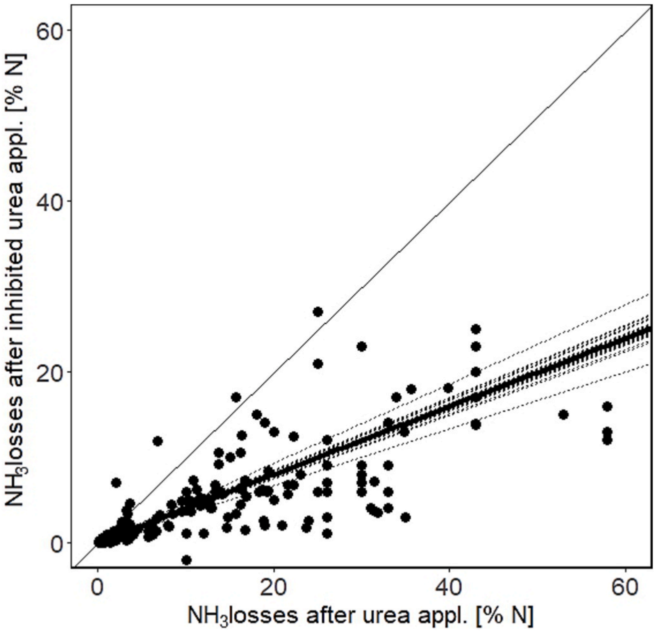

Fig. 1. Relationship between total NH_3 losses (% N of applied fertilizer) from urea and urea + UIs. The bold solid line represents the overall trend in the recorded data (population-level mean effect across all studies), the dotted lines show this relationship for individual authors (author-specific mean effect) and the non-bold solid line represents the 1:1 line.

Table 2
Population effect of abatement factor β_1. The estimated standard deviation between studies (standard deviation of random slope) is 0.24.

	Estimate	Standard error	*t*-value	*p*-value
β_1	0.40	0.03	13.46	$2.39 \cdot 10^{-23}$

4. Discussion

The result of the statistical analysis does not support the assumption that environmental factors, such as soil pH, soil CEC, temperature, or land use, included in the regression model, had a significant effect on the inhibitor performance (Figure S4). This model is most useful for emission inventory purposes, as it does not require knowing the distribution of urea fertilizer application over the agricultural area. Treating urea with UIs reduced NH_3 losses by 60 ± 3 %. This is in line with other literature-based analyses, reporting values between 51.0 % and 63.4 % (Table 1) and confirmed our expectation that the reduction value of 70 %, derived from the guideline of the UNECE Task Force on Reactive Nitrogen (Bittman et al., 2014), likely overestimates the reduction effect of UIs in Central European countries.

There was a tendency of a decrease in the inhibitory effect with increasing temperature (Figure S3). Ammonia losses generally increase with temperature, as the $NH_3/\ NH_4^+$ ratio, as well as the solubility of NH_3 in soil solution decrease, favoring its release into the atmosphere (Black et al., 1985; Denmead et al., 1982). In addition, the activity of the urease enzyme, which is ubiquitous in soils and triggers the release of NH_3 from urea, is enhanced at higher temperatures, causing the $NH_3/\ NH_4^+$ concentration in the soil solution to increase rapidly (Gould et al., 1973). At the same time, the resistance of UIs to degradation decreases with temperature (Carmona et al., 1990). A significant negative correlation between the UIs efficacy and temperature has been observed by Fan et al. (2022). They found a maximum reduction in NH_3 losses of 67 % (61–73 %) at low seasonal mean air temperatures around 10 °C. Compared to other microbial induced N transformation processes in the soil, the urease enzyme remains active even at low temperatures around 0°C (Engel et al., 2011; Ni et al., 2014). The temperature dependence was not significant in the model, probably because of the small database and limited temperature range in the data.

No effect of soil pH on the reduction efficiency of UIs on NH_3 losses was observed for the investigated pH range between 4.6 and 7.8. This is in line with other studies, investigating the effect of soil pH on the efficiency of UIs (Li et al., 2018; Silva et al., 2017). Only alkaline soils with pH of >8 are expected to increase the inhibition duration, as degradation of the compounds is delayed under alkaline conditions (Engel et al., 2015). Studies with soil pHs > 8 were excluded from this statistical analysis, as they are not found on arable land in Germany. However, Fan et al. (2022) found a clear dependency of the inhibitor efficacy on soil pH, even in the range of soil pH, considered in this study. They reported a maximum reduction of NH_3 losses at soil pH around 7.

We did not find any effect of soil CEC on the reduction efficiency of the UIs. This is in line with Silva et al. (2017) and Fan et al. (2022), who investigated the effect of soil organic carbon contents and soil texture on the reduction of NH_3 losses after urea + UIs application. Both soil properties influence soil CEC. In general, the reduction of NH_3 losses with increasing soil CEC is attributed to a higher NH_4^+ sorption capacity (Fenn & Kissel, 1976; Pelster et al., 2018; Sommer et al., 2004). As the efficiency of UIs generally decreases with NH_3 losses from the untreated urea, it is likely that the soil CEC also has an effect (Sunderlage & Cook, 2018). However, the number of studies providing data on soil CEC was rare.

Land use is also known to affect NH_3 losses. In particular, higher NH_3 losses in grasslands are expected to result from higher soil carbon values and urease activity, which promote the hydrolysis of urea and the enzyme activity in the soil, as well as by the dense grass cover, impeding the infiltration of the dissolved fertilizer into the soil (Black et al., 1989;

Chadwick et al., 2005). As confirmed by Fan et al. 2022, increased NH_3 losses on grasslands can elevate the UIs efficiency. However, in accordance with Li et al. (2018), we found no effect of land use on the inhibitory effect.

In summary, no significant effect of influencing factors was observed for Central European conditions. We expect that various factors, the unbalanced data set, and varying measurement methods contributed to this outcome. In addition, for several of these factors a non-linear influence can be expected, in some cases rather an optimum function. Theoretical expectations on the effect of factors on emission processes are, therefore, not refuted by this analysis. The number of observations and studies was probably too low to provide sufficient statistical power for extracting and disentangling such effects, taking into account imbalanced data, missing ancillary data and rather large author-specific (and site-specific) effects.

5. Conclusions

We found an abatement factor of 60 % for the application of stabilized urea, mainly from studies in which NBPT was used as the active component of the inhibitor. Other frequently used active ingredients, such as 2-NPT or NBPT/NPPT, are rather underrepresented in the literature, clearly indicating that a large knowledge gap on their specific quantitative mitigation effects exists. More detailed information on experimental conditions and complete data sets are crucial for estimating the effects of environmental factors, and to derive regional emission factors at the national level for improving the calculation of emissions for national inventories. We therefore call for further studies producing more balanced and comprehensive data sets as well as harmonized measurement protocols, which would enable transfer of theoretical knowledge to data driven emission reporting.

CRediT authorship contribution statement

Julia Schoof: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Roland Fuß:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Sebastian Wulf:** Writing – review & editing, Supervision, Project administration, Methodology. **Andreas Pacholski:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Andreas Pacholski reports financial support was provided by German Development Agency for Agriculture. Julia Schoof reports financial support was provided by German Development Agency for Agriculture. Sebastian Wulf reports financial support was provided by German Development Agency for Agriculture. Roland Fuss reports financial support was provided by German Development Agency for Agriculture. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2025.117285.

Data availability

Data will be made available on request.

References

Bittman, S., Dedina, M., Howard, C.M., Oenema, O., Sutton, M.A. (2014). *Options for Ammonia Mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen.*

Black, A.S., Sherlock, R.R., Smith, N.P., Cameron, K.C., 1989. Ammonia volatilisation from urea broadcast in spring on to autumn-sown wheat. *N. Z. J. Crop Hortic. Sci.* 17 (2), 175–182. https://doi.org/10.1080/01140671.1989.10428028.

Black, A.S., Sherlock, R.R., Smith, N.P., Cameron, K.C., Goh, K.M., 1985. Effects of form of nitrogen, season, and urea application rate on ammonia volatilisation from pastures. *N. Z. J. Agric. Res.* 28 (4), 469–474.

Bremner, J.M., 1995. Recent research on problems in the use of urea as a nitrogen fertilizer. *Fertil. Res.* 42 (1–3), 321–329. https://doi.org/10.1007/bf00750524.

Byrne, M.P., Tobin, J.T., Forrestal, P.J., Danaher, M., Nkwonta, C.G., Richards, K., Cummins, E., Hogan, S.A., O'Callaghan, T.F., 2020. Urease and nitrification inhibitors—As mitigation tools for greenhouse gas emissions in sustainable dairy systems: a review. *Sustainability* 12 (15). https://doi.org/10.3390/su12156018.

Canfield, D.E., Glazer, A.N., Falkowski, P.G., 2010. The evolution and future of earth's nitrogen cycle. *Science* 330 (6001), 192–196. https://doi.org/10.1126/science.1186120.

Cantarella, H., Otto, R., Soares, J.R., Silva, A.G.d.B., 2018. Agronomic efficiency of NBPT as a urease inhibitor: a review. *J. Adv. Res.* 13, 19–27. https://doi.org/10.1016/j.jare.2018.05.008.

Carmona, G., Christianson, C.B., Byrnes, B.H., 1990. Temperature and low concentration effects of the urease inhibitor N-(n-butyl) thiophosphoric triamide (nBTPT) on ammonia volatilization from urea. *Soil Biol. Biochem.* 22 (7), 933–937. https://doi.org/10.1016/0038-0717(90)90132-j.

Chadwick, D., Misselbrook, T., Gilhespy, S., Williams, J., Bhogal, A., Sagoo, L., Nicholson, F., Webb, J., Anthony, S., Chambers, B. (2005). *WP1b Ammonia emissions and crop N use efficiency: Component report for Defra Project NT2605 (CSA 6579)*. http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=11983#Objective.

Denmead, O.T., Freney, J.R., Simpson, J.R., 1982. Dynamics of ammonia volatilization during furrow irrigation of maize. *Soil Sci. Soc. Am. J.* 46 (1), 149–155. https://doi.org/10.2136/sssaj1982.03615995004600010028x.

Drury, C.F., Yang, X., Reynolds, W.D., Calder, W., Oloya, T.O., Woodley, A.L., 2017. Combining urease and nitrification inhibitors with incorporation reduces ammonia and nitrous oxide emissions and increases corn yields. *J. Environ. Qual.* 46 (5), 939–949. https://doi.org/10.2134/jeq2017.03.0106.

Du Preez, C.C., Burger, R.T., 1987. Laboratory measurements of ammonia volatilization from five nitrogen-containing fertilizers after surface application at different rates on a neutral to alkaline soil. *S. Afr. J. Plant Soil* 4 (1), 17–20. https://doi.org/10.1080/02571862.1987.10634229.

DüV (2017). *Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen (Düngeverordnung) DüV vom 26. Mai 2017 (BGBl. I S.1305), zuletzt geändert durch Artikel 1 der Verordnung vom 28. April 2020 (BGBl. I S. 846*.

DWD, 2025. https://dwd.de/DE/leistungen/klimadatendeutschland/vielj_mittelwerte.html, accessed 25.03.2025.

EMEP/EEA (2019). *Air pollutant emission inventory guidebook - 2019* (EEA Report, Issue. https://www.eea.europa.eu/publications/emep-eea-guidebook-2019.

EMEP/EEA (2023). *Air pollutant emission inventory guidebook - 2023* (EEA Report, Issue. https://www.eea.europa.eu//publications/emep-eea-guidebook-2023.

Engel, R., Jones, C., Wallander, R., 2011. Ammonia volatilization from urea and mitigation by NBPT following surface application to cold soils. *Soil Sci. Soc. Am. J.* 75 (6), 2348–2357. https://doi.org/10.2136/sssaj2011.0229.

Engel, R.E., Towey, B.D., Gravens, E., 2015. Degradation of the urease inhibitor NBPT as affected by soil pH. *Soil Sci. Soc. Am. J.* 79 (6), 1674–1683. https://doi.org/10.2136/sssaj2015.05.0169.

Fan, D., He, W., Smith, W.N., Drury, C.F., Jiang, R., Grant, B.B., Shi, Y., Song, D., Chen, Y., Wang, X., He, P., Zou, G., 2022. Global evaluation of inhibitor impacts on ammonia and nitrous oxide emissions from agricultural soils: a meta-analysis. *Glob. Chang. Biol.* 28 (17), 5121–5141. https://doi.org/10.1111/gcb.16294.

Fenn, L.B., Kissel, D.E., 1976. The influence of cation exchange capacity and depth of incorporation on ammonia volatilization from ammonium compounds applied to calcareous soils. *Soil Sci. Soc. Am. J.* 40 (3), 394–398. https://doi.org/10.2136/sssaj1976.03615995004000030026x.

Fertilizers Europe (2022): Fertilizer Industry Facts & Figures 2022 https://www.fertilizerseurope.com/wp-content/uploads/2022/09/Industry-Facts-and-Figures-2022.pdf (accessed 13 June 2024).

Gould, W.D., Cook, F.D., Webster, G.R., 1973. Factors affecting urea hydrolysis in several alberta soils. *Plant Soil* 38 (2), 393–401. https://doi.org/10.1007/bf00779021.

Hafner, S.D., Pacholski, A.S., Bittman, S., Burchill, W., Bussink, W., Chantigny, M., et al., 2018. The ALFAM2 database on ammonia emission from field-applied manure: description and illustrative analysis. *Agric. For. Meteorol.* 258, 66–79. https://doi.org/10.1016/j.agrformet.2017.11.027.

Hu, Y., Flessa, H., Vos, C., Fuss, R., Schmidhalter, U., 2024. Successful NH3 abatement policies and regulations in German agriculture. Sci. Total Environ. 956, 177362. https://doi.org/10.1016/j.scitotenv.2024.177362.

Kamp, J.N., Hafner, S.D., Huijsmans, J., van Boheemen, K., Goetze, H., Pacholski, A.S., Pedersen, J., 2024. Comparison of two micrometeorological and three enclosure methods for measuring ammonia emission after slurry application in two field experiments. Agric. For. Meteorol. 354, 110077. https://doi.org/10.1016/j.agrformet.2024.110077.

Li, T., Zhang, W., Yin, J., Chadwick, D., Norse, D., Lu, Y., Liu, X., Chen, X., Zhang, F., Powlson, D., Dou, Z., 2018. Enhanced-efficiency fertilizers are not a panacea for resolving the nitrogen problem. *Glob. Chang. Biol.* 24 (2), e511–e521. https://doi.org/10.1111/gcb.13918.

Lütke Entrup, N., Schäfer, B.C. (2011). Lehrbuch des Pflanzenbaues - Band 2: Kulturpflanzen (Vol. 3). AgroConcept.

Matse, Dumsane Themba; Krol, Dominika J.; Richards, Karl G.; Danaher, Martin; Cummins, Enda; Wang, Xin; Forrestal, Patrick J. (2024): Field efficacy of urease inhibitors for mitigation of ammonia emissions in agricultural field settings: a systematic review. In: Front. Environ. Sci. 12, Artikel 1462098, S. 719. DOI: 10.3389/fenvs.2024.1462098.

Ni, K., Pacholski, A., Kage, H., 2014. Ammonia volatilization after application of urea to winter wheat over 3 years affected by novel urease and nitrification inhibitors. *Agric. Ecosyst. Environ.* 197, 184–194. https://doi.org/10.1016/j.agee.2014.08.007.

Ohnemus, T., Spott, O., Thiel, E., 2021. Spatial distribution of urea induced ammonia loss potentials of German cropland soils. *Geoderma* 394. https://doi.org/10.1016/j.geoderma.2021.115025.

Pan, B., Lam, S.K., Mosier, A., Luo, Y., Chen, D., 2016. Ammonia volatilization from synthetic fertilizers and its mitigation strategies: a global synthesis. *Agric. Ecosyst. Environ.* 232, 283–289. https://doi.org/10.1016/j.agee.2016.08.019.

Pelster, D.E., Chantigny, M.H., Angers, D.A., Bertrand, N., MacDonald, J.D., Rochette, P., 2018. Can soil clay content predict ammonia volatilization losses from subsurface-banded urea in eastern Canadian soils? *Can. J. Soil Sci.* 98 (3), 556–565. https://doi.org/10.1139/cjss-2018-0036.

Pinheiro, J., Bates, D. (2023). *nlme: Linear and Nonlinear Mixed Effects Models*. In (Version 3.1-162) [R package]. R Core Team. https://CRAN.R-project.org/package=nlme.

Poeplau, C., Don, A., Flessa, H., Heidkamp, A., Jacobs, A., Prietz, R., 2020. Erste Bodenzustandserhebung Landwirtschaft – Kerndatensatz. doi: 10.3220/DATA20200203151139.

Pozzer, A., Tsimpidi, A.P., Karydis, V.A., de Meij, A., Lelieveld, J., 2017. Impact of agricultural emission reductions on fine-particulate matter and public health. *Atmos. Chem. Phys.* 17 (20), 12813–12826. https://doi.org/10.5194/acp-17-12813-2017.

R Core Team (2023). *R: A Language and Environment for Statistical Computing.* In R Foundation for Statistical Computing. https://www.R-project.org/.

Rochette, P., Angers, D.A., Chantigny, M.H., Gasser, M.-O., MacDonald, J.D., Pelster, D. E., Bertrand, N., 2013. NH3 volatilization, soil concentration and soil pH following subsurface banding of urea at increasing rates. *Can. J. Soil Sci.* 93 (2), 261–268. https://doi.org/10.4141/CJSS2012-095.

Scotto di Perta, E., Fiorentino, N., Carozzi, M., Cervelli, E., Pindozzi, S., 2020. A review of chamber and micrometeorological methods to quantify NH3 emissions from fertilisers field application. *Int. J. Agron.* 2020, 1–16. https://doi.org/10.1155/2020/8909784.

Silva, A.G.B., Sequeira, C.H., Sermarini, R.A., Otto, R., 2017. Urease inhibitor NBPT on ammonia volatilization and crop productivity: a meta-analysis. *Agron. J.* 109 (1), 1–13. https://doi.org/10.2134/agronj2016.04.0200.

Skorupka, M., Nosalewicz, A., 2021. Ammonia volatilization from fertilizer urea—A new challenge for agriculture and industry in view of growing global demand for food and energy crops. *Agriculture* 11 (9), 822. https://doi.org/10.3390/agriculture11090822.

Sommer, S.G., Schjoerring, J.K., Denmead, O.T. (2004). Ammonia Emission from Mineral Fertilizers and Fertilized Crops. In (pp. 557-622). doi: 10.1016/s0065-2113(03)82008-4.

Sunderlage, B., Cook, R.L., 2018. Soil property and fertilizer additive effects on ammonia volatilization from urea. *Soil Sci. Soc. Am. J.* 82 (1), 253–259. https://doi.org/10.2136/sssaj2017.05.0151.

Ti, C., Xia, L., Chang, S.X., Yan, X., 2019. Potential for mitigating global agricultural ammonia emission: a meta-analysis. *Environ. Pollut.* 245, 141–148. https://doi.org/10.1016/j.envpol.2018.10.124.

UBA (2023). *German Informative Inventory Report 2023 (IIR)*. German Environment Agency (UBA). https://iir.umweltbundesamt.de/2024/general/key_categories/start (accessed 10 May 2024).

Velthof, G.L., Oenema, O., Postmus, J., Prins, W.H., 1990. In situ field measurements of ammonia volatilization from urea and calcium ammonium nitrate applied to grassland. Meststoffen (1/2), 41–45.

Vos, C., Rösemann, C., Haenel, H.-D., Dämmgen, U., Döring, U., Wulf, S., Eurich-Menden, B., Freibauer, A., Döhler, H., Steuer, B., Osterburg, B., Fuß, R. (2022). *Calculations of gaseous and particulate emissions from German agriculture 1990 – 2020. Report on methods and data (RMD) Submission 2022* (Thuenen Report, Issue.

Whitehead, D.C., Raistrick, N., 1990. Ammonia volatilization from five nitrogen compounds used as fertilizers following surface application to soils. *J. Soil Sci.* 41 (3), 387–394.

WRB (2015). World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps (Vol. 106). FAO.

Zuur, A.F., Ieno, E.N., Elphick, C.S., 2010. A protocol for data exploration to avoid common statistical problems. *Methods Ecol. Evol.* 1 (1), 3–14. https://doi.org/10.1111/j.2041-210X.2009.00001.x.

Zuur, A.F., Ieno, E.N., Walker, N., Saveliev, A.A., Smith, G.M., 2009. *Mixed Effects Models and Extensions in Ecology With R.* Springer.