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Emission factors for ammonia and nitrous oxide emissions following immediate manure incorporation on two contrasting soil types

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HIGHLIGHTS

- Immediate incorporation of solid manures by plough reduced NH_3 emissions by *c.* 90%.
- Immediate incorporation by disc and by tine reduced NH_3 emissions by *c.* 60%.
- Immediate incorporation of solid manures does not necessarily increase N_2O emissions.
- The impacts of immediate incorporation on N_2O emissions may be related to soil type.

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ABSTRACT

We carried out four replicated field experiments to measure the impacts of immediate incorporation of solid manures on emissions of ammonia (NH_3) and nitrous oxide (N_2O). Four manures: cattle farmyard manure (FYM); pig FYM; layer manure and broiler manure were applied to the soil surface or immediately incorporated by mouldboard plough, disc or tine. Two of the experiments were carried out on a clay soil and two on a sandy soil to find out whether soil type interacted with incorporation technique to influence emissions of NH_3 or N_2O. Ammonia emissions were measured for 1 or 2 weeks while N_2O emissions were measured for 60 days in one experiment and for a complete year in the other three experiments.

Immediate incorporation by plough reduced NH_3 emissions by *c.* 90% and by *c.* 60% by disc and tine ($P < 0.001$). There was no effect of soil type on NH_3 abatement efficiency by plough or tine but the disc was less effective on the coarse sandy soil.

Cross-site analysis indicated no effect of incorporation by disc or tine on emissions of N_2O–N after 60 days but incorporation by plough increased direct emissions of N_2O–N compared with surface application of manure ($P < 0.001$). Direct emissions of N_2O–N, at *c.* 0.67% of total N applied, were substantially greater at the coarse-textured site than at the heavy clay site (0.04% of total N applied; $P < 0.001$). The impact of incorporation on total annual direct emissions of N_2O–N differed in the three experiments where emissions were measured for a full year. There was no effect of incorporation on N_2O–N emissions in the first experiment on the clay soil, and in the second experiment at this site incorporation by plough or disc, but not tine, reduced direct emissions of N_2O ($P = 0.006$). However on the sandy soil direct emissions of N_2O–N were increased when manures were incorporated by plough ($P = 0.002$) but not when incorporated by disc or tine.

These results confirm that immediate incorporation of solid manures by plough is the most effective means of reducing NH_3 emissions following the application of solid manures. The results also indicate that immediate incorporation of solid manures to reduce NH_3 emissions does not necessarily increase emissions of N_2O. However, the impacts of immediate incorporation on emissions of N_2O may be related to soil type with a greater possibility of emission increases on coarse sandy soils.

1. Introduction

Following application of livestock manures to land, manure nitrogen (N) may be lost from the soil/plant system in forms that lead

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to pollution. Emissions of ammonia (NH_3), when deposited to terrestrial and aquatic ecosystems, increase N eutrophication and soil acidification (Butterbach-Bahl et al., 2011; Dise et al., 2011). Ammonia forms secondary particulates in the atmosphere by reacting with SO_x and NO_x (Renard et al., 2004). There is evidence that particles <2.5 μm diameter ($PM_{2.5}$) have a linear, no-threshold adverse effect on human health (Brunekreef and Holgate, 2002). Ammonium particulates are a major source of $PM_{2.5}$ with agriculture contributing *c.* 80% of the precursor NH_3. Although NH_3-derived aerosols are only one source of $PM_{2.5}$, Rohr and Wyzga (2012) reported that epidemiological studies have not fully exonerated any major component class of $PM_{2.5}$ mass from having an adverse impact on health. Nitrous oxide (N_2O) contributes to global warming (Bouwman, 1990) and to stratospheric ozone depletion (Crutzen, 1981). As well as contributing to global N enrichment and climate change such emissions also represent a loss of crop nutrients (e.g. Webb et al., 2013).

The Gothenburg Protocol to reduce atmospheric pollution (UNECE, 2000) limits national emissions of NH_3. To help meet this agreement, the EU has agreed on a National Emissions Ceilings Directive (NECD), under which the U.K. target for NH_3 emission is a maximum of 297 × 10^3 t a^{-1} NH_3 (EC, 2010a). Under the Kyoto protocol on Climate Change, signatories committed themselves to greenhouse gas (GHG) emission reduction targets, including N_2O. For example, the UK has set a national target of an overall 80% reduction in GHG emissions by 2050 and the agriculture sector is committed to playing its part in contributing to this goal. The adoption of the Nitrates Directive 91/676 (EEC, 1991) and Water Framework (EC, 2010b) Directives has lead to member states preparing action plans to reduce NO_3^- leaching, including that from livestock manure application.

The rapid incorporation of solid manures into tillage land has been identified as an effective means of reducing NH_3 emissions. Published data indicate that rapid incorporation of FYM may reduce NH_3 emission by 40%–90%, with the greatest reduction coming from ploughing (Mulder and Huijsmans, 1994; Webb et al., 2010).

Concerns have, however, been expressed that rapid incorporation of manure into soil, in order to reduce NH_3 emissions, will increase the pool of mineral N in soil and lead to increased emissions of N_2O (Bouwman, 1996). Few papers have been published which report the impact of solid manure application using NH_3 abatement techniques on emissions of N_2O and some of those published were incubation studies and hence extrapolation of their results to field-scale application needs caution. In a review of field studies which measured emissions of both NH_3 and N_2O following rapid incorporation of solid manures, Webb et al. (2010) reported that incorporation may reduce emissions of NH_3 while not increasing, or even reducing, those of N_2O.

The objectives of the work reported here were, first, to make a balanced comparison of the impact of two contrasting soils types on the efficiency of a range of incorporation techniques in reducing NH_3 emissions following the application of solid manures. Second, to measure the effects of these incorporation techniques on subsequent emissions of N_2O over the following 12 months. Third, to assess whether there was any interaction between soil type and incorporation method on emissions of NH_3 or N_2O or on any trade-offs between emissions of those two gases following immediate incorporation.

2. Materials and methods

Between February 2003 and October 2005, 4 experiments were carried out at two sites of contrasting soil type to measure the impact of immediate incorporation of solid manures on emissions of NH_3 and N_2O. Incorporation began as soon as manure spreading had been completed. We tested four types of solid manure, cattle farmyard manure (FYM), pig FYM, layer manure and broiler litter. The four application treatments were as follows:

1. Manure left on surface.
2. Immediate incorporation by plough.
3. Immediate incorporation by disc.
4. Immediate incorporation by spring tine.

Each incorporation treatment was applied as a single pass, as is the standard practice in the UK to rapidly incorporate manures. When non-inversion tillage is used to incorporate manures it is usual to carry out further cultivation to establish a seedbed. However, this would normally be done some time later, and not have any measurable effect on NH_3 emissions. The dimensions of incorporation machinery used are given in Table 1. Manures were applied by hand at rates intended to apply 150 kg ha^{-1} N^{-1} based on standard analysis of livestock manures used in the UK (Webb et al., 2013). Due to the variability in the N content among the manures sourced in the different years of the project the actual amounts of N in the manures applied varied considerably. The amounts of manures applied in t ha^{-1} are given in Table 1.

There was an additional control plot (no manure applied and no incorporation) in each block to provide estimates of background emissions of N_2O, giving a total of 17 plots per block. Each of the 17 treatments was replicated four times in a randomised block design with treatments applied to each block in successive weeks in order to allow efficient use of resources, e.g. wind tunnels to measure NH_3.

((4 manure types * 4 application treatments) + control) * 4 replicates = 68 plots.

Each plot was 6 × 10 m^2 with a 3 m race and 15 m gaps between blocks. Samples of manure were taken from each plot and analysed for % dry matter (DM), total-C, total-N and total ammoniacal-N (TAN).

2.1. Sites

The two sites were at ADAS Gleadthorpe (GL) in north Nottinghamshire, UK, and ADAS Drayton (DT) in Warwickshire, UK. The soil at GL is a free draining loamy sand of the Cuckney Soil Series, described by Ragg et al. (1984) as slightly stony loamy sand to a depth of *c.* 70 cm with sand below and pH generally >6.5. These soils are mainly under arable rotations often including crops of potatoes and sugarbeet. The soil at GL comprises 77% sand and 6% clay. The soil at DT is of the Evesham Soil Series described (Clayden

Table 1
Dimensions of incorporation machinery used in field experiments.

Implement	Site	
	Gleadthorpe	Drayton
Plough		
Furrow width (mm)	360	350
Number of shares	4	3
Depth of operation (mm)	230	230
Discs[a]		
Disc diameters (mm)	510 front, 460 rear	700
Disc spacing (mm)	200	230
Depth of operation (mm)	120	150
Tines		
Type	Spring	Spring
Width of points (mm)	40	30
Leg spacing (mm)	160	250
Depth of operation (mm)	100	100

[a] Pressing not used in these experiments.

and Hollis, 1984) as stoneless seasonally waterlogged swelling clayey soils calcareous to within 400 mm depth and often to the surface with pH typically *c.* 7.5. Topsoils have a moderate to strong structure. In summer the soils shrink on drying and cracks develop at the surface, extending deep into the subsoil. Evesham soils are either under grassland or autumn-sown combinable crops. The soils at DT comprised 14% sand and 64% clay. Experiments were carried out at GL in spring 2003 (GL03) and autumn 2004 (GL04). At Drayton experiments were carried out in early autumn in both 2003 (DT03) and 2005 (DT05) as on this very heavy soil spring cultivations are not practical.

2.2. Ammonia emissions

To obtain replicated NH_3 loss measurements and perform statistical analysis, multi-factorial replicated field plot experiments, using comparatively small plots, are needed (Petersen, 1994). To measure NH_3 emissions on plots of the size needed to provide good replication, wind tunnels (one per plot), based on the design of Lockyer (1984), were used. Ammonia emissions were measured for 4 days following application of cattle and pig FYM and for 2 weeks after poultry manure application. The wind tunnels remained in place for the duration of the measurements. We recognised that dynamic chamber systems may overestimate NH_3 losses and determine NH_3 loss potentials rather than actual NH_3 losses under field conditions (Sommer et al., 2004). However, dynamic chamber methods, including wind tunnels (Loubet et al., 1999; Ryden and Lockyer, 1985), can be used in replicated field experiments for comparison of treatment effects such as the relative efficacy of abatement techniques and have been shown to provide robust results (Misselbrook et al., 2005).

In general these techniques need pumping systems and thus comparatively large infrastructures, restricting the number of experimental plots that can be measured simultaneously (Gericke et al., 2011). These small plot experiments are also a prerequisite for simultaneous measurements of crop yield and greenhouse gas emissions at the same location. Hence, on the recommendation of a statistician, the fully balanced and replicated experimental design detailed above was chosen, establishing each of the 4 blocks in successive weeks.

2.3. Direct nitrous oxide emissions

Direct measurements of N_2O were made from two static flux chambers (40 cm wide × 40 cm long × 25 cm high), placed in random positions on each plot (covering a total surface area of 0.32 m^2) after the treatment had been completed. A water-filled channel running around the upper rim of the chamber allowed an air-tight seal to form following chamber enclosure with a lid (Dobbie et al., 1999). Chambers were pushed into the soil up to a depth of 5 cm and headspace samples taken from inside the chamber were analysed as soon as possible after collection (to minimise potential leakage) by gas chromatography. The N_2O flux was calculated based on the increase in N_2O concentration inside the chamber over a 40-min enclosure period. The chambers remained in the soil throughout the experiment, except when farm operations (e.g. drilling) necessitated their removal. In order to permit sampling from the growing crops of barley at GL and wheat at DT, at the time of sampling an additional chamber was stacked (using the water-filled channel) onto each permanent chamber. Nitrous oxide emission measurements were carried out immediately following manure application and at regular intervals over a *c.* 60 day period to give a total of 12 measurements. Three of the 4 experiments were continued over a further 10 months with samples taken at *c.* 10 day intervals to give *c.* 40 measurements over the 12 months, the exact number of samples depending upon the harvest date in relation to the date of crop establishment. Winters were mild during these measurement periods and hence there were no spring thaw events. The additional measurements were taken in order to calculate emissions over a full calendar year so that the results were directly comparable with the Intergovernmental Panel on Climate Change (IPPC) default emission factor (EF) and to include potential emissions resulting from manure mineralisation.

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.

2.4. Indirect nitrous oxide emissions

Indirect emissions of N_2O were calculated using IPCC methodology (IPCC, 2006), i.e. 1.0% of NH_3 emissions measured from each plot and 0.75% of NO_3–N leached. The MANNER-NPK model (Nicholson et al., 2009) was used to calculate NO_3–N leaching losses for each treatment from each site where the manures were applied in the autumn (i.e. experiments DT03, GL04 and DT05). Most input data (i.e. manure analysis and information on incorporation, soil, crop and weather) were recorded or measured at each site. The date of the end of field drainage was estimated using IRRIGUIDE (Bailey and Spackman, 1996).

2.5. Statistical analysis

Total NH_3 emissions were calculated using the generic Michaelis–Menten function described by Sogaard et al. (2001), modified to give the sum of emissions before and after incorporation:

$$L = L_{\text{Max}} \cdot \left(\frac{\Delta t}{\Delta t + K_m} \cdot \left(1 - \frac{\Delta t}{\Delta t + K_m} \right) \right) \quad (1)$$

where L is the percentage of volatilizable N emitted, L_{Max} is the maximum percentage emission, Δt is the time lag between application and incorporation and K_m is a manure-specific rate parameter equal to the time at which 50% of the volatilizable N has been emitted. Wind tunnels were set up as soon as manure spreading was completed on the control (unincorporated) plots and as soon as incorporation was completed on the treatment plots. Hence Δt was 0 and K_m was the value measured for each plot.

We examined total emissions derived from applying the Michaelis–Menten and best-fit functions to the results from each plot. Following consultation with a senior statistician, we decided that the Michaelis–Menten function best described the NH_3 emissions data obtained from the field experiments. Applying this biological function consistently to individual plot data produced standardised values for total NH_3 emissions over fixed time periods which could then be subjected to further statistical analysis in order to obtain robust treatment comparisons.

The results of manure analysis for each experiment were subject to analysis of variance (ANOVA) to determine whether there were any differences in the amounts of N applied to treatments in each block. Ammonia emission from each plot was calculated as the mean of individual wind tunnels. Analysis of variance was used to determine significant differences among application methods for each site and all the estimates of NH_3 abatement efficiency were combined for a cross-site ANOVA to determine if there was any systematic difference in abatement between the two sites. The abatement efficiency was determined as the mean reduction in emission, expressed as % of TAN applied, by the incorporation technique divided by the mean emission measured from the manure left on the surface.

A potential problem with our experimental design was that NH_3 emissions from a plot on which emissions would be expected to be large (i.e. unincorporated manure) might drift onto a plot on which emissions would otherwise be small (e.g. immediate incorporation by plough). Gericke et al. (2011) addressed this problem by examining their data and excluding plots from further analysis if a replicate deviated by more than twice the standard deviation from the mean value of the other three replicates.

Data on NH_3 and N_2O emissions were statistically analysed using ANOVA, repeated fixed measures ANOVA and regression analysis in GENSTAT version 8.1 (Lawes Agricultural Trust, 1993). Data were log transformed prior to analysis where necessary. Two data sets of both direct and total N_2O emissions were analysed consisting of measurements taken over the initial *c*. 60 d measurement period and the full 365 d measurement period. Since measurements were made for 60 days at all four sites those data were also subjected to cross-site ANOVA. Differences between means were taken to be significantly when $P < 0.1$.

3. Results

3.1. Manure application

Analyses of the manures applied, as averages per site, are given in Table 2. At GL03 there were differences in the amounts of N applied in cattle FYM among the blocks. At DT03 there were differences among the blocks in the amounts of N applied in all the manures. Where there were differences in the amounts of N applied among blocks NH_3–N and N_2O–N emissions were calculated as proportions of N and TAN applied per block.

3.2. Ammonia emissions

None of the replicates came close to deviating from the mean value of the other three replicates by more than twice the standard deviation. Hence no results needed to be discarded. On average NH_3 emissions from unincorporated manures were not greatly different to those used in the UK Ammonia Emissions Inventory (UKAEI) (Misselbrook et al., 2012). We measured average NH_3 emissions from unincorporated FYM of 64% of TAN, slightly less than the average of 68% of TAN used in the UKAEI. Average emissions from unincorporated poultry manures in these studies were 51% of TAN, similar to the 52% used in the UKAEI (Table 3). Emissions from unincorporated manures tended to be least at GL03, where average air temperatures ranged from 5 to 7 °C compared with temperatures of 10–18 °C (Table 4) following autumn application in the other 3 experiments. Average emissions following application in autumn at GL04 were less than following autumn application at DT in both years despite temperatures being similar and wind speed being greater at GL04 than at DT in either year (Table 4). The greater average emission at DT in both years was due to much larger emissions from layer manure. It is not clear from the analyses of the layer manures used why this difference occurred. Emissions greater than 100% of TAN are sometimes recorded from solid manures and this can arise with poultry manures from hydrolysis of uric acid after application.

Table 3
Ammonia emissions from surface applied manure, % total ammoniacal nitrogen (TAN) applied. Results presented from individual site ANOVAs.

	Gleadthorpe 2003	Drayton 2003	Gleadthorpe 2004	Drayton 2005	Mean
Cattle FYM	38.4	76.8	52.8	59.1	57
Pig FYM	32.1	73.5	85.0	97.6	72
Layer	25.7	104.3	38.9	49.5	55
Broiler	68.0	18.6	26.5	73.8	47
Mean	41.1	68.3	50.8	70.0	
SED	6.0	7.1	7.1	5.7	

3.3. Ammonia abatement

Mean NH_3 abatement, when averaged across all incorporation treatments, was greater at DT (75%) than at GL (67%) ($P = 0.053$). Abatement was greater from ploughing (92%, $P < 0.001$) than from disc or tine (Table 5). There was an interaction ($P < 0.001$) between site and incorporation method, incorporation by disc being more effective at DT (73%) than at GL (52%). This is considered due to the smaller and lighter implement at GL being less effective at incorporating the manures into the dry soil at GL and it is the reduced abatement efficiency of incorporation by disc that led to the difference in overall abatement efficiency between the two sites. There was also an interaction between manure type and abatement method with the tine reducing emissions from layer manure less than for the other manures. The layer manures were spread uniformly across the plots but due to the relatively small amounts of

Table 2
Characteristics of manures used in experiments to measure ammonia and nitrous oxide emissions following manure incorporation.

Manure type	Site	Dry matter (%)	C (total)	N (total)	Total ammoniacal nitrogen (TAN)	Manure applied	Amount of straw
			(kg t^{-1}, fresh wt)			(t dry weight)	
Cattle	1. Gleadthorpe03	18.9	75.0	3.4	0.4	8.5	Medium
	2. Drayton03	37.8	136.8	10.3	1.6	5.5	Very high
	3. Gleadthorpe04	17.6	65.0	3.5	0.3	7.5	Medium
	4. Drayton05	42.1	154.0	1.2	0.1	52.5	Very high
Pig	1. Gleadthorpe03	23.7	91.5	9.6	4.9	3.5	Medium
	2. Drayton03	26.7	94.8	10.8	3.2	3.5	Medium
	3. Gleadthorpe04	28.1	101.1	11.3	2.6	3.5	Medium
	4. Drayton05	29.7	9.8	0.9	0.2	49.5	Medium
Layer	1. Gleadthorpe03	20.7	63.3	11.6	6.3	2.5	None
	2. Drayton03	45.7	114.7	16.1	4.5	4.5	None
	3. Gleadthorpe04	28.1	80.1	16.0	9.6	2.5	None
	4. Drayton05	29.9	8.4	2.1	1.4	21.5	None
Broiler	1. Gleadthorpe03	54.8	214.8	18.6	4.9	4.5	Low
	2. Drayton03	74.3	260.0	39.1	3.4	3.0	Low
	3. Gleadthorpe04	43.3	156.8	11.4	1.9	5.5	Low
	4. Drayton05	62.5	23.4	3.3	1.0	28.5	Low

Table 4
Average weather conditions in the week after manure application and soil moisture contents in control plots at time of treatment.

Site	Dates treatments established	Air temperature, °C	Solar radiation, MJ m^{-2}	Wind speed, m s^{-1}	Rainfall, mm	Average relative humidity, %	Soil moisture content, %
Gleadthorpe 2003							
Block 1	25-02-2003	5.4	5.9	2.1	1.6	86	11.8
Block 2	03-03-2003	6.5	5.5	3.3	2.0	83	14.0
Block 3	10-03-2003	7.1	8.5	3.5	0.3	74	13.3
Block 4	17-03-2003	4.7	12.0	1.2	0.0	78	12.6
Drayton 2003							
Block 1	01-09-2003	15.1	12.7	0.6	0.0	73	25.8
Block 2	16-09-2003	16.4	11.6	1.0	0.0	74	23.6
Block 3	23-09-2003	9.8	12.7	0.9	0.0	76	23.5
Block 4	30-09-2003	11.1	6.8	1.4	0.3	81	24.5
Gleadthorpe 2004							
Block 1	01-09-2004	16.4	14.9	1.3	0.0	76	13.9
Block 2	06-09-2004	17.3	13.4	1.7	0.3	79	8.7
Block 3	13-09-2004	14.1	11.3	4.8	1.4	75	8.1
Block 4	20-09-2004	13.5	9.5	5.0	0.6	72	9.6
Drayton 2005							
Block 1	16-08-2005	18.0	15.7	0.1	0.1	82	24.5
Block 2	23-08-2005	15.0	12.9	<0.1	<0.1	85	26.4
Block 3	30-08-2005	18.9	15.5	<0.1	<0.1	82	26.2
Block 4	06-09-2005	18.0	9.6	0.1	0.1	91	24.4

manure, which was generally rather moist (Table 2), it was concentrated in patches on the soil surface, some of which were little disturbed by the action of the tine. Otherwise abatement by each implement was reasonably consistent among the manures.

3.4. Nitrous oxide emissions, 60 days

Cross-site ANOVA indicated there was no effect of block ($P = 0.138$) on the direct emissions of N_2O–N measured over 60 days but site, manure type and application method ($P < 0.001$) all had significant impacts (Table 6). Direct emissions of N_2O–N after 60 days were equivalent to 0.67% of total N applied at GT but 0.04% of total N applied at DT. Direct N_2O–N emissions from cattle FYM were much less than direct N_2O–N emissions from the other manures (Table 6). Incorporation by plough led to the greatest direct N_2O–N emissions but emissions following manure incorporation by disc and tine were not greater than emissions following surface application of manures (Table 6).

Table 5
The effect of manure type, incorporation technique and site on mean ammonia abatement efficiencies (% reduction of NH_3–N emission).

Factor					df	SED	P
Manure type	Cattle FYM	Pig FYM	Layer	Broiler			
	65.7	77.8	66.6	72.5	3	5.50	0.112
Incorporation technique	Plough	Disc	Tine				
	91.5a	60.9b	60.0b		2	4.76	<0.001
Site	Gleadthorpe	Drayton			1		
	66.8	74.5				3.89	0.054
Manure v Incorporation	Cattle FYM	Pig FYM	Layer	Broiler			
Plough	92.6a^{1}	96.0a^{1}	90.3a^{1}	87.1a^{1}			
Disc	56.6a^{2}	69.5a^{2}	65.7a^{2}	65.7a^{2}	11	9.53	<0.001
Tine	62.5a^{2}	69.0a^{2}	43.8b^{3}	64.8a^{2}			
Site v Incorporation	Plough	Disc	Tine				
Gleadthorpe	90.9a^{1}	51.7b^{1}	61.2b^{1}		11	6.74	<0.001
Drayton	92.1a^{1}	72.6b^{2}	58.9c^{1}				

Values in the same row followed by the same letter are not significantly different.
Values in the same column followed by the superscript number are not significantly different.

3.5. Nitrous oxide emissions, 365 days

No cross site ANOVA was possible as measurements were only carried out for 60 days at GL03. The impacts of immediate incorporation on N_2O emissions over a whole year are reported for the remaining 3 sites individually.

3.5.1. Drayton 2003

In this experiment there was no effect ($P > 0.1$) of incorporation technique or block on annual direct N_2O–N emissions as the percentage of total manure N applied. Over the whole year direct N_2O–N losses from layer manure, as a percentage of total manure N applied, (0.81%) were greater than from cattle FYM (0.55% of total N applied) and pig FYM (0.65% of total N applied) ($P < 0.068$). Direct N_2O–N emissions from broiler manure were intermediate (Table 7). Similar trends were estimated for total N_2O–N emissions, with no effect of block or incorporation on emissions. Total N_2O–N emissions were greatest from layer manure (0.97% of total N applied) and least from cattle FYM (0.64% of total N applied) ($P < 0.008$).

Table 6
Cross site analysis – the effect of site, manure type and incorporation technique on cumulative nitrous oxide emissions calculated over 60 days (% total N applied).

Factor					SED	P
Site	Gleadthorpe	Drayton				
Direct	0.67	0.04			0.073	<0.001
Manure type	Cattle FYM	Pig FYM	Layer	Broiler		
Direct	0.05a	0.37b	0.57b	0.42b	0.103	<0.001
Application technique	Surface	Plough	Disc	Tine		
Direct	0.20a	0.67b	0.32a	0.23a	0.103	<0.001
Man v Incorp	Cattle FYM	Pig FYM	Layer	Broiler		
Surface	0.04a^{1}	0.23a^{1}	0.28a^{1}	0.24a^{1}		
Plough	0.07a^{1}	0.80bc^{2}	1.11c^{2}	0.69b^{2}	0.204	<0.001
Disc	0.07a^{1}	0.28ab^{1}	0.50b^{1}	0.42ab^{1,2}		
Tine	<0.01a^{1}	0.18a^{1}	0.41a^{1}	0.34a^{1,2}		

Values in the same row followed by the same letter are not significantly different ($P < 0.1$).
Values in the same column followed by the superscript number are not significantly different ($P < 0.1$).

Table 7
The effect of manure type and incorporation technique on cumulative nitrous oxide emissions calculated over 365 days at Drayton 2003. (N_2O–N as % of total N applied).

					SED	*P*
Manure type	Cattle	Pig	Layer	Broiler		
Direct	0.55a	0.65a	0.81b	0.71 ab	0.096	0.068
Total	0.64a	0.78 ab	0.97b	0.73a	0.094	0.008
Incorporation technique	Surface	Plough	Disc	Tine		
Direct	0.66	0.70	0.77	0.59	0.096	NS
Total	0.84	0.75	0.85	0.68	0.094	NS

Values in the same row followed by the same letter are not significantly different ($P < 0.1$).

Table 8
The effect of manure type & incorporation technique on cumulative nitrous oxide emissions calculated over 365 days at Gleadthorpe 365 d (N_2O–N as % of N applied).

					SED	*P*
Manure type	Cattle	Pig	Layer	Broiler		
Direct	0.09a	0.59 ab	1.30c	0.71b	0.236	<0.001
Total	0.12a	0.69b	1.43c	0.75b	0.233	<0.001
Incorporation technique	Surface	Plough	Disc	Tine		
Direct	0.31a	1.22b	0.73a	0.43a	0.236	0.002
Total	0.45a	1.22b	0.81a	0.51a	0.233	0.006

Values in the same row followed by the same letter are not significantly different ($P < 0.1$).

3.5.2. Gleadthorpe 2004

There was no effect of block on either direct or total emissions of N_2O–N ($P < 0.01$). Immediate incorporation by plough increased direct and total N_2O–N emissions compared with all other application methods ($P = 0.002$ and 0.006 respectively) (Table 8). Emissions of N_2O–N were also influenced by manure type ($P < 0.001$) with the greatest emissions from layer manure and least from cattle FYM (Table 8).

3.5.3. Drayton 2005

In contrast with DT03 there was a significant effect of block ($P < 0.001$) but no linear relationship with time of treatment application. The greatest direct emissions of N_2O–N were measured from block I and the least from blocks II and III. Average air temperatures in the week after treatment application were similar for blocks I, II and IV but *c.* 3 °C less for Block II. In this experiment immediate incorporation by plough and disc reduced direct and total N_2O–N emissions compared with surface application, with the greatest reduction (40%) arising from incorporation by plough and reductions of *c.* 25% from incorporation by disc (Table 9). Total emissions of N_2O–N were reduced by all forms of incorporation ($P < 0.006$). Direct N_2O–N emissions were less from cattle FYM (0.3% of total N applied) than from the other 3 manures (*c.* 0.5% of total N applied). Total N_2O–N emissions were also less from cattle manure than from the other three manure types ($P < 0.001$).

4. Discussion

4.1. Effect of immediate incorporation on emissions of ammonia

Few studies have reported the abatement that can be obtained by immediate incorporation of solid manures. Webb et al. (2004) found that immediate incorporation by plough of pig FYM reduced emissions of NH_3 by an average of 92%. McGinn and Sommer (2007) measured a reduction in NH_3 emissions of *c.* 80% from immediate incorporation by a double-offset cultivator to a depth of 15 cm. Rohde and Karlsson (2002) measured a 90% reduction in NH_3–N emissions from broiler manure incorporated after 4 h by harrow, considerably greater than the abatement obtained by non-inversion techniques in the experiments reported here. In the study of Rohde and Karlsson (2002) the land had already been harrowed and this may have assisted soil and manure mixing when subsequently harrowed. Sagoo et al. (2007) reported that ploughing in broiler manure within 4 or 24 h of land application reduced NH_3 emissions by >70% compared with surface spreading. Discing within 4 h reduced NH_3 losses by 30% and 58% for the conventionally stored and sheet stored broiler litter, respectively. In a modelling study Webb et al. (2006) found that, despite the faster work rates, immediate incorporation by disc or tine, at estimated abatement efficiencies of 60 and 50% respectively, did not lead to greater reductions in NH_3 emissions than immediate incorporation by plough.

Table 9
The effect of manure type and incorporation technique on cumulative nitrous oxide emissions calculated over 365 days at Drayton 2005. (N_2O–N as % of N applied.)

					SED	*P*
Manure type	Cattle	Pig	Layer	Broiler		
Direct	0.30a	0.52b	0.51b	0.49b	0.063	0.003
Total	0.35a	0.68b	0.75b	0.60b	0.073	<0.001
Incorporation technique	Surface	Plough	Disc	Tine		
Direct	0.57a	0.34b	0.43b	0.49 ab	0.063	0.006
Total	0.82a	0.40b	0.52b	0.65b	0.073	<0.001

Values in the same row followed by the same letter are not significantly different ($P < 0.1$).

4.2. Total direct emissions N_2O in comparison with IPCC default

At DT direct annual N_2O–N emissions from all manures that were not immediately incorporated were always <1.0% of the total N applied from the 2 experiments (range 0.30–0.78%). At GL04 only annual direct N_2O–N emissions from cattle manure were <1.0% of the total N applied with emissions from layer manure of 2.4% of the total N applied. Pelster et al. (2012) reported direct annual N_2O–N emissions of 1.8% of the total N applied from the application of poultry manure. The nature of the poultry manure was not stated but the reported dry matter contents suggest broiler litter was used. The large N_2O–N emission was attributed to the large C concentration of the manure (Pelster et al., 2012).

4.3. Effect of soil type on emissions of nitrous oxide

Pelster et al. (2012) concluded manure-N only increases N_2O emissions on soils with low C contents since denitrifiers in coarser soils are limited more by C than N availability. However, Körschens et al. (1998) concluded that microbial activity in soils is related to active SOC, derived from recent C inputs as plant residues, root exudates etc., and that under similar cropping systems the concentrations of active carbon in fine-and coarse-textured soils are similar. Hence explaining differences in N_2O emissions among soils of different texture according to their total SOC content may be erroneous. Soil organic carbon was not among the significant factors in the explanatory model of N_2O emissions developed by Rees et al. (2012).

Pelster et al. (2012) also reported that studies in which manure application led to greater N_2O emissions than from mineral fertilizers were generally on coarse-textured and well drained soils. In contrast on moderate- to fine-textured soils N_2O emissions were no different or greater from mineral N fertilizers. These conclusions are consistent with the view that on clay soils N_2O emissions arise primarily from denitrification and are NO_3^- limited, and hence more likely to be increased by addition of NO_3^-. In contrast coarse-textured soils may be NH_4^+ limited and hence nitrification may be stimulated by the addition of manures which provide a substrate for nitrification and N mineralization. In heavy soils, where denitrification is limited by NO_3^- availability, the addition of solid manures will not lead to a large increase in denitrification.

4.4. Effect of incorporation on emissions of nitrous oxide

In this study incorporation by plough, disc and tine reduced NH_3 emissions ($P < 0.001$) by 91%, 62% and 60%, respectively compared with losses from manure which remained on the soil surface. 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. It may therefore be expected that greater N_2O emissions would be measured following incorporation by ploughing than from by discing or using tines, and in turn than from when manure was left on the soil surface. Total annual N_2O emissions were much better related to N_2O emissions calculated over 60 days at GL (R^2 82%) than at DT (R^2 15%), although the relationship was highly significant at both sites ($P < 0.001$). This perhaps suggests that a greater proportion of total annual emissions at GL were derived from nitrification of the NH_4^+ applied than at DT.

Velthof et al. (2003) postulated that the impacts of application techniques will be moderated by O_2 impacts on N_2O production, local N concentrations in soil and the length of the diffusion path of N_2O to the atmosphere. The longer this diffusion path, the greater the chance that the N_2O produced in the soil is reduced to N_2. Velthof et al. (2003) also reported that manures with a C:N ratio > 15 would lead to initial immobilization of N, thus reducing or postponing N_2O emission. Mutegi et al. (2010), also concluded that greater soil porosity and gas diffusivity in coarse-textured soils could enable the escape of N_2O generated in soil from both nitrification and denitrification of organic residues.

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 not incorporated. Unlike the highly porous loamy sand at GL the increase in length of the diffusion pathway combined with a heavier textured soil and/or a high soil moisture content at DT had the potential to reduce the N_2O diffusion rate through the soil matrix, providing a greater opportunity for microbial reduction of N_2O to N_2 and hence less emission of N_2O at the surface. In contrast, where denitrification was unlikely to be intense, as in the moderate rainfall area and on the light, sandy soil at GL, ploughing appeared to result in the greatest N_2O loss.

4.5. Emission factors for ammonia and nitrous oxide following manure incorporation

There are very few published estimates of the effects of manure incorporation on emissions of NH_3 or N_2O. These results provide 3 additional datasets of NH_3 and total annual N_2O–N emissions from four types of solid manure applied to the surface and incorporated by three implements. Emissions of NH_3 following immediate manure incorporation by plough, disc and tine were 9, 39 and 40% respectively of the surface emission. Annual direct N_2O–N emissions following manure application to the soil surface averaged 0.6 and 0.3% of total N applied on the clay and sandy soils respectively.

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