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A field-based comparison of ammonia emissions from six Irish soil types following urea fertiliser application

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Abstract

Ammonia (NH_3) emissions from a range of soil types have been found to differ under laboratory conditions. However, there is lack of studies comparing NH_3 emissions from different soil types under field conditions. The objective was to compare NH_3 emissions from six different soil types under similar environmental conditions in the field following urea fertiliser application. The study was conducted on a lysimeter unit and NH_3 emissions were measured, using wind tunnels, from six different soil types with varying soil characteristics following urea fertiliser application (80 kg N/ha). On average, 17.6% (% total N applied) was volatilised, and there was no significant difference in NH_3 emissions across all soil types. Soil variables, including pH, cation exchange capacity and volumetric moisture, were not able to account for the variation in emissions. Further field studies are required to improve the urea-NH_3 emission factor used for Ireland's NH_3 inventory.

Keywords

ammonia volatilisation • fertiliser • grassland • soil type • urea

Introduction

Fertiliser N applications are subject to ammonia (NH_3) volatilisation losses, particularly upon urea application, which may reduce N use efficiency and represent a substantial economic loss of N from agriculture. NH_3 volatilisation also contributes to indirect nitrous oxide emissions (Martikainen, 1985) and is related to the deterioration of regional air quality, as well as eutrophication and acidification of natural ecosystems (Asman, 1998). As a result, a number of European countries have been set annual emissions ceilings for NH_3 under the National Emission Ceilings Directive (European Commission, 2001). Meeting these ceiling obligations presents a challenge for Irish agriculture, which accounts for 98% of national NH_3 emissions.

NH_3 emissions from urea fertiliser on grassland in Ireland and the UK have been found to be quite variable, ranging from 8 to 68% of applied N (Chambers and Dampney, 2009; Forrestal *et al*., 2015) and may be due to differences in temperature, precipitation and wind speed following urea application (Black *et al*., 1987; Hatch *et al*., 1990; Sommer *et al*., 1991, 2003; Sanz-Cobena *et al*., 2011). Another important factor that may contribute to this range in emissions is the variation of soil types, with different physical and chemical characteristics (Stevens *et al*., 1989; Watson *et al*., 1994; He *et al*., 1999). Direct comparisons of NH_3 emissions from different soil types are limited to laboratory-based studies (McGarry *et al*., 1987; Watson *et al*., 1994), while the majority of field-based studies on NH_3 emissions from N fertilisers have been conducted on only one or two sites (Chambers and Dampney, 2009; Forrestal *et al*., 2015). NH_3 emission factors (EFs) used for fertiliser N in national NH_3 inventories are based on field studies and do not take soil type into account. Thus, there is a need for field-based comparisons of NH_3 emissions from different soil types. The objective of this study was to compare NH_3 emissions from six different soil types under similar environmental conditions in the field following urea fertiliser application.

Materials and methods

Experimental site

This experiment was conducted on a lysimeter unit at Teagasc, Johnstown Castle Research Centre, County Wexford, Ireland (52°180′N, 6°300′W; 62 m above sea level). The 30-yr mean annual precipitation and air temperature at the site are 1,037.5 mm and 10.4 °C, respectively. The establishment of the lysimeter unit is described in full by Ryan and Fanning (1996). The lysimeter unit consisted of replicated (n = 9) undisturbed

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monoliths of soils (diameter: 0.6 m; depth: 1 m) encased in rigid fibreglass cylinders, which were collected from six grassland sites across the Republic of Ireland in 1990. The soils were chosen to encompass a range of typical soil types, drainage characteristics and soil parent material (Table 1). Each lysimeter has a perennial ryegrass (*Lolium perenne* L.) sward, which was reseeded in April 2015. In the year before the commencement of this experiment, the lysimeters were fertilised with a total of 160 kg N/ha in four equal applications, the last being in June 2015. Herbage was cut to a height of 4–5 cm using a pair of hand shears and removed at least 1 wk before the commencement of the experiment.

Experimental design

The experiment was based on a completely randomised design with six soil types (treatments) and three replicates per soil type. The six soil types were named after the locations from which they were collected in Ireland and represent a range of drainage classes from light to heavy as follows: Oak Park, Clonroche, Elton, Rathangan, Castlecomer and Johnstown. The characteristics of each soil are presented in Table 1. The lysimeter soils had similar parent material and, to some extent, similar World Reference Base (WRB) classifications (WRB, 2014), but contrasting texture, structure and drainage properties (Table 1) (Kramers *et al*., 2012).

Weather and soil conditions

Meteorological parameters including air temperature (in degrees Celsius), rainfall (in millimetres) and wind speed (in metres per second) were recorded on an hourly basis at the nearest automatic weather station “Johnstown Castle” by the Irish Meteorological Service (Met Éireann) (approximately 500 m distant from the study site). Additionally, volumetric soil moisture at 0–5 cm depth was determined daily during the experiment using a handheld soil moisture probe (Delta-T Devices, Cambridge, UK).

Application of urea fertiliser and simulated rainfall event

On 7 September 2015, 6.71 L of water (the equivalent of 25.4 mm of rainfall) was applied to each of the 18 lysimeters using a watering can with a rosette attachment to accentuate the drainage capacity of each soil type, which would be manifested in terms of soil surface moisture at the time of urea application. This simulated rainfall event also ensured that soil moisture was sufficient to promote urea hydrolysis after urea application, given the fact that rainfall had to be excluded from the lysimeters for the duration of the study due to the configuration of the NH_3 measurement equipment on the lysimeter units. Urea fertiliser was subsequently applied to each lysimeter by hand at a rate of 80 kg N/ha.

NH_3 emission measurements

A system of 18 wind tunnels (Lockyer, 1984) was used to measure NH_3 volatilisation. Each wind tunnel unit consisted of (i) a canopy (0.5 m × 2 m) made of polycarbonate, (ii) a galvanised sheet steel duct and (iii) a control box. The wind tunnel canopy was placed over each lysimeter immediately after urea application and it stayed in place until the end of the experiment. Wind speed through the wind tunnels was set at 1 m/s (air flow rate of 0.229 m^3/s), which was chosen to mimic atmospheric wind speed above the soil surface. Air entering and leaving the wind tunnel canopy was sampled and pumped

Table 1. Soil classification and properties of the six soils used in this experiment

Site	Soil type[1]	Parent material	Texture	Field capacity[2] (%)	CEC[3] (meq/100 g)	pH[4]	Sand[5] %	Silt %	Clay %
Oakpark	Haplic Cambisol	Fluvioglacial gravels	Sandy loam	19.5	46.0 ± 9.3	6.56 ± 0.1	67	23	11
Castlecomer (Gortaclareen)	Albic Gleyic Lixsol (Humic)	Fine loamy drift with siliceous stones	Fine loam	31.6	55.7 ± 7.2	6.34 ± 0.1	24	48	28
Clonroche	Haplic Cambisol	Glacial drift	Loam	24.8	48.8 ± 11.3	6.64 ± 0.1	44	39	17
Elton	Cutanic Luvisol	Glacial drift	Loam	24.1	66.5 ± 3.4	6.27 ± 0.0	48	35	17
Rathangan (Kilrush)	Luvic Stagnosol	Glacial sea drift	Loam	25.3	51.6 ± 6.7	6.10 ± 0.1	44	37	19
Johnstown	Luvic Gleysol	Coarse loamy drift with siliceous stones	Loam	21.3	25.8 ± 0.0	6.46 ± 0.0	58	30	12

[1]WRB (2014).
[2]Field capacity for each soil was estimated using sand and clay contents according to the methodology of Saxton *et al*. (1986).
[3]Mean ± s.d. (n = 3) soil type cation exchange capacity at 0–20 cm depth.
[4]Mean ± s.d. (n = 3) soil type pH at 0–10 cm depth. The range in pH across the 18 individual lysimeters was 5.8–7.
[5]Sand: 2000–63 mm; silt: 63–2 mm; clay: <2 mm.

through two individual conical absorption flasks (i.e. acid traps), which contained 100 mL of 0.02 M orthophosphoric acid (H_3PO_4, 85%; Merck, Darmstadt, Germany). Emissions were measured continuously for a period of 14 d after application. The acid traps were replaced every approximate 24 h until the 11th day after application, and final samples were collected after 72 h (Day 14) on the final day of the experiment. The acid trap samples were analysed for their ammonium-N content, and the NH_3-N loss (in kilograms per hectare) was calculated as described by Fischer *et al*. (2016).

Data analysis

All data were statistically analysed using SAS 9.3 (2011; SAS Institute Inc., Cary, NC, USA). Data were checked for normality by assessing residual normality and variance. The effects of soil type and measurement date, as well as their interaction, on daily NH_3 emissions and volumetric soil moisture were analysed using analysis of variance (ANOVA), with measurement date included as a repeated measure in the model. The treatment effect on cumulative NH_3 loss was analysed using ANOVA. Post-hoc least significant difference (LSD) multiple-comparison tests were carried out to determine differences between treatment means. Pearson's correlation and multiple linear regression analyses were conducted using individual lysimeter data (n = 18) to test for relationships between NH_3 emissions and soil variables. A statistical probability of $P < 0.05$ was considered significant for all statistical tests.

Results

Weather and soil conditions

The mean daily air temperature ranged from 11 to 15 °C (mean: 12.9 °C), mean daily wind speed was 3.68 m/s and the cumulative precipitation was 58.8 mm during the experiment. There was a significant ($P < 0.01$) interaction between soil type and measurement date on soil moisture during the study (Figure 1). All soil types had similar volumetric soil moisture on the date of urea application, with the exception of Oakpark, which had lower moisture. Soil moisture declined from the start to the end of the experiment for all soil types; however, the decline in soil moisture on the Johnstown soil type was more variable and lower than that of all other soil types (Figure 1).

NH_3 emissions

Daily NH_3 emissions ranged from 0 to 5.58 kg N/ha and there was no significant difference in daily emissions across soil types (Figure 2). However, daily NH_3 emissions varied significantly across measurement dates ($P < 0.001$), with

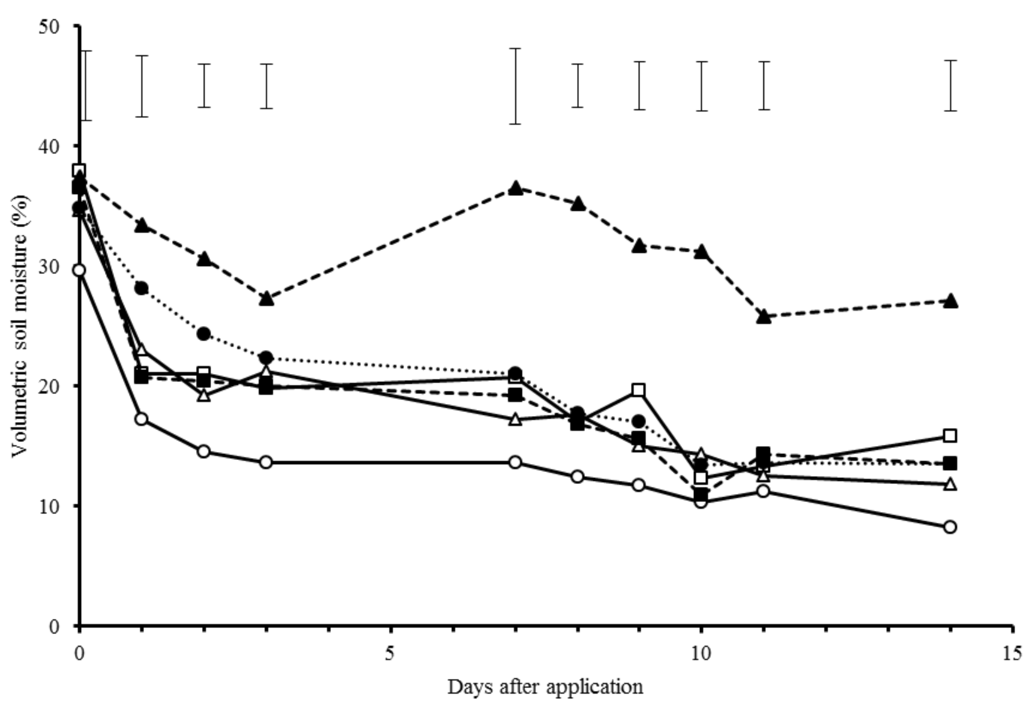

Figure 1. Temporal trend in soil volumetric moisture content for each soil type (○, Oakpark; □ Castlecomer; △, Clonroche; ●, Elton; ■, Rathangan; and ▲, Johnstown) during the experimental period. Error bar represents the standard error of the mean (n = 3).

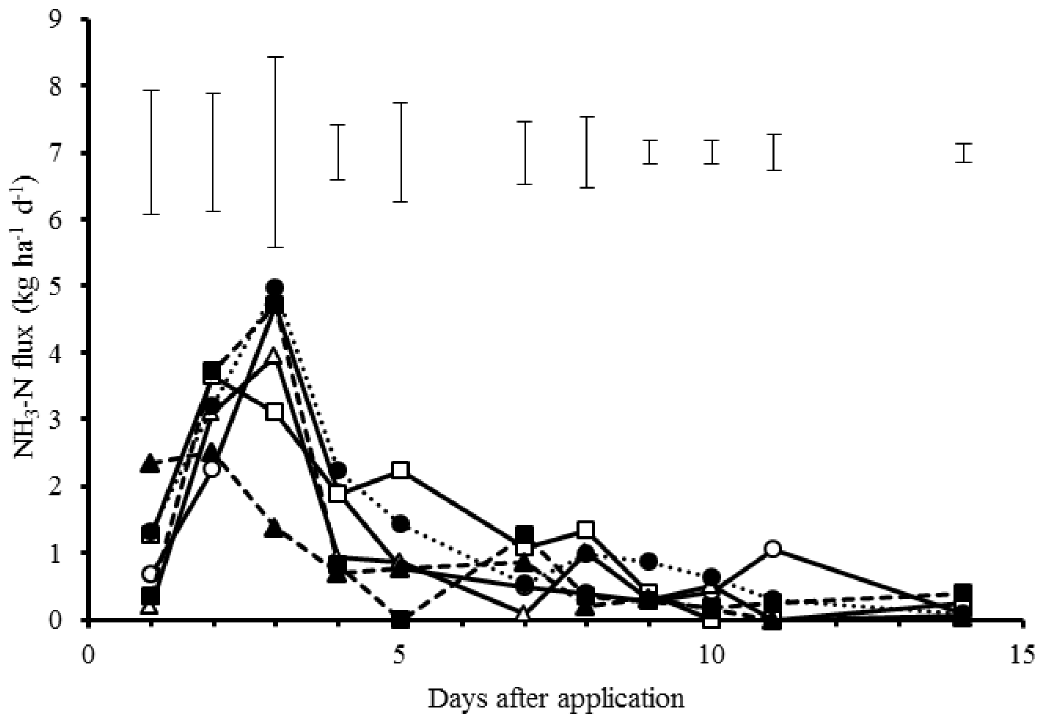

Figure 2. Temporal trend in daily NH_3-N emissions (kilograms per hectare) from each soil type (○, Oakpark; □ Castlecomer; △, Clonroche; ●, Elton; ■, Rathangan; and ▲, Johnstown) during the experimental period. Error bar represents the standard error of the mean (n = 3).

emissions peaking within 3 d after fertiliser application on each soil type and then declining slowly until the end of the measurement period (Figure 2). The majority (>85%) of the cumulative emissions during the experiment occurred for each soil type within 1 wk (7 d) of fertiliser application.

There was no significant difference between soil types in terms of cumulative emissions (kg NH_3-N/ha) or the percentage of N applied lost as NH_3-N at the end of the experiment (Table 2). NH_3 EFs (percentage of N applied) for the six soil types ranged from 12.8% to 21.5% and averaged (mean ± s.d.) 17.6 ± 6.2 across soil types. There were no significant relationships between NH_3-N emissions (percentage of N applied) and soil variables such as pH, cation exchange capacity (CEC) and volumetric soil moisture content following Pearson's correlation and multiple linear regression analyses.

Table 2. Cumulative ammonia emission (mean ± s.d.) and the percentage of applied nitrogen lost as ammonia during the experimental period **(n = 3)**

	NH_3-N emissions	
	(kg/ha)	**(% N applied)** [1]
Oakpark	14 ± 4.6	17.0[a]
Castlecomer	17 ± 3.0	20.9[a]
Clonroche	11 ± 4.8	13.9[a]
Elton	17 ± 6.4	21.5[a]
Rathangan	13 ± 4.4	17.8[a]
Johnstown	10 ± 8.9	12.8[a]

[1]Values in the same column followed by a different letter are significantly different at $P < 0.05$.

Discussion

Temporal and cumulative NH_3 emissions

The daily temporal NH_3 emissions from each soil type followed a similar trend as in previous field studies, wherein emissions peaked on Day 2 or Day 3 following urea application and declined thereafter (Chambers and Dampney, 2009; Forrestal *et al*., 2015). Watson *et al*. (1994) also found peak NH_3 emissions to occur on Day 3 (range 1.8–4.5 d), on average, following urea application to 16 different soils in a laboratory study. The NH_3 emissions in this study are on the lower side of the reported urea-NH_3 emissions in studies using wind tunnels on grassland (Table 3). These previous studies were conducted on field plots and generally over a larger number of applications, including summer applications, which would be subject to higher temperatures and solar radiation, which are conducive to higher volatilisation losses (Huijsmans *et al*., 2001).

Soil type and NH_3 emissions

Watson *et al*. (1994) compared NH_3 volatilisation from 16 different grassland soils with various chemical and physical properties under controlled laboratory conditions following the application of 100 kg N/ha as urea. There were significant differences between the different soils, which ranged from 5.8% to 38.9% of the N applied. Multiple regression analysis revealed that the soil properties pH (by KCl extraction) (range: 4.9–7.4) and titratable acidity explained up to 95% of the variation in NH_3 emissions across the 16 soils. Chambers and Dampney (2009) found NH_3 emissions to range from 10% to 58% of N applied as urea at six different sites with varying soil types. However, these measurements were not conducted in parallel and were therefore subject to varying weather conditions following urea application. There was no significant difference in NH_3 emissions between the different soil types in the current field-based study. This could be due to the relatively high spatial variability and low sample size associated with field-based measurements of such emissions. Van der Weerden and Jarvis (1997), in a field plot study investigating emissions from urea, reported similar NH_3 emissions for sandy clay loam (pH: 6) and clay loam (pH: 5.6) soils in the UK (Table 3).

He *et al*. (1999), in a controlled laboratory study, found NH_3 emissions to increase by 150% as the soil pH increased from 4.5 to 5.5 and by 10% from 5.5 to 6.5. Further increasing the soil pH to 7.5 and 8.5 had no significant effect on NH_3 emissions compared to a soil pH of 6.5. The range of soil pH across the soil types in this study was lower than that in the studies mentioned herein and was most likely too small to influence NH_3 emissions from the applied urea under field conditions. Chambers and Dampney (2009) also found no relationship between NH_3 emissions and soil pH, CEC, clay content or organic carbon content.

Implications for national inventories

This study and other recent field-based studies suggest that urea-NH_3 EFs do not differ between different soil types in cases where the soils are actively managed for soil pH through soil fertility planning. This finding may have implications for the calculation of urea-based NH_3 emissions in national inventories in terms of the disaggregation of the urea-NH_3 EF based on soil type. Further field-based studies are required across a larger range of soil types and seasonal weather conditions to improve the quantitative accuracy of the urea-NH_3 EF used for the Irish national inventory.

Conclusions

NH_3 emissions (% of N applied) did not differ significantly between the six soil types in this study and ranged from 5 to 29. The relatively small range observed in measured soil variables; pH, CEC and volumetric moisture were not able

Table 3. Summary of literature reporting ammonia emissions following urea application to grassland

Soil type	n[1]	Country	Method	N application rate (kg/ha)	NH_3-N emission (% of N applied)	Reference
Sandy clay loam	1	UK	Wind tunnels	90–120	30	Van der Weerden and Jarvis, 1997
Clay loam	1	UK	Wind tunnels	90–120	28	Van der Weerden and Jarvis, 1997
Loam	2	Ireland	Wind tunnels	80	36	Forrestal *et al*., 2015
Silty clay loam	4	UK	Wind tunnels	100	31	Chambers and Dampney, 2009
Course sandy loam	1	UK	Wind tunnels	100	43	Chambers and Dampney, 2009
Sandy loam	1	UK	Wind tunnels	100	12	Chambers and Dampney, 2009
Sandy loam	1	Denmark	Wind tunnels	80-120	25	Sommer and Jensen, 1994
N.a.	1	Canada	bLs[2]	80	29	Sommer *et al*., 2005
N.a.	1	Chile	IHF[3]	100	12	Salazar *et al*., 2012
Loam	1	UK	Wind tunnels	200	15	Ryden and Lockyer, 1985
N.a.	1	UK	Wind tunnels	70–100	20	Ryden *et al*., 1987
Silty loam	1	Australia	Micro-met	40	30	Suter *et al*., 2013
Clay	1	Netherlands	Wind tunnels	80–120	23	Velthof *et al*., 1990

[1]Number of sites per soil type included in the study.
[2]Backward Lagrangian stochastic dispersion technique.
[3]Integrated horizontal flux technique.
[N.a]Not available

to explain any of the variation in measured NH_3 emissions. The results of this study represent only the second study of NH_3 emissions from urea fertiliser on Irish grasslands. Further field studies are required to improve the accuracy of urea-NH_3 EF used for Irelands national inventory.

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