The effect of solid manure incorporation on nitrous oxide emissions

Thorman, R.E.[1], Webb, J.[2~], Yamulki, S.[3#], Chadwick, D.R.[3], Bennett, G.[4], McMillan, S.[5]*
Kingston, H.[1], Donovan, N.[3] and Misselbrook, T.H.[3]
[1]ADAS Boxworth, Battlegate Road, Boxworth, Cambridge, CB23 4NN, UK
[2]ADAS Wolverhampton, Wergs Road, Wolverhampton, WV6 8TQ, UK
[3]North Wyke Research, Okehampton, Devon, EX20 2SB, UK
[4]ADAS Gleadthorpe, Meden Vale, Mansfield, Nottingham., NG20 9PF, UK
[5]ADAS Drayton, Alcester Road, Stratford upon Avon, Warwickshire, CV37 9RQ, UK
~Now at, AEA Energy & Environment, Didcot, OX11 0QR, UK
#Now at, Forest Research, Alice Holt Lodge, Farnham, Surrey, GU10 4LH, UK
**Corresponding author: rachel.thorman@adas.co.uk*

Introduction

Around 46 million tonnes of solid manure are applied annually to agricultural land in the UK (Williams *et al*., 2000). These applications are a valuable source of plant available nutrients, however, they also pose a significant diffuse pollution risk. The deposition of emitted ammonia (NH_3) can lead to soil acidification and nitrogen (N) enrichment of sensitive habitats (Fangmeier *et al*., 1994). Agriculture is the principal source of atmospheric NH_3 in the UK, accounting for 265 kt NH_3 per year or *c*.80% of total emissions (Misselbrook *et al*., 2000). The land spreading of livestock manures is estimated to be responsible for approximately one third of the total UK NH_3 emissions from agriculture, of which *c*.50% is estimated to come from solid manures (Defra, 2000).

Following the application of solid manures to arable land and prior to grass re-seeds, rapid incorporation of manure into the soil has been identified as a practical and cost-effective abatement option to reduce NH_3 emissions (Webb *et al*., 2005; Webb *et al*., 2006a). The reduced NH_3 loss, however, conserves N and thereby increases the pool of soil mineral N. This N may subsequently be available for microbial nitrification and denitrification, and the production of nitrous oxide (N_2O). Webb *et al*. (2004), however, suggest that if solid manure is buried through ploughing, the increased length of the diffusion pathway through the soil matrix may lead to a reduction in background levels of N_2O emissions and that this effect may continue for at least 30 days i.e. incorporation can appear to be a 'win-win' technique for reducing NH_3 and N_2O emissions from solid manure in the short term.

Nitrous oxide is a powerful greenhouse gas (GHG) due to its global warming potential (GWP). In the current UK GHG inventory (2005), the GWP of N_2O is 310 times that of carbon dioxide (Baggott *et al*., 2007). The inventory estimates that 67% of N_2O is produced from agriculture, of which *c*.62% is *directly* emitted from agricultural soils e.g. following the application of livestock manure, mineral nitrogen fertiliser etc. (Baggott *et al*., 2007). As part of the Kyoto protocol, the UK has agreed to a legally binding reduction in GHG emissions of 12.5% from 1990 levels by the period 2008-12. In order to comply with existing and forthcoming Directives (e.g. National Emissions Ceilings Directive etc.), the UK government is also committed to reducing NH_3 losses to the environment. Measures implemented to mitigate N losses via NH_3 volatilisation, such as the rapid incorporation of manure, may however, have implications on N_2O emissions. This paper presents data from a study to quantify the effect on direct N_2O emissions of the NH_3 abatement technique of incorporating solid manures into the soil by plough, disc or tined cultivation.

Materials and Methods

Six experiments were carried out at four UK sites: at site 1 (experiment 1) on a loamy sand soil, at ADAS Gleadthorpe, central England; at site 2 (experiment 2) on a heavy, clay soil, at ADAS Drayton, central England; at site 3 (experiments 3 & 4) on a sandy loam soil, at

IGER North Wyke, south west England and at site 4 (experiments 5 & 6) on a clay loam soil, at IGER North Wyke. Nitrous oxide emissions were measured from replicated (x4) plots (6x10 m) following solid manure applications in either spring (February/March) or early autumn (August/September). The plots were established on cereal stubble or on bare arable ground. Cattle farmyard manure (FYM), pig FYM, layer manure or broiler litter were spread at a target application rate of 250 kg N ha^{-1} and either left on the soil surface or immediately incorporated into the soil by ploughing (to *c*.20-25 cm depth), discing (to *c*.10-15 cm depth) or tine (to *c*.10 cm depth) cultivation. Control treatments were included where no manure was added and no incorporation took place.

Direct measurements of N_2O were made from two static flux chambers (40 cm wide x 40 cm long x 25 cm high), that were placed in random positions on each plot (covering a total surface area of 0.32 m^2) after the incorporation treatment had been completed. Chambers were pushed into the soil up to a depth of 5 cm to ensure an airtight seal and headspace samples analysed as soon as possible after collection (to minimise potential leakage) by gas chromatography. The N_2O flux was calculated based on the linear increase in N_2O concentration inside the chamber over a 40-minute enclosure period. Nitrous oxide emission measurements were carried out immediately following manure application and at regular intervals over a *c*.60 day period. Experiments 2, 4, 5 & 6 were continued to achieve a 365d measurement period. Cumulative fluxes of N_2O following land spreading were calculated using the *trapezoidal rule*. Nitrous oxide emission factors (EFs) were calculated by subtracting the fluxes from the control plots and expressed as the percentage of total-N applied in the manure. ANOVA was conducted to determine experiment and treatment differences.

Results and Discussion

Effect of incorporation

Results from these sites showed that incorporation reduced NH_3 emissions ($P<0.001$), with plough, disc and tine reducing emissions by 88%, 62% and 56%, respectively compared to losses from manure which remained on the soil surface (Webb *et al*., 2006b). As indicated previously, the reduced NH_3 loss would conserve N thus increasing soil N potentially available to N_2O producing micro-organisms. Furthermore, following ploughing, the complete burial of manure and the reduced oxygen concentration from its decomposition was likely to have resulted in the formation of anaerobic micro-sites within the soil matrix suitable for denitrification and subsequent generation of N_2O. The relative effect of incorporation on N_2O emissions was, however, different between experiments ($P<0.001$), primarily due to the difference in the relative effect of ploughing compared to the other incorporation treatments (Table 1). In experiment 1 there was a significant increase in N_2O emission from ploughing, whilst in experiments 4 & 5 there was a significant decrease. This discrepancy in the effect of ploughing on N_2O loss between sites is probably related to differences in soil conditions.

Table 1. The effect of incorporation on the mean cumulative N_2O-N loss expressed as a % of the total manure N applied per experiment

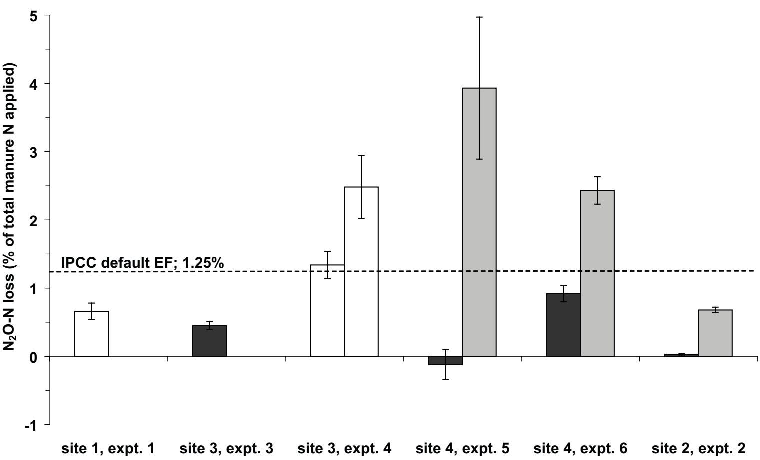
Experiment	Surface	Plough	Disc	Tine
1	0.36	1.39	0.44	0.45
2	0.04	0.01	0.03	0.03
3	0.33	0.46	0.52	0.51
4	1.44	0.54	1.75	1.62
5	0.07	-1.00	0.23	0.23
6	1.07	0.79	0.96	0.87

In experiments 2, 4, 5 & 6 where, to varying degrees, denitrification was likely to be the most dominant source of N_2O emission, ploughing appeared to reduce N_2O emissions. Following ploughing, the N_2O diffusion pathway from the site of production to the soil surface would generally have been longer compared with incorporation by disc/tine or where the manure was left on the soil surface i.e. no incorporation. Unlike the highly porous loamy sand at site 1, experiment 1, the increase in length of the diffusion pathway combined with a heavier textured soil and/or a high soil moisture content had the potential to reduce the N_2O diffusion rate through the soil matrix, providing a greater opportunity for N_2O reduction to N_2 and hence less emission of N_2O at the surface. In contrast, where denitrification was unlikely to be intense as at site 1, experiment 1, ploughing appeared to result in the greatest N_2O loss and at site 3, experiment 3, all 3 incorporation techniques appeared to increase losses compared with the surface treatment, respectively. Evidence from the literature also indicates an uncertain effect of ploughing/simulated incorporation of solid/liquid manures such that, depending on site conditions, the impact on N_2O may be neutral, or result in enhanced or reduced emissions (Velthof *et al*., 2003; Thorman *et al*., 2006; Thorman *et al*., 2007).

Nitrous oxide emission factors

The mean N_2O emission factor (EF) calculated over a *c*.60 day measurement period varied between the 6 experiments ($P<0.1$), with values ranging from - 0.12% of total N applied (site 4, experiment 5) to 1.34% of total N applied (site 3, experiment 4) (Figure 1). Across the 4 experiments where N_2O was measured over 365 d, the mean calculated EF ranged from 0.68% of total N applied (site 2, experiment 2) to 3.93% of total N applied (site 4, experiment 5) (Figure 1) with all EFs more than twice the magnitude of those calculated over the corresponding *c*.60 d. Both the *c*.60 d and 365 d EFs from this experiment were within the range of losses (<0.001-7.33%), found in the literature (Paul *et al*., 1993; Watanabe *et al*., 1997; Chadwick *et al*., 2000; Thorman *et al*., 2003a; Thorman *et al*., 2003b; Velthof *et al*., 2003; Thorman *et al*., 2006; Thorman *et al*., 2007).

Figure 1. Cumulative N_2O-N loss following autumn (solid bars) or spring (stripy bars) solid manure application calculated over a *c*.60 d (black bars) or 365 d (light grey bars) period. Error bars represent ± 1 standard error of the mean



The variability in both the *c*.60 d EFs and 365 d EFs between experiments was probably the result of differences and interactions between soil texture, soil temperature and rainfall during the measurement periods. The heavy clay texture of the soil at site 2 (experiment 2) and the clay loam soil at site 4 (experiments 5 & 6) would have restricted diffusion of N_2O to the atmosphere, whereas the lighter textured loamy sand and sandy loam soil of sites 1 (experiment 1) and 3 (experiments 3 & 4) would have impeded gas diffusion to a lesser extent resulting in greater N_2O emissions. Furthermore, Velthof *et al*. (2005) demonstrated that the effect of manure composition on N_2O losses varied greatly between a sandy and a clay soil, which they attributed to interactions with soil properties, such as the organic matter content.

Numerous studies in the literature have shown that N_2O production increases with temperature and can be stimulated with a rise in soil moisture (Dobbie *et al*., 1999; Scott *et al*., 2000), although at very high soil moisture contents (WFPS >90%) N_2O emission will dramatically decline due to complete denitrification and the conversion of N_2O to N_2 (Davidson, 1991). The lowest *c*.60 d EF of -0.12% measured from the autumn application at site 4, experiment 5 (Figure 1) was probably due to intense denitrifying conditions caused by heavy rain (236.8 mm) and relatively warm temperatures (mean air temperature of *c*.14°C) over the monitoring period combined with the clay loam soil texture. The very low EF of 0.03% from the autumn application at site 2 was also probably the result of intense denitrification primarily due to the very heavy textured clay soil restricting gaseous diffusion. Although site 4, experiment 6 was on a clay loam soil, it produced an EF of 0.92% (Figure 1). Cumulative rainfall over the monitoring period was *c*.168.4 mm. Combined with a mean air temperature of 15°C, the soil moisture and texture were likely to stimulate denitrification to such an extent as to generate N_2O at the soil surface.

The EFs obtained from the sites on lighter textured soils were all ≥ 0.45%. Site 1, experiment 1 received the least rainfall (85.8 mm) over the monitoring period, but the loamy sand texture was likely to have allowed N_2O emission from the soil surface contributing to an EF of 0.66% (Figure 1). The considerably greater rainfall totals at site 3, experiment 3, following an autumn application (146.6 mm) and after the spring application at site 3, experiment 4 (174.4 mm) combined with the sandy loam texture were likely to have greatly contributed to the EFs of 0.45% and 1.34% (Figure 1). The autumn application of manure at site 2, experiment 2 and at site 4, experiment 5 meant that there was a gradual decrease in temperature over the *c*.60 d period with a concurrent increase in rainfall. Conversely, after the autumn application at site 4, experiment 6 and following the 2 spring applications, warm temperatures tended to coincide with substantial rainfall, which would have encouraged N_2O production, indicated by the relatively large N_2O loss from site 3, experiment 4.

The current UK GHG inventory (Baggott *et al*., 2007) is calculated using the default Intergovernmental Panel on Climate Change (IPCC) EFs. Following the application of livestock manure, N_2O loss is calculated using the default EF for direct N_2O emission from soil i.e. 1.25% of total N applied is lost as N_2O (IPCC, 1996). It is acknowledged that this default EF has now been reduced to 1% (IPCC, 2006), although this is not yet used to calculate the UK inventory. The 1996 default EF is more than twice the magnitude of the mean *c*.60 d EF (0.55%; range -4.49% to 6.72%) from the 6 experiments. The default IPCC EF, however, relates to the estimate of emission over one calendar year and is therefore not directly comparable. The EFs calculated over 365 d are, however comparable. Across the 4 experiments, the mean *c*.365 d EF of 2.38% is about twice that of the IPCC default value and highlights the need to calculate EFs over the same length of time as the IPCC default value in order to avoid the underestimation of N_2O losses.

On average only 20% of the cumulative emission calculated over the 365 d measurement period had been emitted over the corresponding initial *c*.60 d following an autumn manure application and <50% of the 365 d cumulative emission had been emitted over the corresponding initial *c*.60 d following the spring manure application. This emphasises the importance of long term monitoring from solid manures to take into account the available N released over time following mineralisation of organic manure N, which may potentially be used for N_2O production. In the literature, the results of a laboratory experiment demonstrated that mineralisation of organic N in animal manures released a steady supply of mineral N into the soil over the 12-26 week period following application (Chae and Tabatabai, 1986). Mineralisation of organic manure N is a microbially mediated process so the mineralisation rate is likely to be affected by temperature (Swift *et al*., 1979). Consequently mineralisation is likely to occur in the late spring to early summer period as a result of a rise in soil temperature. Presumably the smaller proportion of the cumulative N_2O loss emitted following the autumn applications compared to the spring application was the result of emissions generally declining due to the onset of winter and the associated drop in temperature, whereas following the spring application there was no inhibition of N_2O production caused by declining temperatures. Emission peaks over the summer were related to increases in soil moisture stimulating emissions presumably from mineralised organic N. Similarly, at the sites where manure was applied in the autumn, emissions greater than or of a similar magnitude to those measured within the first 2 weeks following manure application were measured during April to June.

Conclusions

This study shows that the effect of rapid incorporation by ploughing on N_2O loss was inconsistent. In conditions likely to induce intense denitrification (i.e. a heavy soil texture and/or a high soil moisture content) ploughing is likely to reduce N_2O emissions and may be used as a 'win-win' technique to mitigate both NH_3 and N_2O losses. However, in conditions where denitrification is unlikely to be intense (i.e. a light soil texture and/or a low soil moisture content) ploughing may increase N_2O emissions. However, notwithstanding the variation among these results, they demonstrate that the incorporation of manures in order to reduce NH_3 emissions does not always lead to increased emissions of N_2O.

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