Review of the efficiency of methods to reduce emissions of ammonia following the application of manures to land, their costs, potential agronomic benefits and impacts on emissions of nitrous oxide

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SUMMARY

1. Review of measured reductions in ammonia emissions from reduced-emission spreading techniques

Based on simple averages of the reported abatement efficiencies of NH_3 emissions, abatement is greater from the use of trailing shoe (TS) (65%) and open-slot injection (OSI) (70-80%) machines than from the trailing hose (TH) (35%). There is considerable variation in the efficiencies reported, especially for TH (0-75%) but also OSI (23-99%). Variation in emissions following the use of the TS appeared to be somewhat less (38-70%), although this may be due to there being fewer studies reported of the TS.

Table 1. Summary of results of experiments to measure the abatement efficiency of reduced-emission slurry spreading machinery, % reduction in NH_3 emissions compared with broadcasting to surface. The range is the range of the means reported in each paper considered.

Machine	Cropping	Papers	Experiments	Mean % reduction		Range (%)
				Overall	Weighted	
Slot Injec.	Grass	5	56	80	86	60-99
	Tillage	5	9	70	49	23-94
Deep Injec	Tillage	2	5	95	97	95-99
Trail shoe	Grass	2	37	64	65	57-70
Trail shoe	Tillage	2	2	64	64	38-90*
Trail hose	Grass	5	45	35	41	0-74
Trail hose	Tillage	7	16	37	48	0-75

*this result was obtained from a machine that placed the slurry within the soil

On grassland OSI and TS are much more effective than TH, and OSI and TH appear to produce reasonably reliable abatement, and this is also the case when the comparison is made using weighted means. On tillage land OSI is on average less effective than on grass and, if the weighted mean is used (49%), not necessarily more effective than TH (weighted mean 48%).

Based on these assessments it seems reasonable to conclude that OSI and TS offer similar potentials for NH_3 abatement on grassland. While the average abatement reported for OSI tends to be greater than for TS there does not appear to be any compelling reason to recommend the use of one machine in preference to the other. However, the mean effectiveness of the TH in reducing NH_3 emissions appears to be consistently, even significantly, much less effective than OSI or TS.

When manures are applied to arable land emissions of NH_3 can be reduced by at least 90% if incorporation by plough takes place immediately after application. A delay of as little as 4 h can reduce the abatement efficiency to only between 45 and

65%. Immediate incorporation using non-inversion cultivators can reduce NH_3 emissions following the application of slurry by *c*. 70% and following solid manures by *c*. 60%.

1.1 Identification of factors influencing effectiveness of technique

1.1.1 Machinery design

Ammonia abatement potential from OSI has been reported to increase with increasing volume of slots, accounting for 88% of the variance in NH_3 emissions. Injection depth was reported to be the main factor in increasing slot volume. To be effective in both reducing emissions of NH_3 and increasing the availability of slurry-N, injection needs to be to a depth of at least 5 cm and the space between injector tines should be no more than 30 cm when applying up to 30 m^3 of slurry.

Injection by machines with two angled disc coulters has been shown to be more effective than by machines with only one.

1.1.1 External factors

The efficiency of abatement of applying slurry by TH to cereal crops has been shown in some studies to increase with increasing crop height and density, although some papers report no correlation with crop height, only a greater reduction when slurry was applied to a crop by TH than when TH application was to bare ground.

Regression on grass height has been used to account for *c*. 50% of the variance in NH_3 abatement when slurry is applied by TS.

In one study at least the efficiency of OSI on tillage land was reduced by the build-up, under some conditions, of stubble trash in front of the injection tines.

2. Review of impact of techniques to reduce ammonia emissions on emissions of nitrous oxide

Results suggest that injection may either increase or have no impact on emissions of N_2O, while incorporation of FYM appears to reduce or have no impact on N_2O emissions. The addition of readily-metabolizable C in slurry has been proposed as a mechanism for increasing emissions of N_2O by more than would be expected due to the additional N entering the soil as a result of NH_3 abatement. This addition of readily-metabolizable slurry-C, without significantly aerating the soil, is likely to increase denitrification activity. In contrast, there is evidence that readily-degradable-C is lost as part of the effluent arising during storage of solid manures. Hence the C added to soil by incorporation of solid manures will have less effect on microbial metabolism.

In an incubation study N_2O emissions were greatest when pig manure was placed at 5 cm ($P < 0.05$), least when placed at 10 cm ($P < 0.05$) and intermediate for surface application, thorough mixing and placement at 5 cm. *These results suggest that while injection to 5 cm might increase emissions of N_2O, deeper injection might reduce them.* There are a number of reasons why reduced-NH_3 emission application techniques would not always lead to greater emissions of N_2O:

injection or incorporation by increasing the length of the diffusion path from the site of denitrification to the soil surface may lead to a greater proportion of denitrified N being emitted as N_2 (hence the results of deeper placement in the incubation study reported above);

the subsequent soil moisture status and hence aeration may not be suitable for increased N_2O production;

in soils already well-supplied with both readily-metabolizable C and mineral N any increase in N_2O emission may be too small to have a significant effect.

the impact of subsequent weather on soil moisture content and WFPS will also effect subsequent emissions of N_2O.

3. Review of agronomic benefits from use of reduced emission spreading techniques

3.1 Impacts on uptake of manure-N by crop

Apparent N recovery (ANR) of surface-applied slurry manure has been found to be less than that of OSI-manure. The more effective abatement techniques, such as OSI or immediate incorporation into soil, are more effective in increasing N uptake than less effective abatement techniques such as TH.

Studies of N uptake following application of manures by reduced-emission techniques have not always measured statistically significant increases in N uptake. However, we conclude that this is due to the difficulties of reliably measuring relatively small changes in N against a background of large N fluxes. We therefore propose that estimates of the additional N recovered by crops following the use of reduced-emission spreading techniques may be based on mass-balance calculations of the amount of NH_3-N conserved and hence available for uptake by crops.

Results suggest that to enable adequate uptake of slurry-N the band width of all reduced-emission machines should be no more than 30 cm.

It has been suggested that injection and incorporation of manures could increase crop N uptake not only by reducing NH_3 volatilization, but also by introducing manure-N to the soil closer to the roots. This could be particularly important when slurry is injected into soils that have developed a soil moisture deficit (SMD) and hence downward movement of surface applied slurry is constrained. However, any effect of placement could be due to improved uptake of manure-P rather than manure-N.

3.2 Impacts on crop yield

Yield can be reduced by OSI and by TS. Damage from OSI can arise from the injector cutting contact between roots and soil, while TS may lead to damage if their is inadequate depth control. However, effective injection appears to be able to compensate for these losses, by increasing N supply.

3.3 Impacts on timeliness of application

Reduced-emission techniques such as TH, TS and OSI may allow more working days in spring than the conventional SP. By increasing opportunities to apply slurry in spring, when crop demand for N is greatest, rather than in summer if this is the usual practice, N recovery from slurry and crop response to that N can be increased. However, not all locations are limited by available machinery working days in spring.

3.4 Impacts of silage quality

Application by shallow injection and, particularly by TS, can increase flexibility of slurry management by allowing more spreading at shorter intervals before cutting than with conventional surface broadcasting, without detriment to silage quality.

However, if the grass is allowed to grow too tall before injection coulters may fail to penetrate the soil leading to sward damage and silage contamination. Overall, TS appears less likely to lead to sward damage or herbage contamination, while producing increases on N_{off} generally equal to those obtained when slurry was applied by injection.

3.5 impacts on grazing

Similar effects have been reported with respect to the palatability of herbage, when slurry was applied to taller grass there was a reduction in efficiency of application by injector and a decrease in palatability. But when slurry was applied to shorter grass, following silage cutting, the cattle responded as well to pastures on which injection was used as to TS, and both were better than surface application.

4. Report on farmer and contractor experience of using reduced-emission spreading techniques within the UK

There has been a large increase in the uptake of reduced-NH_3 emission machines over the past year or two. The main reasons given are the savings in N fertilizer, especially with recent increases in N prices, and odour reduction (especially on pig farms) in specific locations. It is not always clear whether savings in fertilizer are entirely due to the machine or could have been achieved by more considered use of SP spreading.

Some farmers are reluctant to spread in the evening because of a greater likelihood of complaints about odour when neighbours are home.

In general, the capital cost of ownership is too great for individual farmers and most use contractors.

Shallow injectors are popular for use on grassland unless conditions are such that there is poor soil penetration (esp. very heavy or stony soils) or soils are too wet. Trailing shoes overcome some of these problems, and may be increasing in popularity

Many farmers were not able to use the machine to apply all the slurry produced on their farm and often used the SP for a proportion. This was due to difficult soil conditions (too wet or too dry at times of the year, stony or steeply sloping land, some slurry too thick or containing stones etc, inaccessibility of some fields).

5. Costs

5.1 Review of costs of using reduced-emission spreading techniques within the UK

The current additional costs of applying slurry by OSI, TS and TH in the UK were estimated to the same for all three machines at £0.52 m^{-3}. Estimates of the additional costs of using reduced-NH_3 emission machines are critically dependent on the assumptions used, particularly with respect to work rates and the volumes of slurry to be applied each year. As a check on the reliability of our estimates comparison was made with the additional charges made by contractors for spreading slurry using reduced-NH_3 emission machines. UK contractors appear to charge 20-30% more for application with reduced-NH_3 emission machines than for SP. The additional contractor's charge for these machines over SP is estimated to be between £0.28 and £0.42p m^{-3}. Contractors would be expected to accrue less additional cost, since they should be applying large enough volumes to slurry throughout the year to make better use of the machines than most farmers. Nevertheless, the broad similarity in our estimate of the likely additional costs to farmers with the additional costs levied by contractors suggests we have not seriously underestimated these additional costs. The cost of rapid incorporation of manures was estimated to be £0.54 m^{-3} for slurry and solid manures. While our estimates of additional costs appear reasonable, is likely to vary substantially among farms, and likely to be greater on small farms with only moderate volumes of slurry to be spread.

5.2 Comparison of specific UK study on costs with cost estimates produced by a concurrent EU study

Table 1 below provides a comparison of additional costs of using reduced-NH_3 emission slurry-spreading machine estimated for the UK as part of this review with some recent cost estimates from other European countries collated by KTBL.

Table 1. Estimates of the additional costs of applying manures by reduced-NH_3 spreading techniques, 2009. All costs are in £ m^{-3}. The costs provided by KTBL were converted at 1.1€ /£.

	T hose	T Shoe	Slot Injec	*Imm. Incorp.
UK, March 2009, calculation for this review	0.52	0.52	0.52	0.54
UK, March 2009, actual contractor charges	0.35	0.35	0.35	NA
KTBL from Germany		2.59	3.50	0.73-0.82
KTBL from Italy			1.79	0.00
KTBL from Spain		1.05	1.09	0.48-1.47
KTBL from Denmark			0.68	1.30

*This is the estimated maximum additional cost, based on the assumption that immediate incorporation would be an additional operation, that might take place weeks or even months before cultivating the land for drilling, and that subsequent weed growth, soil settling, capping due to rainfall, would mean that incorporating manures to reduce emissions would not reduce the cultivation required to produce a seedbed. The cost is based on the application of 50 m^3 ha^{-1} slurry or 50 t ha^{-1} solid manure

Table 1 suggests spreading costs are much less in the UK than elsewhere. However, this impression may be exaggerated due to recent changes in exchange rates. The greater costs from Germany may reflect generally smaller farm sizes and hence smaller volumes of slurry to be spread. Some earlier estimates by KTBL showed that for yearly volumes spread of 3000 m^3 additional costs of TS at £1.45, were only *c.* 40% of the costs for yearly volumes of 1000 m^3.

5.3 Assessment of value of potential benefits, e.g. from increased N uptake

Estimates of the financial savings were made on the basis of the expected increase in available-N arising from reduced emissions of NH_3-N. Increases in available-N the size we expect from the amount of manure-TAN applied and the efficiency of the technique employed.

These uptakes and cost benefits will only accrue when slurry is applied at times when the N conserved will not be at risk of loss by leaching. The precise time when this risk will no longer apply will depend on soil type and excess winter rainfall (EWR), and can vary considerably even within a single country. However, as a guideline, these additional uptakes should be accrued when slurry is applied in February onward. Except for semi-arid areas, where EWR is negligible, there will be no increase in crop N uptake from reduced-emission spreading when slurry and manure are applied in late summer/early autumn. before autumn-sown crops.

Table 2. Estimation of the value of slurry-N conserved by reduced-emission slurry applicators using UK estimate only.

	Surface	T hose	T Shoe	Slot Injec	*Other
Slurry volume, m^3	30	30	30	30	50
N applied, kg	150	150	150	150	250
TAN applied, kg	75	75	75	75	125
NH_3 emission %	50	50	50	50	50
% abatement	0	40	65	80	95
N conserved, kg	0	15	24	30	59
Value of extra N available, £ per 30 m^3 slurry (50 m^3 for immediate incorporation)	0	14.1	22.6	28.2	55.8
Value of extra N uptake, £ per m^3 slurry	0	0.47	0.75	0.94	1.12
Additional cost of abatement		0.52	0.52	0.52	0.54
Net cost of abatement		0.05	-0.23	-0.42	-0.58

Based on a price of £325 per t ammonium nitrate on 6 February 2009. This equates to £0.94 per kg N
*immediate incorporation by plough

5.3.1 Sensitivity to price changes

In the month or so that has elapsed since table 2 was prepared the UK price of N fertilizer has decreased to £0.77/kg. We have therefore produced estimates of the break-even price of fertilizer-N, above which the application of slurry by reduced-NH_3 slurry spreaders becomes cost-effective.

Table 3. Break-even price of fertilizer-N, above which the application of slurry by reduced-NH_3 slurry spreaders becomes cost-effective.

	T Hose	T Shoe	Slot Injec	*Other
Additional cost of abatement, £ m^{-3}	0.52	0.52	0.52	0.54
Assumed slurry volume, m^3	30	30	30	50
N conserved, kg	15	24	30	59
N conserved, m^{-3}	0.5	0.8	1.0	1.2
Break-even N price, £/kg	1.04	0.65	0.52	0.45
Equivalent AN fertilizer price, £/t	359	224	180	157

*immediate incorporation by plough

A similar sensitivity could be carried out with respect to the effect of the estimates of additional costs of using the machines.

Table 4 presents a reference table which enables estimates to be made of the abatement potentials and fertilizer-N prices at which reduced-NH_3 emission spreading techniques become cost-effective, based on our assumptions of work rates etc. Similar tables could be prepared to illustrate the influence of assumed work rates, volumes of slurry applied each year, etc.

This initial table indicates that, based on our cost assumptions, TS and OSI machines may be cost effective when the price for AN fertilizer exceeds £225 and £200/t respectively. However, for the TH to be cost-effective AN would need to be >£350/t.

To make reliable estimates of the potential savings from other benefits of reduced-NH_3 emission spreading techniques, such as reduced silage taint or reduced odour emissions, was more complex, since application of slurry by SP will not always lead to silage taint (depending on the interval between application and silage making), and not all farmers provoke complaints about odour following manure spreading.

However, estimates of the potential costs of such problems indicate potential savings could be from £0-£3.70 m^{-3} for reduced silage taint to £0-£10.00 m^{-3} for reduced odour nuisance. The upper range of potential costs for the latter illustrates why injection has been adopted by some pig farmers to reduce odour nuisance.

Table 4. Reference table for the break-even unit cost (£ m^{-3} slurry) for reduced-NH_3 emission slurry spreading machines. To take account of differences in the price of fertilizer-N and the abatement efficiency.

% Abate	30	40	50	60	70	80	90
N fertilizer £/t							
100	0.11	0.14	0.18	0.22	0.25	0.29	0.33
150	0.16	0.22	0.27	0.33	0.38	0.43	0.49
200	0.22	0.29	0.36	0.43	0.51	0.58	0.65
250	0.27	0.36	0.45	0.54	0.63	0.72	0.82
300	0.33	0.43	0.54	0.65	0.76	0.87	0.98
325	0.35	0.47	0.59	0.71	0.82	0.94	1.06
350	0.38	0.51	0.63	0.76	0.89	1.01	1.14
400	0.43	0.58	0.72	0.87	1.01	1.16	1.30

6. Conclusions

6.1 Suggested abatement efficiencies to be used in Guidance document update and summary of relevant factors.

The answer to this depends on the answer to the vexed question of whether the Guidelines present a single abatement efficiency for each machine, or a range. The view may be expressed that in a *Guidance* document ranges should not be cited as they can confuse the reader who needs guidance. In addition, when calculating national emissions of NH_3 and the potential for abatement, single values for abatement are often all that the models are able to make use of. Hence we propose at most two values for each type of machine, in some cases differentiating between arable and grassland. The results are presented and discussed in detail in Annex 1. Suggestions are given in Table 5.

Table 5. Results of one-way anova of the three datasets reporting abatement efficiencies, expressed as % reduction of unabated emissions, for all three types of machine.

Machine	Mean % reduction		
	Trail hose	Trail shoe	Slot Injec.
Grass	35	65	80
Arable	40	NA	70

To acknowledge the uncertainty in these means it would seem reasonable to provide ranges as ±1 SD of the ANOVA reported in Annex 1. This would provide the following

Table 6. Possible means with ranges of abatement efficiencies, expressed as % reduction of unabated emissions,.

Machine	Mean % reduction		
	Trail hose	Trail shoe	Slot Injec.
Grass	35 (30-40)	65 (50-80)	80 (60-100)
Arable	35 (30-40)	NA	70 (50-90)

6.2 What are the impacts of reduced-emission spreading techniques on emissions of N_2O?

There are not enough field studies reporting both NH_3-N emissions and N_2O emissions measured over 12 months to draw firm conclusions. The available data suggest a different pattern of results for slurry and FYM:

- Following application of slurry by reduced-NH_3 emission spreading techniques emissions were usually greater than when manures were surface-applied, although differences were not always significant;

- When solid manures are rapidly incorporated N_2O emissions have often been less than from surface application, in some cases significantly less.

It has been suggested that the effect of the added C in manures on denitrification and N_2O emissions would be greatest in soils with little SOM. On the evidence presented here it does appear to be the case that while injection of slurry tends to increase emissions of N_2O, incorporation of manures by cultivation does not, and may decrease them

6.3 What are the current additional costs and to what extent are they mitigated by agronomic benefits?

Current additional costs of the use of reduced-emission slurry-spreading machines range from the UK estimate of *c*. £0.35-0.50 m^{-3} slurry applied to £3.50 from Germany.

The only agronomic benefit which could be properly costed was that of the additional made available by reducing emissions of NH_3-N. Nevertheless, at current prices of fertilizer-N this benefit would entirely mitigate the additional UK costs of applying slurry by TS or OSI, but not by the use of TH. At current fertilizer-N prices slurry application by OSI would also be cost-effective in Denmark, but not in Spain, Italy or Germany.

6.4 What has been farmer and contractor experience of using reduced-emission spreading techniques within the UK?

While UK farmer response has been generally positive a crucial caveat needs to be borne in mind, that many farmers are not using reduced-emission machines to apply all the slurry produced on their farm.

6.5 Recommendations for choice of machine according to crop and local farming conditions.

6.5.1 Grassland

Given the difference in efficacy of OSI and TS is only moderate it appears reasonable to recommend both machines for use on grassland leaving the choice to be made on the basis of cost, other operational considerations or local conditions. The lesser abatement efficiency of the TS machine may be compensated by observations that it offers the greatest potential for contamination-free application in pastures with taller herbage. The TH machine is much less effective at reducing emissions of NH_3 and does not appear an appropriate choice for grassland.

6.5.2 Arable

Where manures, both liquid and solid, are applied to land immediate incorporation by plough is the most effective option. Immediate incorporation can be carried out with existing machinery, and hence does not require additional capital cost, although costs may be incurred either through the need to employ contractors to enable spreading and incorporation to be carried out simultaneously, or due to lost opportunity costs if farm staff are used who could have been employed on other, time critical, tasks such as drilling.

The limitation to immediate incorporation is that in areas where the majority of tillage land is autumn-sown, and where there is excess winter rainfall, the N conserved by reducing emissions of NH_3 is likely to be lost by nitrate leaching. In order to overcome this limitation two alternatives are possible.

- Injection machines are can be used in the presence of a growing arable crop in late winter or early spring.

- Application by TH to growing crops in Spring.

In both cases the reduction in NH_3 emissions will still be less than from immediate incorporation, but much more of the N conserved will be available for crop uptake.

Given that no single machine may be the best for application to all crops in all seasons the greater use of contractors to spread manures may be the best way to optimize the agronomic potential of reduced-NH_3 emission spreaders.

Appendix 1, review of ammonia abatement efficiency

Introduction (after Bittman et al., 2005)

The conventional method of spreading slurry, surface broadcasting by splashplate (SP) applicator, is rapid and inexpensive. However, broadcasting of manure is typically uneven, especially under windy conditions (Huther, 1988). Broadcast manure may also damage grass swards (Christie, 1987; Prins and Snijders, 1987; Wightman et al., 1997) and contaminate crops with microorganisms that can impede silage fermentation (Anderson and Christie, 1995; Steffens and Lorenz, 1998). Surface-applied manure may also enter watercourses via runoff (Uusi-Kamppa and Heinonen-Tanski, 2001). Crop response to broadcast application of manures is often inconsistent (Bittman et al., 1999), and this probably discourages farmers from using them as a primary nutrient source and from making the recommended reductions in fertilizer-N application to make allowance for the available-N supplied in the manures. This inconsistent crop response is largely attributed to ammonia (NH_3) volatilization. Ammonia volatilization may be reduced by minimizing exposure of the manure surface to air and improving contact with the soil (Sommer and Hutchings, 2001). Ammonia losses are greater from broadcasting slurry on stubble than on bare soil, particularly if the manure has a high dry matter content, because of increased exposure to the air and reduced infiltration rate (Frost, 1994). Ammonia volatilization is negatively correlated with the rate of infiltration of manure into the soil. Injection or incorporation of manure (Sommer and Hutchings, 2001) places manures within the soil, effectively bypassing infiltration. However, despite conserving NH_3, injection of manure may reduce yield of perennial grasses (Rees et al., 1993; Tunney and Molloy, 1986; Prins and Snijders, 1987). Such yield reductions are attributed to the cutting of roots during injection, drying of the soil (Prins and Snijders, 1987), and anaerobic and toxic conditions from concentrating the manure in the injection slots (Tunney and Molloy, 1986). The yield reduction is greater with multiple applications over the season (Prins and Snijders, 1987). Manure injection may not be practical on stony or sloping land or on farms lacking access to powerful tractors. The direct ground injection (DGI) system forces finely separated manure under pressure into the soil with little soil disturbance (Morken and Sakshaug, 1998). Surface-banding slurry manure with trailing-shoe (TS) or trailing-hose (TH) implements (band spreaders) is a compromise between injection and broadcasting. Band spreading implements apply manure more uniformly than splashplates (Huther, 1988) and TS machines place the manure beneath grass canopies so that little adheres to and contaminates foliage. Slurry applied by surface banding typically enables greater yields than when slurry is broadcast (Lorenz and Steffens, 1997; Stevens and Laughlin, 1997; Bittman et al., 1999). Also, by delivering manure under the grass canopy, more time is available for spreading manure without contaminating the grass as it regrows (Bittman et al., 1999). Although injection conserves more ammonium-N (NH_4-N), surface banding and broadcasting may be less expensive than injection (Rodhe and Rammer, 2001).

Below brief summaries are given of the results of studies carried out to assess the efficiency with which reduced-emission slurry application machines reduced emissions of NH_3. Results of the impacts of reduced-emission equipment on emissions of nitrous oxide (N_2O) and on subsequent crop N uptake are reported in separate sections. Results are summarised in table form in Annex 1.

Slurry

Nyord et al., 2008, injection and trailing hose

Surface application of separated slurry led to 33% of TAN lost as NH_3. Injection was carried out using an open slot OSI machine placing slurry at two depths, 3 and 7 cm. The authors concluded that injection needs to be to at least 5 cm to be effective. The lack of effectiveness of the TH machine in reducing NH_3 emissions was attributed to the small leaf area of the wheat crop (at GS3) providing little shelter for the slurry.

Bittman et al., 2005, trailing hose alone and with soil aeration

In an earlier paper Douglas et al. (1995) had suggested that aerating soil might improve infiltration of manure, but Gordon et al. (2000) and Chen et al. (2001) found that aeration before broadcasting dairy slurry did not reduce NH_3 emissions or improve yield. Slots that cover less that 3% of the surface area of a field were considered unlikely to help infiltration of manure into the soil. To increase the amount of manure that infiltrates via aeration slots and to benefit from the advantages of banding, a manure applicator was designed that bands the slurry directly over the row of slots made by an aerator. This applicator can reduce odour from pig manure relative to surface broadcasting (Lau et al., 2003), albeit it proved difficult to report these reductions in a meaningful way. The objective of this study was to compare three methods of applying liquid dairy manure on grass: conventional broadcasting, surface banding, and surface banding over aeration-type soil openings. The study examined volatilization of NH_3 and yield and N uptake by two grass species, tall fescue, and orchardgrass.

Reductions in NH_3 emissions of between 0 and 57% were reported, with a mean of 46%. The combination of aeration and TH was more effective in Spring, and this was thought to be due to better slurry infiltration without aeration into the drier soils in August. The authors concluded that aeration can be used on fields or under conditions when injectors may not be used or might cause sward damage. '*Although there appeared to be a relatively small benefit in yield or N uptake, the aeration application can be applied several times in one year without reducing forage production. Averaged over all harvests BS increased yield and N uptake by 7% compared with surface application while the aeration approach increased yield and N uptake by 4 and 8% respectively* '

Rodhe and Etana, 2005, surface application with trailing hoses, shallow injection with three techniques, where only one injected the slurry properly on all three soils

Applications made after first cut when soils were dry and weather warm. No comparison available with surface-applied control, the control was surface application with TH. Emissions from the only injector, which managed to place the slurry to 5 cm depth were consistently less than from TH and the other two types of injectors, giving average emissions of half of the TH. Two of the three injectors were not able to insert the slurry below the soil surface. One, was the pressure injector, the other was the machine with a single disc in front of the injection tine. The effective injector was the one with two angled disc coulters.

There were no significant differences in N recovery.

The authors concluded 'that there is a need to study the influence of the shape of a cut on crop damage more systematically'. (There is an ongoing project in Sv, where crop damage from different knives and injectors is being measured; it will be finished in 2010). Factors among others that could influence the extent of crop damage are direction of cut (horizontal or vertical), depth and width of cut, compaction or fracture of the soil as well as other factors like the botanical composition and growing state of the crop, weather and soil conditions. In the present study, no visible damage to the crops by injection could be seen. Another explanation could be that nitrogen (N) had been immobilised or lost in other ways such as denitrification and therefore not been available to plants. In addition, the distance between slurry trails could affect the utilisation of nutrients by plants.

This study reported that the working depth of the injector increased as soil water content increased. Furthermore, the cone penetration resistance decreased with increased soil water content. Thus, estimating soil strength can be used as one parameter for the optimum occasion for slurry injection in order to achieve sufficient working depths. A soil water content of about 15% for light soils and 20 for heavier seemed to give a satisfactory working depth.

Rodhe et al., 2004, open- and closed-slot injection

Two types of injection were studied, open and closed slots. Studies were carried out in a laboratory using a soil bin, and in the field. Open-slot injectors had double-disc coulters followed by a tine, whereas closed slot machines were equipped with a single disc followed by a tine. The tines, through which the slurry was injected, were of small (32 mm), medium (37 mm), or large (42 mm) diameter and each type was tested with a sharp or vaulted tip. Ammonia emissions were only measured in one experiment from open slot and from closed slot with the narrowest tine and vaulted tip.

In field experiments the hollow (tubulator) tine machine required less draught force than the double-disc (DD) tine. Generally, the DD needed significantly ($P<0.001$) greater force to be pressed into the soil compared with the other tines. Horizontal forces tended to be greater for open slot than for closed slot, not always significant at 5 cm, but always significant when injection was to 8 cm (8 cm for the DD, 5 cm for the tubulator tine with 42 mm diameter and 5 cm depth=same application rate). Tines were effective in placing slurry below the soil surface when working at an injection depth of 5-6 cm. The difference in depth of placement was similar for both types of injector, but the DD injector left 20-30 mm wide exposed slurry at the soil surface.

The authors concluded that the optimum type of injection equipment will be influenced by volume to be spread. This shows that with a tubulator tine, the NH_3 loss could be reduced to a minimum with the same working depth and with about the same draught force as a DD tine.

Chen et al., 2004

Four application methods were compared, OSI, TS, TH and surface application following a pass with a soil aerator. There were 3 replicates. Control plots, to which no manure was applied, were included to assess the impacts on yield and sward damage. Application rates were not explicitly recorded, but based on manure analyses cited, and the target N application rate, 57 and 94 $m^3 ha^{-1}$ of dilute pig slurry appear to have been applied.

Only NH_3 concentrations were measured using Draeger tubes, hence NH_3 abatement efficiencies cannot be derived.

Thompson and Meisinger, 2004, slurry incorporation by rotovator

Ammonia emissions from the incorporated treatment were not measured. Total denitrification was measured only following the Spring slurry application. In these experiments losses of NH_3 following surface application of slurry were moderate at 19% of TAN. Total denitrification losses increased by 52% from 11 to 17% of TAN.

The only other explicit results for incorporation by rotovation were those of Pain et al. (1991). Those studies reporting abatement following slurry incorporation by non-inversion techniques (Huijsmans et al., 2003; Thompson and Meisinger, 2002) suggest an abatement efficiency of 70% or more can be achieved. Hence it is possible that in this study incorporation reduced NH_3 emissions from 19 to 6% of TAN, conserving 13% of the TAN applied, or *c.* 12.1 kg from the reported application of 91 kg ha^{-1} TAN applied. Of the TAN conserved *c.* 50% was subsequently lost by denitrification. However, account needs to be taken of the potential indirect losses of N_2O arising following deposition of NH_3-N. These indirect losses of N_2O may have been reduced by up to 70% by incorporation. It is not possible to make an accurate estimate of total N_2O losses since the direct emissions were not measured. However, some indication may be estimated. Incorporation, by conserving 13% of the TAN applied, and *c.* 4% of the N applied (since in the slurry applied TAN was 30% of N) and hence potentially incorporation should have increased N_2O emissions by 4% compared with surface application. However, total denitrification increased by 52%, hence from these results it appears that incorporation increased direct N_2O emissions by much more than would be expected soley due to the increased conservation of N in the soil. I.e. of the *c.* 12 kg N conserved by incorporation, *c.* 5 kg were lost by denitrification. Therefore there appears to be an increase in denitrification above that to be expected from the additional N input. When expressed as a % of slurry-N added to soil, i.e making allowance for the N lost as NH_3, 3.8% of N was lost by denitrification when the slurry was surface-applied, but 5.1% of total N was lost by denitrification when slurry was incorporated.

Matilla and Joki-Tokola, 2003, open-slot injection and trailing hose

Injection of pig slurry reduced NH_3 emissions almost completely, but TH reduced emissions only on the day of application but not overall. Only average results across years were presented. This approach is probably reasonable, since measurements were made by the JTI (dynamic chamber) method.

Huijsmans et al., 2003, several application techniques to tillage land

Huijsmans et al. (2003) reviewed the results of 25 field experiments carried out in the Netherlands, comprising 58 plots, on arable land. The experiments covered the period March to September only: in some countries manures may be spread outside that period. Ten different application techniques were reviewed, and were place into three groups: surface; placement (ploughing and injection); surface incorporation (incomplete incorporation).

The weighted means, expressed as total cumulative volatilization, were 68% for surface spreading, 17% for incorporation and 2% for placement.

Volatilization increased with TAN content and manure application rate (but not as a % of TAN applied). Increasing the mean wind speed from 2 to 5 ms^{-1} resulted on average in an 65% increase in total volatilization for surface spreading and 74% for surface incorporation, and in 5% decrease in total volatilization for deep placement. In contrast, increasing the mean ambient temperature from 10°C to 20°C resulted in increases in total volatilization of on average 54%, 73% and 84% for surface spreading, surface incorporation and deep placement, respectively.

It may be inferred from these results that application by injection or immediate incorporation in the winter period when temperatures are lower, would enhance the effectiveness of these approaches, albeit the baseline, unabated, emissions would also be less.

Details of injector design not given, apparently one type of machine was used for all experiments.

Hansen et al., 2003, comparison of different types of injection machines with trailing hose

The objective of this work was to assess the NH_3 abatement potential of different injection techniques, in particular with respect to injection depth and slot volume. Injection efficiency was measured as injection depth and slot volume, the latter measured using plaster casts. Additional energy demand was estimated in 1999. Comparison was with slurry applied by TH rather than overall surface application. The authors make the point that when slurry is applied by TH to grassland, unlike cereals, the crop does not provide shade or reduce wind speed. Presentation of results was by graph, so it is difficult to assess precise impact of injection in relation to TH. Ammonia abatement potential was reported to increase with increasing volume of slots, accounting for 88% of the variance in NH_3 emissions. Injection depth was reported to be the main factor in increasing slot volume. An injection depth of > 5 cm was considered necessary to ensure full injection of 30 m^3 slurry.

Hansen et al. (2003) also made an estimate, based on the additional draught required for injection, of the impact of injection on CO_2 emissions. The estimate was an additional 0.3-0.7% to the current estimate of CO_2 emissions from agricultural field work.

Thompson and Meisinger, 2002, incorporation of slurry by mouldboard and chisel plough and by disc harrow

Experiments included immediate incorporation of dairy slurry with different implements. In one of the three experiments emissions from unincorporated slurry may have been underestimated, hence underestimating the abatement from the incorporation treatments. In the other two experiments NH_3-N emissions were reduced by 90, 83 and 99% by immediate incorporation by disc harrow, chisel plough and mouldboard plough respectively. Abatement measured from disc harrow and mouldboard plough were not significantly different but were significantly greater than from chisel plough.

Wulf et al. 2002, injection

Injector, custom-made, tractor drawn, 10 cm, 30 cm spacing. Ammonia emissions were reduced by 75 and 65% following injection to arable and grassland respectively. Emissions of N_2O were approximately doubled on arable land by injection and increased by around *3 on grassland. Measurements of N_2O emissions were made for 6 weeks.

Rodhe and Rammer, 2002, open-slot and pressurized injection and trailing hose

This study also looked at the ensilability of the crop, and made measurements of grass contamination by the slurry. An economic evaluation was carried out.

Pressurized injection left the greatest amounts of slurry on the crop surface (23%) and OSI with V-shaped disc coulters the least (14%).

Grass yields were measured. In year 1 yields were limited by dry conditions, there was much variability and no significant difference between treatments and the unmanured control was reported. In year 2 TH and the two slot injection approaches gave greater yields than the unmanured control or pressurized injection treatments.

The economic simulations showed that, under the set options, it was less profitable to use shallow injection compared with broadcast spreading or TH. The least cost method (broadcast spreading) was the most economically advantageous up to 7000 m^3 of slurry handled per year. When handling larger amount of slurry, TH was more profitable than broadcasting.

Application before the second silage cut in summer was more profitable than spreading before the first cut in spring. The revenues from utilizing the N and the costs of soil compaction depended very much on the time of spreading. For broadcast and TH the revenues from utilizing N, and the variable costs for soil compaction, were less when spreading in the summer compared with the spring. The cost of soil compaction using a 6 m injector was twice that of broadcast and TH with 12 m working widths, with the same size of tanker and wheel equipment. At the same time, greater revenues from N utilization were achieved with the injector compared with the other two methods. Both the fixed and variable cost for the injector were greater than the corresponding values for the broadcast spreader and the TH. The high variable cost was due to the injector's rather small working width, which resulted in greater costs of spreading and soil compaction. Total fixed and variable costs of slurry handling, including transport and costs of soil compaction, were cited at (€/t) 4.05, 5.10 and 6.76 for surface, TH and OSI application respectively.

Misselbrook et al. (2002), open-slot injection, trailing hose, trailing shoe
This study reported a large number of mainly pair-wise comparisons between surface broadcast and either TH, TS or OSI. Overall average reductions (with the number of experiments in brackets) are given in Appendix 1. On arable land efficiencies for both TS and OSI were substantially less than on grassland. The authors suggested that the poor performance of OSl on arable land may have been a consequence of the applications being made to cereal stubble and the build-up, under some conditions, of stubble trash in front of the injection tines. Regression on grass height explained 47% of the variance in NH_3 abatement from use of the TS on grass. The technique was ineffective (0% reduction) when slurry was applied at 40 m^3 ha^{-1} to a recently grazed sward.

Huijsmans et al., 2001, open-slot injection and trailing hose
Huijsmans et al. (2001) reviewed the results of 45 field experiments, carried out in the Netherlands, comprising 110 plots, on grassland. Surface application by splash plate, band spreading by TH and injection by open-slot machines up to 5 cm depth. Application rates were moderate, 14 m^3 for surface and TH, 22 m^3 for injection.

Measurements were by micrometeorological mass balance. Statistical analysis indicated that 50% of the variation in emissions was due to application technique. Abatement efficacy appeared independent of soil type but abatement using the TH increased with increasing grass height. Emissions, as kg NH_3-N ha^{-1}, increased from all application techniques as the amount of slurry applied increased, by the least following injection and by the most for surface application.

Rahman et al., 2001
One study was carried out using a soil bin and the other was a field study. Ammonia concentrations were measured, but not fluxes. Crop yields were reported. Neither injection rate nor manure application rate affected forage yields. But the greatest amount of slurry, injected to the greatest depth, did significantly increase yield. The authors reported that 'It is apparent that the tillage action of the injection tools caused some yield reduction. However, application of manure at the greater injection depth and the highest rate seemed to balance out the yield losses.'.

Sommer and Olesen, 2000, model of emissions following trailing hose application
Slurry was applied by TH to cereal crops or bare soil from March to early June on order to collect data to validate a model of NH_3 emissions. Increasing wind speed increased NH_3 emissions over the first two measurement periods, but not overall, while increasing solar radiation and rainfall increased and decreased overall emissions respectively. The greatest correlation (R^2 75% overall $P<0.001$) was with relative surface water content, drier soils increasing the rate of slurry infiltration.

There was a doubling of the NH_3 volatilization rate from April to May and from May to June. The volatilization rate for an application at noon was *2 that of an application in the morning or evening, confirming earlier findings that applying slurry in the evening may reduce NH_3 volatilization. Application of slurry in a 60 cm high crop causes a reduction of about 75% in volatilization compared with application of slurry to a fallow soil also confirming earlier findings.

Ferm et al., 1999
Greater emissions were reported from the experiment in which slurry was applied in warm, dry weather than at the site at which slurry was applied to a moist soil. Over the six sites at which NH_3 measurements were made, emission reduction when TH was compared with broadcasting ranged from –11 to 96%, average 21%.

At the two sites where N_2O emissions were measured following application by TH, direct N_2O emissions were greater when slurry was applied by TH than when broadcast. After taking account of indirect emissions of N_2O following deposition of NH_3, the difference between treatments decreased, but was still greater following TH.

Malgeryd (1998), open-slot injection, trailing shoe and trailing hose
This paper reports a comparison of NH_3 emissions following application of pig slurry to a barley crop by means of TH, TS, and OSI with emissions following surface broadcasting. However, the TS applicator is described as ‘trenching with sliding foot’ and hence suggests that the TS placed the slurry under the soil. If this is so it may explain why it produced abatement similar to that of the OSI (90%). The TH reduced NH_3 emissions by 40% when applied to a growing cereal crop but not when applied to bare soil. Harrowing 4 h after broadcast application of cattle slurry reduced NH_3 emissions by 60% and from cattle FYM by 90%.

Dosch and Gutser, 1996, injection and trailing shoe
Ammonia and total denitrification measurements were not carried out in the same experiments.

The authors also measured CO_2 emissions and reported that these, produced by microbial respiration which also lead to O_2 consumption in a confined area, increased denitrification. However, in spite of this enhanced CO_2 evolution, the denitrification rate was relatively slow immediately after injection. This was attributed to denitrification being limited by the amount of NO_3-N in the soil, which will be small in the immediate aftermath of slurry application. Later, following nitrification of the NH_4-N added in the slurry the denitrification rate will be limited by metabolizable-C. After 3-4 weeks, metabolizable-C was reported to be oxidised and hence despite the availability of NO_3-N denitrification was limited. This may account for the differences in the impacts of rapid incorporation on N_2O emissions noted between slurry and FYM. Slurry supplies metabolizable-C which can be used as a substrate for nitrification and denitrification leading to an immediate increase in emissions of N_2O. Concentrations of metabolizable-C in litter-based manures are smaller, often as a result of leaching of soluble-C during manure storage, and hence additions of these manures provide less stimulus to microbial activity than additions of slurries.

Rubæk et al., 1996
Two experiments were carried out comparing emissions of NH_3 and total denitrification following the application of cattle slurry and the digestate from a centralized anaerobic digestion plant by TH or open-slot injection. Injection reduced NH_3 emissions by *c.* 65% compared with TH. In the first year injection increased total denitrification by an order of magnitude, in the second year there was no difference in total denitrification between treatments. Denitrification was measured for 21 days.

Pain et al. (1991)
These results were not included in the review of Huijsmans et al. (2003). Wind tunnel experiments were carried out on sand and clay soils, of incorporation of pig slurry by plough, rotovator or tines. Incorporation techniques tested were varied according to soil type. Ploughing was to 15 cm on the clay soil but to 30 cm on the sandy soil. A rigid tine cultivator was used on the clay soil and a spring tine with lightweight roller on the sandy soil. A rotary harrow was used on the clay soil and a rotovator on the sandy soil. Incorporation immediately after application or after intervals of 3 and 6 h was assessed for all methods of incorporation.

Three series of experiments were carried out, 2 on the clay soil, one on the sandy soil. On one of the series on the clay soil measurements were made using a micrometeorological method, in the other 2 series measurements were made using wind tunnels. The absolute abatement measured differed by *c.* 10% between the two measurement techniques, but there did not appear to be a significant bias. The trend of results was the same from both measurement techniques, and on both soil types. Immediate incorporation by plough was almost the most effective technique, always reducing NH_3 emissions by at least 90%. Delaying incorporation by plough by 3 or 6 h reduced the abatement efficiency for all techniques, to *c.* 60% for plough.

Estimation of mean abatement
Clearly the estimation of a single mean abatement efficiency is misleading as abatement will depend on several factors, not just the broad type of machine. However, for guidance purposes when preparing national inventories of NH_3, or proposals to reduce emissions of NH_3 at the national scale, an indication of the likely mean abatement may be needed, and this can be combined with the range of reported abatement and some guidance on factors that particularly influence the abatement achieved. Table 1 below presents the mean results of the studies reported above and below is a brief summary of the factors reported to most influence abatement.

Two means are reported, an overall arithmetic mean and a mean weighted by the number of experiments carried out or reported by each author. The number of reported studies is probably not large enough to justify a median abatement estimate. While a weighted mean seems the most appropriate way of estimating the overall mean, it does raise some questions, for example the results of Sommer and Olesen (2002) for the TH report both the greatest abatement and the largest number of experiments. While Misselbrook et al. (2002) report by far the smallest abatement efficiency for open-slot injection on arable land, but their result is the mean of 5 experiments while the other four studies were based on one experiment each.

Table 1. Summary of results of experiments to measure the abatement efficiency of reduced-emission slurry spreading machinery, % reduction in NH_3 emissions compared with broadcasting to surface. The range is the range of the means reported in each paper.

Machine	Cropping	Papers	Experiments	Mean % reduction		Range (%)
				Overall	Weighted	
Slot Injec.	Grass	5	56	80	86	60-99
	Tillage	5	9	70	49	23-94
Deep Injec	Tillage	2	5	95	97	95-99
Trail shoe	Grass	2	37	64	65	57-70
Trail shoe	Tillage	2	2	64	64	38-90*
Trail hose	Grass	5	45	35	41	0-74
Trail hose	Tillage	7	16	37	48	0-75

*this result was obtained from a machine that placed the slurry within the soil

For the OSI and the TH the results on grassland appear more consistent (when looking at the range) than on tillage. Results from use of the TH were very variable in both cases. The substantial increase in the mean abatement for TH on tillage land is a consequence of the weighting given to the results of Sommer and Olesen (2000). This may not be entirely appropriate as the result sited was for application to a cereal canopy of 60 cm, which might be considered an optimum approach. We conclude that the most reasonable guidance to the abatement efficiency of these machines is given by the unweighted mean. However, the greater abatement that may be achieved using the TH when cereal crops are at the stem erect stage is considered later when making suggestions for the most appropriate machine under a range of circumstances.

There were three datasets which reported results for all three types of machine. These data were subject to simple one-way anova. The results are presented below.

Table 2. Results of one-way anova of the three datasets reporting abatement efficiencies for all three types of machine.

Machine	Mean % reduction	SD	P
Slot Injec.	77	21.7	0.015
Trail shoe	72	17.1	0.015
Trail hose	26	5.1	0.015

Since only three studies could be evaluated in this way it was not possible to discriminate between arable and grass. A one-way Anova was carried out on all the data. Again, the difference in average efficiency was significantly different among machines (P = 0.003). Means for OSI and TS were 80 and 72% respectively, similar to those cited in table 2 above. The mean for TH, at 36% was somewhat greater.

While statistical analysis may hardly seem appropriate for data of this type the results of the Anovas, together with scrutiny of the means in table 1 do suggest some clear conclusions:

- On grassland OSI and TS are much more effective than TH, and OSI and TH appear to produce reasonably reliable abatement.

- On tillage land OSI is on average less effective than on grass and, if the weighted means are used, not necessarily more effective than TH.

Some studies of OSI (Rodhe and Etana, 2005; Hansen et al., 2003; Rubaek et al., 1996) did not include a comparison with NH_3 emissions following application by broadcasting. Instead the comparison was with surface application by TH. Based on the results presented in table 2, in such studies OSI would be expected to reduce emissions of NH_3 by *c*. 70%. In fact only the study of Rubaek et al. (1996) did so, OSI reducing NH_3 emissions by an average of 66% compared with emissions from TH. Rodhe and Etana (2005) studied pressurised injection and OSI to *c*. 2 or 4.5 cm depth. There were no differences in NH_3 emissions between OSI to *c*. 2 cm and TH and pressurised injection only reduced NH_3 emissions by *c*. 10% compared with TH. Injection to *c*. 4.5 cm reduced NH_3 emissions by *c*. 50% compared with TH, illustrating the importance of depth of injection. Emissions following application by TH averaged 74% of TAN over the three years of the study, so the lack of advantage of OSI to 2.5 cm and pressurised injection appear to be due to those machines performing poorly, rather than because the TH appeared to be particularly effective. The results of Hansen et al. (2003) also showed less than expected advantages of a range of OSI over TH, the abatement being on *c*. 30-40% of emissions from TH. Differences among treatments were smaller in year 1 when NH_3 emissions from TH were only 17% of TAN.

Based on these assessments it seems reasonable to conclude that OSI and TS offer similar potentials for NH_3 abatement on grassland. While the average abatement reported for OSI tends than for TS there does not appear to be any compelling reason to recommend the use of one in preference to the other. However, the mean effectiveness of the TH in reducing NH_3 emissions appears to be consistently, even significantly, much less effective than OSI or TS.

Below is a summary of the proposed explanations for the variation in results obtained.

Factors affecting abatement efficiencies

Trailing hose

Sommer et al. (1997) concluded efficiency of TH to cereal crops increased with increasing crop height and density. An algorithm was subsequently developed which predicted that for slurry applications to cereal crops, the abatement efficiency would increase by slightly less than 1% for every 1 cm increase in crop height. For slurry application to grassland, the abatement efficiency was predicted to increase by *c*. 5% for every 1 cm increase in sward height (Thorman et al., 2008). Malgeryd (1998) also found that TH reduced NH_3 losses when applied to a growing crop but not when applied to a bare soil, although Misselbrook et al. (2002) did measure reductions from TH-spread slurry applied to cereal stubbles. Sommer et al. (1997) also found TH to be less efficient on a wet soil when infiltration was reduced (but see below). Sommer and Olesen concluded the greatest correlation with the efficacy of abatement by TH was with slurry infiltration and this may explain why Misselbrook et al. (2002) measured a reduction in emissions following application by TH to stubbles, infiltration may have been easier in a dry soil.

Dutch studies (Mulder and Huijsmans 1994) showed abatement efficiency to increase with increasing height of the grass sward, but to decrease with increasing application rate. Results were examined to see if any trends in abatement efficiency could be seen in respect of time of year of application. No consistent differences were seen for grassland. Other factors such as grass height, soil moisture status and application rate, none of which would be consistently related to the time of year, are likely to be the cause of variation in results. While within series of experiments the effectiveness of TH could be quite well related to crop height, average efficiencies from application to cereal stubbles by Mulder and Huijsmans (1994) and Misselbrook et al. (2002) at 32% were not much less than the average efficiency of applications to a growing crop (39%). If an increase in 1 cm in crop height only increases abatement by 1% (Thorman et al., 2008), then this small difference is to be expected.

Experience of the Danish Advisory Centre and of farmers is that the effectiveness of the TH for reducing emissions is much less for cattle slurry than for pig slurry (Hutchings pers. comm.). This might be because cattle slurry is more glutinous and fibrous, and the plant canopy is often fairly short and dense. This combination can mean that the strip of slurry ends up perched on top of the plant canopy i.e. exposed to the atmosphere but not in contact with the soil. Examination of published results does not indicate any trend among published papers to suggest consistently better results were obtained with pig than with cattle slurry, although often studies used either cattle or pig slurry but not both and hence slurry type will be confounded with other variables. Huijsmans et al. (2001) report by far the largest number of experiments and applied both cattle and pig slurry by TH. Mean abatement from cattle slurry was 61% (18 experiments) while mean abatement for pig slurry was 67% (5 experiments). The reported ranges were similar at 36-84% and 35-90% for cattle and pig slurry respectively. This similarity may arise because in the Nl pig slurry is often applied at DM of *c.* 10%, greater than the DM of cattle slurry in that country. In some other countries at least (e.g. UK) pig slurry is usually of a lesser DM than cattle slurry. Hence although not apparently confirmed by published data, a greater effectiveness of the TH for more dilute and less viscous slurries appears likely.

Trailing Shoe

Misselbrook et al. (2002) found regression on grass height explained 47% of the variance in NH_3 abatement. The technique was ineffective (0% reduction) when slurry was applied at 40 m^3 ha^{-1} to a recently grazed sward. Mulder and Huijsmans (1994) found the TS to be less effective when slurry was applied at 16 m^3 ha^{-1} than when it was applied at 8 m^3 ha^{-1}. This was attributed to more soiling of grass at the greater application rate. They also considered long grass to increase the effectiveness of the technique. There is perhaps a potential conflict here since, in the UK at least, farmers like to apply slurry to fairly short aftermaths soon after cutting to maximise the interval before the next silage cut in order to reduce the risk of silage taint. However, such small applications may not be practical for commercial farms, and are not possible with some commercial machines (S. Bittman, pers. comm.).

The TS appeared to work less well in February and March than between May and December in the study of Misselbrook et al. (2002), but Mulder and Huijsmans' (1994) results over the same period show no differences in efficiency.

Shallow Open-slot Injection

On average OSI reduced NH_3 losses by 70% or more, but the UK studies produced smaller average efficiencies. Pain and Misselbrook (1997) found rainfall after application reduced the effectiveness of shallow injection. However, treatments were applied at similar times of the year in most studies and there is no obvious explanation for the lesser efficiency measured in the UK. The results of Mulder and Huijsmans (1994) and Misselbrook et al. (2002) showed no difference according to season. The smaller average efficiencies measured by Pain and Misselbrook (1997) were not due to applications being made at different times of year to the other studies.

To be effective in both reducing emissions of NH_3 and increasing the availability of slurry-N, injection needs to be to a depth of at least 5 cm and the space between injector tines should be no more than 30 cm.

Ammonia abatement potential has been reported to increase with increasing volume of slots, accounting for 88% of the variance in NH_3 emissions. Injection depth was reported to be the main factor in increasing slot volume. An injection depth of > 5 cm was considered necessary to ensure full injection of 30 m^3 slurry.

Some studies reported sward damage and subsequent yield loss from injection. However, effective injection appeared to be able to compensate for these losses, apparently by increasing N supply.

Solid manure incorporation

Mkhabela et al., 2008

This paper reports work which was not a study of incorporation *per se*, rather a comparison of conventional and zero tillage. Manures were incorporated, 'soon after spreading', but the interval between spreading and incorporation was not cited. Nevertheless, this is a useful study as emissions of N_2O were also measured for a full year after FYM application, and for two months after slurry was applied. Hence data are available on the effects of incorporation on emissions of both NH_3 and N_2O.

Incorporating manure reduced emissions of both NH_3 and N_2O, although there were no control plots to measure background emissions of N_2O. Greater denitrification and N_2O production under NT was considered to be in part due to the presence of greater amounts of available-C under NT and greater aeration under CT created by tillage.

Webb et al., 2006

In four field experiments, on light sandy or heavy clay soils, cattle and pig FYM, layer manure and broiler manure were immediately incorporated by plough, disc or tine in 4 replicates of each treatment. Emissions of NH_3 were measured using wind tunnels. On average immediate incorporation by plough gave the greatest reduction in NH_3 emissions for all manures and at both sites, with an overall average reduction of 95%. Abatement obtained by discs and tine were smaller, on average 60%, but variable and there were no consistent trends among manures or between sites. It had been expected that discs would be more effective than tines and the latter would be more effective at incorporating the poultry manures than the FYM. However, in both experiments on the sandy soil (one winter, one autumn) the soil was dry and the disc was not very effective in breaking into the hard soil. The soil at the clay site was moist in late summer as well as in spring and the disc was more effective.

Webb et al., 2004

Immediate incorporation by plough of pig FYM reduced emissions of NH_3 by an average of 92% in two experiments. There were also two experiments in which cattle FYM was incorporated within 4 h. This reduced NH_3 emissions by 43%, compared with a reduction of 65% from incorporating pig FYM within 4 h.

Emissions of N_2O in the two months following application and incorporation of pig FYM were small at *c*. 0.01% of the N applied and there were no differences between treatments. Emissions of N_2O were larger following application and incorporation of cattle FYM were larger, up to 0.3% of applied N and were significantly less when manure was incorporated.

Rohde and Karlsson, 2002

Compared NH_3-N emissions from broiler manure left on the soil surface or incorporated after 4h by harrow.

Table 3. Summary of results of experiments to measure the abatement efficiency of incorporating manures, % reduction in NH_3 emissions compared with broadcasting to surface. The range is the range of the means reported in each paper.

Machine	Manure	Papers	Experiments	Mean	Weighted mean	Range
Plough	Slurry	3	8	92	94	78-99
Disc	Slurry	2	12	80	74	69-90
Tine	Slurry	1	12	66	68	
Harrow	Slurry	2	3	68	69	60-69
Plough	FYM	3	9	91	92	86-95
Disc	FYM	1	5	63		
Tine	FYM	1	5	57		
Harrow	FYM	1	1	90		

Practicalities of field-scale application

Some estimates of the abatement potential of reduced-emission manure spreading techniques have been carried out on small plots and with small-scale experimental equipment, e.g the small-plot applicator used by Smith et al. (2000). In an earlier review, Webb et al. (2008) discriminated between results obtained by such equipment or using commercial machines on small plots and results obtained using commercial machines at the field scale but did not find any substantial differences in the mean abatement estimates reported.

When considering abatement by incorporation the work rates of different machines also needs to be taken into account. Huijsmans et al. (1999), using a modelling approach (CESAR), concluded that although incorporation of slurry by plough gave much greater reduction in NH_3 emissions than incorporation by other means at the plot scale, at the field scale the much greater work rate of machines such as tines could lead to more rapid completion of incorporation across the field and greater reduction in emissions from the whole field. However, using a very similar modelling approach for solid manures (MAVIS), Webb et al. (2006) found that the rate of incorporation by disc or tine was not fast enough to produce greater reductions in NH_3 emissions than incorporation by plough regardless of the size of the field or the approach to application and incorporation. The different model outputs arose largely because of differences in the machinery work rates used in the models.

The question of machinery work rate also needs to be taken into account when extrapolating experimental results to national strategies to reduce emissions of NH_3. It may be that in an experiment, even using commercial machinery at the field scale, the tractor is driven at only moderate speeds and the guidelines for using machinery are followed diligently. This may not be so in commercial practice, especially if the machines are operated by contractors who are paid by the area spread and eager to maximise their income. A demonstration of the use of an open-slot injector witnessed by two of the authors in the Netherlands seemed to be conducted at a speed greater than was appropriate for maximum effectiveness. Published papers do not usually describe the work rate or approach to application used by the operators. In the studies reported by Webb et al. (2006), although conducted on plots (in order to provide adequate replication for the 16 treatments), incorporation was carried out by full-scale equipment with the operator instructed to behave normally. We concluded that the results gave a good simulation of commercial practice, and this may be one reason why the non-inversion incorporation techniques were consistently inferior to ploughing in reducing emissions of NH_3. However, the corollary is that the results can be applied fairly confidently to commercial practice.

When recommending measures to reduce emissions of NH_3, there is a need to not only take account of work rate as well as measured abatement efficiency but, for incorporation, the need to evaluate the time interval between incorporation and spreading. Since incorporation immediately after spreading is often considered impractical, measures such as incorporation within 6 h or even 'within the same day' have been proposed as more practical alternatives. However, for cattle and pig manures, so much of the NH_3 is emitted in the first 6 h after application, *c*. 80% of the unabated total (from Huijsmans et al., 2003), that even a fairly short delay will negate most of the potential benefit. Wulf et al. (2002a) concluded that 'the exponential decrease of emission rates implied that most of these losses can be assigned to emissions within 1 to 2 h after application'. We therefore conclude that, if farmers are to be put to the potential expense and inconvenience of adopting reduced-emission manure spreading techniques, they should be required to adopt those that have been demonstrated to reduce emissions by at least 60%, rather than propose compromise approaches that have only small impacts (but nevertheless require a change of practice and incur additional costs). Responses following circulation of earlier drafts are in agreement. It is feasible to plough immediately after spreading using contractors. S Bittman (pers. comm.) cited a local farmer who has done so on maize land for several years.

Conclusions and recommendations

Effectiveness and choice of machine

Average abatement of NH_3 emissions is greater from the use of TS (65%) and OSI (70-80%) machines than from TH (30-50%).

There is considerable variation in the efficiencies reported, especially for TH (0-75%) but also OSI (23-99%), in particular when OSI is used on arable land. Variation in emissions following the use of the TS appeared to be somewhat less (38-70%), although this may be due to there being fewer studies reported of the TS.

When manures are applied to arable land emissions of NH_3 can be reduced by at least 90% if incorporation by plough takes place immediately after application. A delay of as little as 4 h can reduce the abatement efficiency to between only 45 and 65%. Immediate incorporation using non-inversion cultivators can reduce NH_3 emissions following the application of slurry by *c*. 70% and following solid manures by *c*. 60%.

We propose the following guidelines for reducing NH_3 emissions following manure application. These suggestions are primarily aimed toward farmers buying their own machines and hence aim to suggest the most appropriate machine. If, as seems likely, most farmers would make use of reduced-emission spreading equipment by using a contractor then, over a season, spreading may be carried out by more than one type of machine.

Grassland

Given the difference in efficacy of OSI and TS is only moderate it appears reasonable to recommend both machines for use on grassland leaving the choice to be made on the basis of cost, other operational considerations or local conditions. The lesser abatement efficiency of the TS machine may be compensated by observations that it offers the greatest potential for contamination-free application in pastures with taller herbage (Laws and Pain, 2002; Laws et al., 2002; Lalor and Schulte, 2008).

Factors to be taken into account in deciding which machine to use on grassland would include:

- Is grass the only crop to which slurry is to be applied? If so this might lead farmers to chose TS if there are cost advantages over OSI. If other crops are grown and slurry is to be applied to stubble in spring then an OSI might be preferred because of the potentially greater abatement efficiency and hence greater N recovery by the crop.

- How many silage cuts are taken and how frequently? For an intensive cutting regime, e.g. in some parts of England summer rainfall is sufficient to allow four cuts of silage. This may mean that it is not possible to allow enough time for aftermath re-growth before application by TH if slurry taint is to be avoided, in which case OSI may be preferred.

The TH machine is much less effective at reducing emissions of NH_3 and does not appear an appropriate choice for an all-grass farm. However, for a mixed farm on which a TH machine is already in use to apply slurry to growing crops in Spring, then the use of the TH to apply slurry to grassland would seem appropriate (see below).

These suggestions have been confirmed by farmer feedback that shallow injectors are popular for use on grassland unless conditions are such that there is poor soil penetration (esp. very heavy or stony soils) or soils are too wet.

Arable

Where manures are applied to tillage land immediate incorporation by plough is the most effective option. And incorporation by cultivation can be used for liquid and solid/litter-based manures. Immediate incorporation can be carried out with existing machinery, and hence does not require additional cost, although costs may be incurred either through the need to employ contractors to enable spreading and incorporation to be carried out simultaneously or due to lost opportunity costs if farm staff are used who could have been employed on other, time-critical, tasks such as drilling.

The limitation to immediate incorporation is that in areas where the majority of tillage land is autumn-sown, and where there is excess winter rainfall, the N conserved by reducing emissions of NH_3 is likely to be lost by nitrate leaching (Webb et al., 2001). In order to overcome this limitation two alternatives are possible.

- Injection machines are can be used in the presence of a growing arable crop in late winter or early spring.

- Application by TH to growing crops in Spring.

In both cases the reduction in NH_3 emissions will still be less than from immediate incorporation, but much more of the N conserved will be available for crop uptake.

Other approaches to reducing emissions of ammonia following manure application – 'soft' measures

Mkhabela et al., 2009, dilution and application rate

Emissions of NH_3 and N_2O, were measured to quantify the impacts of very large pig slurry application rates (60-180 m^3 ha^{-1}) and slurry dilution. The experiments were carried out on impermeable to very impermeable soils.

In all but one experiment NH_3 emissions, as % TAN applied, decreased with increasing slurry application rate. This was attributed to drying and crusting 'protecting' slurry enabling a greater infiltration rate, although the reduced surface area to volume ratio would also seem a likely explanation. In 6 of the 8 experiments emissions of N_2O, expressed as % of N applied, also decreased with increasing amount of slurry applied, albeit emissions were only measured for 21 days.

In this experiment similar amounts of N were applied in the diluted and undiluted slurries, so results are directly comparable. This is not always the case with dilution studies as often emissions from similar volumes are compared. Dilution (25, 50 or 100%) reduced NH_3 emissions in 3 of the 6 experiments but did not have any significant impact on emissions of N_2O. Of the 3 experiments in which emissions of NH_3 were significantly reduced by dilution, in only one was there a large (albeit non-significant) difference in emissions of N_2O. In this one experiment the greater emission of N_2O was from undiluted slurry.

Correlations were made with weather conditions which confirmed that NH_3 emissions may be reduced by application under cool conditions, although no correlation with windspeed was reported.

These results also demonstrated a reduction in NH_3 emissions when rainfall following application was simulated. Again, there was no significant impact on emissions of N_2O.

Although this study did not investigate reduced-emission machinery, and hence the results are not so directly relevant to this review, the results do not suggest any inverse relationship between emissions of NH_3 and N_2O. Rather, in these experiments, emissions of the two gases were in tandem. The authors also make the point that emissions of NH_3 ultimately give rise to indirect emissions of N_2O and that the balance between direct and indirect emissions of N_2O must be taken into account when assessing the impact of NH_3 abatement on emissions of N_2O.

Smith et al., 2008, dilution and application rate

Pig manure, either as slurry or solid, was applied by bucket. The objectives were to investigate the effects of manure type, application rate and rainfall before and after application on emissions of NH_3 and N_2O. Rates were 30, 60 and 180 m^3 ha^{-1}. In keeping with most inventories NH_3 emissions were greater from solid than from slurry, but emissions of N_2O were greater in only one experiment when emissions from slurry were greater.

There were no consistent impacts of application rate on emissions of NH_3 expressed as %TAN. The authors reported decreasing proportions of TAN lost as NH_3. Nor were there any impacts on emissions of N_2O. Rainfall before application increased emissions of NH_3, probably due to reduced infiltration. Rainfall after application reduced NH_3 emissions but increased emissions of N_2O in 2 of the 4 experiments. The authors concluded that any trade-off of N_2O emissions from reducing those of NH_3 was not significant,

Switzerland

Reidy and Menzi (2007)

Table 4. Organisational measures for reducing emissions of NH3 following the application of manures to land (from Reidy and Menzi, 2007)

Measure	Potential abatement %	Mode of reduction
Spread under favourable weather conditions	10	Avoid spreading in hot, dry and windy weather
Spread in evenings	*10/**25	
Spread before/during rainfall	*40/**40	
Spread in favourable season	20	

* slurry

** FYM

'Favourable weather conditions for spreading were considered to be a temperature of 12C and RH of 75% compared with average conditions (for CH) of 15 °C and 60% RH.

Spread under favourable weather conditions

Reidy and Menzi (2007) considered that 50% of slurry was applied in cool seasons, However, for the UK the proportions applied in cool seasons appears to be much greater. In the UK NH_3 inventory the proportions of manures applied in 'summer' (Table 5 below) range from 18% of pig slurry applied to grassland to just 2% of beef slurry applied to arable land. However, these data may be somewhat misleading as the term 'summer' refers to the months of May, June and July, and do not include August.

Emissions were considered to be up to 25% less if, during summer, slurry is spread in the evening rather than during the day. Taking into account technical (e.g. available time and equipment) and social limitations (e.g. infringement on a farmer's leisure time, inconvenience for neighbouring populations during the night), the applicability of this measure was estimated at 25%. The applicability under UK conditions is conjectural. Given that the limiting factor on UK farms tends to be labour availability the readiness of farmers to adopt such a practice would depend, to a large extent, on the degree to which labour is provided by family members of by paid or contract staff. For non-family staff the likelihood is that evening work need to be paid at overtime or other premium rates. Family members might be able to carry out such an operation without incurring additional costs, although do so might clash with other activities such as evening milking on dairy farms. It is possible therefore that in practice such a measure, by requiring either additional or premium labour, might incur costs similar to more effective options such as immediate incorporation of manures to arable land. However, on all-grass farms, where incorporation of manures is not an option, spreading in the evening might be attractive as it would not incur the capital cost of buying reduced-emission spreading equipment. There will be other countries where labour availability will be more akin to that in Switzerland than in the UK.

Spread before/during rainfall

The basis for this proposed measure is that if manure, especially slurry, is spread shortly before or during slight rain, emissions are considerably reduced because the ammoniacal fraction of the manure is washed into the soil. Potential abatement of 80% was reported to be possible, although an average abatement of 40% was considered realistic. Reidy and Menzi (2007) acknowledged that the limitation to this measure lies in the limited predictability of the weather and the risk of run-off if the rain proves to be heavier than expected. To be effective, the slurry should be spread no more than 2h before the rain sets in. Again, given the constraints imposed by labour availability on UK farms and the dismal reliability of weather forecasting in the UK, this measure does not seem to offer much scope for adoption. Menzi and Reidy only assigned a maximum applicability of the measure of 10%.

Spread in favourable season

As emissions are in general considered to be greater in summer than in spring and autumn, it would be advisable, from the emission point of view, to minimise the amount of manure spread during summer months. In the UK little manure is applied in summer, the percentages for a range of manures and crops are given below.

Table 5. Proportions of manures that are applied during the summer in the UK

Manure	Land use	% applied
Dairy slurry	Grass	10
	Arable	5
Beef slurry	Grass	13
	Arable	2
Pig slurry	Grass	18
	Arable	10

No breakdown available for summer applications of FYM or poultry manure

However, the definition of summer used (May-July) is somewhat odd, since May is not generally considered to be a summer month. Application of manures in August is likely to be appreciable on arable land as spreading at this time allows incorporation prior to drilling Autumn-sown crops. Hence the above estimates are likely to under-estimate the amounts of manure spread in the hottest months of the year. Nevertheless, given the dominance of autumn-sown crops in the UK and therefore the lack of opportunity for incorporation to arable land between October and August it is difficult to see an alternative to late summer spreading for FYM although poultry manures could be applied to cereal crops in Spring once the have reached the stem erect stage.

Reidy and Menzi (2007) concluded that for CH the maximum combined potential of these measures was 4.1%, while under the realistically feasible scenario a 0.8% reduction might be achieved.

Review of the efficiency of methods to reduce emissions of ammonia following the application of manures to land, their costs, potential agronomic benefits and impacts on emissions of nitrous oxide

Appendix 2, Improved agronomy

Lalor and Schulte, 2008

This work arose in response to the current practice, in Ireland, of applying slurry in summer after herbage has been harvested for silage. This practice arose to reduce the risk of pasture contamination, since in Ireland soils are often too wet for slurry application in spring. Application by splash plate (SP) in spring is confined to pastures with a little herbage mass, but often by the time soil conditions permit damage-free soil trafficking the grass canopy is too large to avoid contamination. This results in applications being postponed until the next available instance of low herbage masses, normally after first-cut silage, when risks of NH_3 loss are greater and the N-fertilizer replacement value is less. By reducing the risk of contamination, reduced-emission methods allow application to pastures with a greater herbage mass, thereby increasing the likelihood of more days when slurry can be spread in the spring when N demand by herbage is greatest, and risk of NH_3 loss is relatively small. *However, it may not be appropriate to extrapolate this reasoning to slurry application in other countries. For example, in the UK the proportions of slurry applied to grassland, currently estimated to be applied in the summer months (defined as May to July in the UK ammonia emissions inventory) are only 10% for dairy slurry, 13% for beef slurry and 18% for pig slurry. In contrast 50% of slurry is considered to be applied in summer in Ireland.*

Reduced-emission application methods (shallow injection (OSI), trailing shoe (TS) and band spreading (BS)) allow more flexible timing of application than the SP method as slurry can be applied to pastures with greater herbage masses by depositing slurry below the herbage canopy, thereby minimizing contamination of herbage (Laws et al., 2002). The TS method was considered to offer the greatest potential for contamination-free application in pastures with taller herbage (Laws and Pain, 2002; Laws et al., 2002), and was assigned the highest threshold.

Model results suggest that TS and OSI could increase the number of days available for spreading by 50% on well-drained soils, and 100% on moderately-drained soils. There was no benefit on poorly-drained soils. The TS increased the number of days on well-drained soils from 3 to 8 and on moderately-drained soils from 0.5 to 6.5. Despite these large relative increases the number of days available was still no more than 8 days out of the 130 investigated.

It also needs to be pointed out that the model output assumes the work-rate of each application method to be equal, and that an available day will result in an equal amount of slurry being applied, irrespective of application method. A decision to adopt a reduced-emission application system on the basis of the number of available days in spring would also need to include comparisons of the work-rate of the different application methods before assuming an advantage in terms of volume of slurry that can be applied in spring. Another consideration is labour availability in the spring so that spreading opportunities in the spring can be maximized.

Nevertheless, even though these results may not be applicable more widely, the conclusion of the authors that '*The relative advantage of the TS method, therefore, is based on the experience that it is the best machine for minimizing sward damage and contamination, and hence retains the highest maximum herbage-mass threshold.*'

is likely to be generally applicable. And given that the mean reported efficiency with which NH_3 emissions are reduced, at *c*. 65%, is not much less than that reported for shallow injection (80%) on grassland, the TS may usually be the most appropriate reduced-emission machine for use on grassland.

Schröder et al. (2007) N recovery

The main objective of this study was to quantify the long-term manurial value of a range of manures. One of the manures, undigested cattle slurry, was applied either to the surface or by injection to between 5 and 7 cm, and it is the results of those treatments which will be mainly considered here. Slurry applications were split over three dates (around April 1, second half of May after first grass cut, second half of June after second grass cut) in a 120 to 100 to 80 ratio, based on N contents to give an average total application of 307 kg N ha^{-1}.

Uptake of N from injected slurry was significantly greater than from surface-applied slurry in only 1 of the 4 years by 18 kg ha^{-1}. There were non-significant increases in the other 3 years (19 and 41 kg ha^{-1}). Ammonia emissions were not measured. However, if a typical emission of 60% of TAN from surface application is assumed ('summer' rate), together with an abatement efficiency of 80% from injection to 5-7 cm, then, from an average application of 307 kg N ha^{-1} slurry-N, of which 50% was TAN, the N conserved may be estimated as *c*. 74 kg N ha^{-1}. The average difference in N uptake between surface-applied and injected slurry was *c*. 29 kg, equivalent to a recovery of *c*. 40% of the TAN assumed to have been conserved by injection, somewhat less than the ANR of 67% cited for fertilizer-N in the same study. Such an estimate of apparent TAN recovery is very dependent on the assumptions used. If emissions from broadcast application were only 40% of TAN then the TAN conserved by injection would be less (*c*. 49 kg N ha^{-1}) and the efficiency of uptake somewhat greater at *c*. 60%.

Matilla, 2006

Harrowing took place on same day, except for peat manure in 1991 and 1992 which was incorporated following morning.

In all years apparent recovery of NH_4-N was greater for incorporated than for surface-applied slurry.

Chen et al., 2004 grass yield and sward damage

The sward damage caused by injection, TS and aeration was assessed by means of control plots on which the machines operated without the application of slurry. It seems that no N was applied to these plots. At one site yield was reduced by 35% by injection in July, but there was no significant difference in September. Lack of depth control caused sward damage. There were no yield reductions from injection at the second site, but there was a 40% yield reduction from TS. The increased nutrient efficiency from injection was found to compensate for any loss of yield from the cutting action of the injector. Yield responses from TS, TH and aeration were similar to those found with the injector. The TH was reported to damage the grass sward in one experiment, this was attributed to the feet being too close together (20 cm). An earlier study (Bittman et al., 1999) had reduced the spacing to 11.5 cm to assess the impact of spacing on yield and reported none.

At one site slot injection reduced yield in July, but not in September. At the other site there was no impact of injection, but yield was reduced by the TS.

Mattila et al., 2003 N recovery

Slurries were applied 2-3 days after first cut in late June or early July.

In 1995 injection *reduced* yield. This was attributed to drought that year and wider spacing (47 cm) than in subsequent years (30 cm) reducing availability of the applied N to the grass furthest from where the slurry was injected. Damage to grass sward was also reported, especially on the peat soil.

Injection increased N uptake in all years at the mineral site and in one of the three years at the peat site. There was no increase from TH.

The authors cite previous work reporting that increasing the tine spacing of the injector from 30 to 50 and 60 cm decreased the yield response. In this study the herbage was only slightly darker around the bands and the authors inferred that this confirmed adequate uptake of slurry-N from 30 cm band width.

Schils and Kok (2003), N recovery

Only 80 kg ha^{-1} N was applied each year as slurry, either alone or with 250 kg ha^{-1} N as fertilizer. The slot injection machine was a Vredo.

In 1999 slurry injection significantly ($P < 0.01$) increased grass yield by *c.* 0.45 t ha^{-1} at the greater N application rate and by *c.* 0.61 t ha^{-1} at the lesser N application rate. In 2000 the yield increases from injection were negligible at the greater N application rate and *c.* 0.68 t ha^{-1} at the lesser N application rate. In 2001 slurry injection significantly ($P < 0.01$) increased grass yield by *c.* 0.14 t ha^{-1} at the greater N application rate and by *c.* 0.74 t ha^{-1} at the lesser N application rate.

At both N levels, N offtake (N_{off}) was significantly greater with injection than with surface application. The average increase in N offtake was 23 kg N ha^{-1} year^{-1}, with a range of 18 to 30 kg N ha^{-1} year^{-1}.

Overall apparent N recovery of the N fertilizer was 79%. The mean ANR of surface-applied slurry manure was 30%, while the mean ANR of slot-injected manure was 44%. This greater recovery was a consequence of better recovery of slurry-N applied for the second and subsequent cuts, there was little difference in ANR at first cut.

The positive effect of slot injection was obtained with applications from June onwards. Slurry manure application in March resulted in a similar N utilization for both application techniques. Application method, slurry manure type or additive use had no effect on changes in soil organic matter or soil N content. Longer-term monitoring would be needed to draw firm conclusions. It was reported that neither application method, slurry manure type or additive use affected the botanical composition of the sward.

The application of 80 kg ha^{-1} N in slurries containing on average 3.9% N, of which *c.* 45% was TAN, might be expected to give rise to NH_3-N emissions of between 40 and 60% of the TAN applied or between 14 and 22 kg NH_3-N ha^{-1}. Details of the operating mode of the injector, such as depth to which the slurry was injected, are not given. But, if injection was to > 5 cm, then the reduction in NH_3-N emission may well have been *c.* 80%, hence increasing the amount of slurry-N available to the grass by between 11 and 18 kg ha^{-1}. In this context the measured increases in N offtake from slurry injection were somewhat greater than might be expected, but only by a small amount, and the apparent discrepancy is not great enough to doubt the accuracy of the measurements. Matilla (2006, PhD) concluded that injection and incorporation of manures could increase crop N uptake not only by reducing NH_3 volatilization, but also by introducing manure-N to the soil closer to the roots. This could be particularly important when slurry is injected into soils that have developed a soil moisture deficit (SMD) and hence downward movement of surface applied slurry is constrained. Any effect of placement could be due to improved uptake of manure-P rather than manure-N.

Rodhe and Rammer, 2002, economics

Grass yields were measured. In year 1 yields were limited by dry conditions, there was much variability and no significant difference between treatments and the unmanured control was reported. In year 2 TH and the two slot injection approaches gave greater yields than the controlled of pressurized injection.

The economic simulations showed that, under the set options, it was less profitable to use shallow injection compared with broadcast spreading or TH. The least cost method (broadcast spreading) was the most economically advantageous up to 7000 m^3 of slurry handled per year. When handling larger amount of slurry, TH was more profitable than broadcasting.

Application before the second silage cut in summer was more profitable than spreading before the first cut in spring. The revenues from utilizing the N and the costs of soil compaction depended very much on the time of spreading. For broadcast and TH the revenues from utilizing N, and the variable costs for soil compaction, were less when spreading in the summer compared with the spring. The cost of soil compaction using a 6 m injector was twice that of broadcast and TH with 12 m working widths, with the same size of tanker and wheel equipment. At the same time, greater revenues from N utilization were achieved with the injector compared with the other two methods. Both the fixed and variable cost for the injector were greater than the corresponding values for the broadcast spreader and the TH. The high variable cost was due to the injector's rather small working width, which result in greater costs of spreading and soil compaction. Total fixed and variable costs of slurry handling, including transport and costs of soil compaction, were cited at (€/t) 4.05, 5.10 and 6.76 for surface, TH and OSI application respectively.

Bittman et al., 1999 yield and N uptake

Bittman et al. (1999) make the point that the majority of studies of the effectiveness of TS machines have been carried out under the temperate maritime conditions of NW Europe. Slurry was applied at two target rates, 50 and 100 kg NH_4-N ha^{-1}, and either 2-3 days after grass was cut (early) or 7-10 days after (late), with 4 replicates of each treatment. The data for each year were combined for each of the three seasons of application (Spring, Summer, Autumn).

When 100 kg ha^{-1} fertilizer-N was applied delaying application reduced yield by 0.2-0.3 t ha^{-1}, but not when only 50 kg ha^{-1} fertilizer-N was applied. This was so in all seasons of application. There was no effect on N uptake of delaying fertilizer-N application. Similar effects have been noted in studies of cereals, that delaying fertilizer-N application may not reduce N uptake, but lack of available-N during leaf expansion may reduce leaf area index (LAI) and hence reduce total assimilate. While N may continue to be taken up later, after LAI has reached its maximum, this N taken up later serves only to increase N concentration in the harvested product.

Yields were greater when slurry applied by TS than by SP, and in summer and autumn the early application gave greater yields than the later. When slurry was applied by TS yields appeared to be equivalent to those obtained using fertilizer-N.

While N uptake following early application of slurry by TS appeared to be equivalent to that from fertilizer-N in summer and autumn, only in summer did N uptake from the use of TS appear to be better than from the use of the SP.

Based on the apparent N recovery (ANR) data provided, the TS improved uptake of the TAN applied by between 40 and 90% when slurry was applied soon after grass cutting, but did not always increase N uptake when slurry application was delayed, although there was a large increase from the summer applications.

The authors concluded that the effectiveness of TAN applied by TS was close to that of fertilizer in all nine experiments, whereas in four of nine experiments the SP performed poorly. Farmers require consistent crop response from manure application in order to use it as the prime source of nutrients.

Maidl et al., 1999, yield and N uptake

This paper in German, but with English abstract and table headings. Slurry was applied to supply 50 or 100 kg ha^{-1} N and comparison made with plots given 50 or 100 kg ha^{-1} fertilizer-N. Incorporation was to between 5 and 10 cm and gave non-significant increases in maize yield and N offtake. From applications of 50 and 100 kg TAN ha^{-1}, unabated NH_3 emissions during May might be estimated at 30 and 60 kg N ha^{-1} respectively. Immediate incorporation might be expected to reduce NH_3 emissions by *c*. 95%, hence the N conserved would be *c*. 29 and 57 kg N ha^{-1}. With 50% recovery of the conserved N, increased uptake of *c*. 14 and 28 kg N ha^{-1} respectively. Measured increases were *c*. 24 and 34 kg N ha^{-1} respectively for silage maize.

Rubæk et al., 1996

In 1993 and 1994 application of slurry by injection increased N uptake at the first cut by only *c*. 5 kg ha^{-1} compared with application by TH, albeit this increase was significant ($P < 0.05$). Fertilizer-N recovery from the first cut, from an application of 80 kg ha^{-1} fertilizer-N, was *c*. 44 and 57% in 1993 and 1994 respectively. In contrast apparent TAN recovery in the first cut from slurry application was 13 and 19% from TH and OSI respectively in 1993 and 15 and 20% respectively in 1994.

Laws et al. (2002) silage quality

Three slurry treatments were studied: broadcast; placement; shallow injection (using a purpose-made, small-plot applicator, not commercial machinery). Results may have been affected by wet weather. At both sites, silage fermentation was poor for treatment S, where slurry was applied 2 weeks prior to harvest. The silages made on treatment I where slurry had been applied 2 weeks before harvest, particularly at North Wyke in 1999, also exhibited the characteristics of poor fermentation. The authors reported that disc injection on tall swards flattened and severed the herbage along the lines of the injection slots and the injection process was impeded. In contrast, the passage of TS caused little damage to tall swards and the slurry was deposited below the grass canopy with minimal contamination of herbage.

Laws and Pain, 2002, grazing preference

These authors make the point that contamination of herbage by slurry as a result of broadcast application may lead to grazing livestock avoiding the contaminated grass for some weeks after application. Application was by SP, open-slot shallow injector (5 cm depth) and TS.

No significant differences were reported in Expt 1 but in Expt 2 application of slurry by Injection and TS appeared to leave the sward more palatable to the cattle.

Injection is spring produced no improvement over application by SP. This was attributed to injection into tall swards leading to compression of, and damage to, the sward and to reduction in injection efficiency leading to herbage contamination. The narrower working width (2.5 m, compared with 6 m for TS and 12 m for SP) also caused wheeling damage. "in contrast, TS slurry application caused minimal herbage damage and was the method to which the animals showed least aversion at this time of year".

When slurry was applied to shorter grass, following silage cutting, the cattle responded as well to pastures on which injection was used as to TS, and both were better than surface application.

Earlier papers

Rees et al., 1993

Surface, TH, shallow (5 cm) injection and deep (15 cm) injection were assessed. Yield results were inconsistent, injection reduced yields at the first cut in both years ($P < 0.05$), but not overall in the year when 3 cuts were taken. This was interpreted as a delayed response due to inhibition of root growth either from increased concentration of N or root damage. Rees et al. (2003) Concluded the agronomic benefits from injection were not greater than from surface application.

Other aspects

De Goede et al. (2003) compared earthworm populations from plots on which slurry had been applied by slot injection and by broadcasting. Total earthworm numbers were reported to be greater where slurry was applied by injection ($P < 0.05$). In a farm comparison results were inconsistent. De Goede et al. (2003) cite the results of an earlier study (Kruk, 1994, the only such studied found), who compared 15 peat meadows on which slurry was applied by slit injection with 15 meadows where the manure was applied onto the surface, found no statistically significant differences in earthworm biomass during the first three weeks after application. Overall de Goede et al. (2003) concluded that injection reduced the number of epigeic earthworms. Anecic and endogeic earthworms were not reduced or even increased. This may be due to less direct contact with the injection device and/or the slurry. Where slot injection reduced earthworm numbers, this also reduced the calculated N mineralization by earthworms.

Table 1. Summary of yield and N offtake impacts. Values cited have been estimated for yields of 10 t ha^{-1} and N offtake of 100 kg ha^{-1} from cited % differences. Comparison is with surface application of manure, not with unmanured control

	T hose		T shoe		Injec		Other	
	Yield	N_{off}	Yield	N_{off}	Yield	N_{off}	Yield	N_{off}
Schröder et al 2007, 1,2&4						NS		
Schröder et al 2007, 3						+15		
Matilla, 2006							[1]+2.6	+100
Bittman et al., 2005	NS	NS					[2]NS	+13
Rohde, Etana, 2005	NS	NS			NS	NS		
Schils, Kok, 2003					0.5	+77		
Bittman et al., 1999				+5				

[1] Harrow, in this study the crop was grass

[2] TH following aeration of soil

It is difficult, or perhaps more accurate to say, inappropriate to suggest overall average effects given the lack of significant difference in many studies. The results of Schröder et al. (2007) are typical in this respect in that in one year there were significant increases in N_{off} when slurry was injected and in three years the recorded increases were not significantly different, despite being larger than the one significant increase. So too with the results of Bittman et al., (2005), over an entire season N_{off} was not significantly greater from abatement methods, but there were some significant increases at some cuts from some manure applications. Given the frequent reports of non-significant increases in yield and N offtake it might be argued that the lack of significance is less indicative of a lack of trend and more likely to be due to the difficulties of measuring a small increase against a considerable background variation with respect to manure application rate, manure composition, background fertility and variable weather, i.e additional N uptake is small in comparison with the sensitivity of agronomic experiments. Hence, as an examination of the agronomic value of reduced-emission manure application techniques it is useful to make some calculations of the expected impacts on N_{off} and then consider whether the measured effects on N_{off} are consistent with our expectations.

Hence, if we use an example whereby a slurry is applied at a rate that supplies 100 kg ha^{-1} TAN.

- If surface-applied an average NH_3-N emission would be around 40-60% of TAN, or 40-60 kg N.

- The abatement efficiencies of TH, TS and OSI are taken to be 40, 65 and 80% respectively

- Hence the application of these techniques would reduce NH_3-N emissions from this standard application of slurry by 16-24, 26-39 and 32-48 kg ha^{-1} N respectively

- Given the reported ANR of manure TAN as between 35 and 65% (Bittman et al., 1999; Schröder et al., 2007) an average of 50% seems appropriate

Hence we would expect to find N_{off} in crops to be increased by between 8 and 24 kg ha^{-1}, depending on the abatement technique used.

The increases in N_{off} which were reported as significant tend ranged from 12-77 kg ha^{-1} from an application of 100 kg ha^{-1} TAN. Hence we might conclude that the reason studies have not always reported significant increases in N_{off} following the application of manures using reduced-emission techniques is not due to there being no increase, but rather the increases being too small or too variable to reach significance.

Hence as a working hypothesis we could propose that the adoption of reduced emission spreading techniques will lead to increases in N_{off} *of the size we expect from the amount of manure-TAN applied and the efficiency of the technique employed. Estimates of the financial savings could then be made on the basis of the expected increase in* N_{off}.

Estimation of additional costs of applying manures by reduced-emission spreading techniques

The additional costs of applying slurry by reduced-NH_3 emission spreading techniques were estimated to be £0.52 m^{-3} for all three types of spreader. These additional costs are much less than those previously used in the NARSES model (Webb et al., 2006), which ranged from £1.44 m^{-3} for the TH to £2.84 m^{-3} for OSI. However, this new cost estimate was within the range of actual costs on commercial farms estimated by project WA0710, which ranged from £0.42-£2.11 m^{-3} on farms which adopted reduced-NH_3 emission spreading without covers for slurry stores. A detailed account of the way in which these additional costs were estimated is given in Appendix 1 below. There are several reasons for the differences with the cost estimates used in the NARSES model:

- Assumed work rate. In this study a work rate of 27 m^3 h^{-1} was used which would have diluted the cost per m3 considerably compared with the earlier assumed work rate of 15 m^3 h^{-1}. Tractor running costs per hour would also be diluted based on my increased workrate.
- Longer period of loan repayment in this study of 10 compared with 7 years previously.
- Reduced amortisation rate of 4.5% pa compared with 7.0% pa in the previous study.

The cost estimated here are similar to those reported to be currently charged by contractors in the UK of £0.35 m^{-3}. The results in table 2 below, using data from project WA0710, illustrate how the volume to slurry to be applied each year greatly influences the estimated cost per m^{-3}. In short, greater slurry volumes spread the additional costs across the greater volume hence reducing unit costs. Hence the cost to contractors, per m^3 applied, would be expected to be at the smaller end of the range estimated for individual farmers.

Table 2. Influence of annual slurry volume on unit costs of reduced-NH_3 emission spreading (from Defra project WA0710)

Farm	Spreader type	Slurry volume m^3	Cost £/ m^3
Dairy 3	Joskin trailing hose	16,000	0.52
Pig 3	Joskin Injector	8300	0.42
Dairy 4	Duport Injector	3500	1.05
Dairy 7	Duport Injector	3100	1.05
Pig 4	Joskin arable/grass injector tanker	2200	2.11
Pig 1*	Veenhuis	14,500	0.23
/Dairy 2*	Duport 4.4 m injector	6500	0.06
Dairy 1*	Duport 4.4 m injector	5000	0.06
Pig 2 *	Joskin Injector	4800	2.15
Dairy 5*	Pichon Injector	3000	1.25

*, covered slurry store

Covering slurry stores, to reduce emissions of NH_3, also reduced the volumes of slurry to be spread, hence confounding the impacts of slurry volume on work rate.

For comparison the additional costs estimated in some other EU countries are provided, courtesy of Brigitte Eurich-Menden (KTBL), together with the additional costs actually charged by some UK contractors when they apply slurry by reduced-NH_3 spreading techniques.

Table 3. Estimates of the additional costs of applying manures by reduced-NH_3 spreading techniques, 2009. All costs are in £ m^{-3}. The costs provided by KTBL were converted at 1.1€ /£.

	T hose	T Shoe	Slot Injec	*Imm. Incorp.
UK, March 2009, calculation for this review	0.52	0.52	0.52	0.54
UK, March 2009, actual contractor charges	0.35	0.35	0.35	0.79
KTBL from Germany		2.59	3.50	0.73
KTBL from Italy			1.79	0.00
KTBL from Spain		1.05	1.09	0.48
KTBL from Denmark			0.68	1.30

*This is the estimated maximum additional cost, based on the assumption that immediate incorporation would be an additional operation, that might take place weeks or even months before cultivating the land for drilling, and that subsequent weed growth, soil settling, capping due to rainfall, would mean that incorporating manures to reduce emissions would not reduce the cultivation required to produce a seedbed. The cost is based on the application of 50 m^3 ha^{-1} slurry or 50 t ha^{-1} solid manure

UK contractors appear to charge 20-30% more for application with reduced-emission machines than for SP. Costs for the SP varied between less than £1 to over £2 m^{-3} applied. A reasonable average would be £1.40 m^{-3}. Thus the additional contractor's charge for these machines over SP is estimated to be between £0.28 and £0.42p m^{-3}. The mean of that range (£0.35) was used in table 3. above. Table 3 suggests spreading costs are much less in the UK than elsewhere. However, this impression may be exaggerated due to recent changes in exchange rates. The greater costs from Germany may reflect generally smaller farm sizes and hence smaller volumes of slurry to be spread. Some earlier estimates by KTBL showed that for yearly volumes spread of 3000 m^3 additional costs of TS at £1.45, were only *c*. 40% of the costs for yearly volumes of 1000 m^3.

Table 4. Estimation of the value of slurry-N conserved by reduced-emission slurry applicators using UK estimate only.

	Surface	T hose	T Shoe	Slot Injec	*Other
Slurry volume, m^3	30	30	30	30	50
N applied, kg	150	150	150	150	250
TAN applied, kg	75	75	75	75	125
NH_3 emission %	50	50	50	50	50
% abatement	0	40	65	80	95
N conserved, kg	0	15	24	30	59
Value of extra N available, £ per 30 m^3 slurry (50 m^3 for immediate incorporation)	0	14.1	22.6	28.2	55.8
Value of extra N uptake, £ per m^3 slurry	0	0.47	0.75	0.94	1.12
Additional cost of abatement		0.52	0.52	0.52	0.54
Net cost of abatement		0.05	-0.23	-0.42	-0.58

Based on a price of £325 per t ammonium nitrate on 6 February 2009. This equates to £0.94 per kg N
*immediate incorporation by plough

These uptakes and cost benefits will only accrue when slurry is applied at times when the N conserved will not be at risk of loss by leaching. The precise time when this risk will no longer apply will depend on soil type and excess winter rainfall (EWR), and can vary considerably even within a single country (see Webb et al., 2001 for UK). However, as a guideline, these additional uptakes should be accrued when slurry is applied in February onward. Except for semi-arid areas, where EWR is negligible, there will be no increase in crop N uptake from reduced-emission spreading when slurry and manure are applied in late summer/early autumn. before autumn-sown crops.

Table 4a. Estimation of the value of slurry-N conserved by reduced-emission slurry applicators using UK estimate only.

	Surface	T hose	T Shoe	Slot Injec	*Other
Slurry volume, m^3	30	30	30	30	50
N applied, kg	150	150	150	150	250
TAN applied, kg	75	75	75	75	125
NH_3 emission %	50	50	50	50	50
% abatement	0	40	65	80	95
N conserved, kg	0	15	24	30	59
Value of extra N available, £ per 30 m^3 slurry (50 m^3 for immediate incorporation)	0	11.6	18.5	23.1	45.7
Value of extra N uptake, £ per m^3 slurry	0	0.39	0.62	0.77	0.91
Additional cost of abatement		0.52	0.52	0.52	0.54
Net cost of abatement		0.14	-0.10	-0.25	-0.37

Based on a price of £265 per t ammonium nitrate on 6 February 2009. This equates to £0.77 per kg N
*immediate incorporation by plough

Table 5. Estimation of the cost of immediate incorporation of slurry by plough

	slurry	FYM	poultry
UK, March 2009, calculation for this review	0.54	0.54	0.54
KTBL from Germany	0.73	0.82	0.82
KTBL from Italy	0.00		
KTBL from Spain	0.48		1.47
KTBL from Denmark	65.50		65.50

Sensitivity to price changes

Table 4 provides an encouraging assessment of the potential cost-effectiveness of using reduced-NH_3 slurry spreaders. However, table 4 was based on N fertilizer prices quoted in the UK in February 2009. This may have been an unrepresentative time to have made the assessment. Table 6 below provides a comparison of a previous estimate of the cost-effectiveness of reduced-NH_3 slurry spreaders.

Table 6. Estimation of the value of slurry-N conserved by reduced-emission slurry applicators – 2003 data.

	Surface	T hose	T Shoe	Slot Injec	*Other
Slurry volume, m^3	30	30	30	30	50
N applied, kg	150	150	150	150	250
TAN applied, kg	75	75	75	75	125
NH_3 emission %	50	50	50	50	50
% abatement	0	40	65	80	95
N conserved, kg	0	15	24	30	59
Value of extra N available, £ per 30 m^3 slurry	0	5.2	8.3	10.3	55.8
Value of extra N uptake, £ per m^3 slurry	0	0.17	0.28	0.35	1.12
Additional cost of abatement	0	1.44	1.64	2.84	0.79
Net cost of abatement		1.27	1.36	2.49	-0.33

Based on a price of *c.* £100 per t ammonium nitrate in 2003. This equates to £0.345 per kg N
*immediate incorporation by plough

In the month or so that has elapsed since table 4 was prepared the UK price of N fertilizer has decreased to £0.77/kg. We have therefore produced estimates of the break-even price of fertilizer-N, above which the application of slurry by reduced-NH_3 slurry spreaders becomes cost-effective.

Table 7. Break-even price of fertilizer-N, above which the application of slurry by reduced-NH_3 slurry spreaders becomes cost-effective.

	Surface	T Hose	T Shoe	Slot Injec	*
Additional cost of abatement, £ m^{-3}	0	0.52	0.52	0.52	0.54
Assumed slurry volume, m^3		30	30	30	50
N conserved, kg		15	24	30	59
N conserved, m^{-3}		0.5	0.8	1.0	1.2
Break-even N price, £/kg		1.04	0.65	0.52	0.45
Equivalent AN fertilizer price, £/t		359	224	180	157

*immediate incorporation by plough

Table 8. Estimation of the value of slurry-N conserved by incorporation to tillage land by plough.

	Immediate	4 h	12 h	24 h
Slurry volume, m^3	50	50	50	50
N applied, kg	250	250	250	250
TAN applied, kg	125	125	125	125
NH_3 emission %	50	50	50	50
Abatement %	94	55	16	12
N conserved	59	34	10	8
Value of extra N available, £ per 50 m^3 slurry	55.2	32.3	9.4	7.1
Value of extra N uptake, £ per m^3 slurry	1.10	0.65	0.19	0.14
Cost of incorporation*	0.54	0.54	0.54	0.54
Net gain from incorporation	0.56	0.11	-0.35	-0.40
pig FYM, t	35	35	35	35
N applied, kg	250	250	250	250
TAN applied, kg	50	50	50	50
NH_3 emission %	68	68	68	68
Abatement %	92	55	16	12
N conserved	31	19	5	4
Value of extra N available, £ per 50 t FYM	29.4	17.6	5.1	3.8
Value of extra N uptake, £ per 50 t FYM	0.84	0.50	0.15	0.11
Cost of incorporation*	0.54	0.54	0.54	0.54
Net gain from incorporation	0.30	-0.04	-0.39	-0.43
Poultry (layer) manure, t	13	13	13	13
N applied, kg	250	250	250	250
TAN applied, kg	120	120	120	120
NH_3 emission %	52	52	52	52
Abatement %	95	85	65	55
N conserved	59	53	41	34
Value of extra N available, £ per 50 t FYM	55.7	49.9	38.1	32.3
Value of extra N uptake, £ per 50 t FYM	4.29	3.84	2.93	2.48
Cost of incorporation*	0.54	0.54	0.54	0.54
Net gain from incorporation	3.75	3.30	2.39	1.94

Slurry abatement estimated from Fig 1. of Huijsmans et al. (2003), FYM and poultry manure abatement from UK inventory.

*Since the cost is that of an operation in addition to those required to prepare the seedbed the cost is the same regardless of the interval

Table 9 below illustrates potential break-even costs of reduced-NH_3 emission slurry spreading machines according to their mean abatement potential and cost of AN fertilizer, based on the work rates etc. used in this study. Similar reference tables could be produced according to other assumptions regarding work rate etc.

Table 9. Reference table for the break-even unit cost (£ m^{-3} slurry) for reduced-NH_3 emission slurry spreading machines. To take account of differences in the price of fertilizer-N and the abatement efficiency.

% Abate	30	40	50	60	70	80	90
N fert £/t							
100	0.11	0.14	0.18	0.22	0.25	0.29	0.33
150	0.16	0.22	0.27	0.33	0.38	0.43	0.49
200	0.22	0.29	0.36	0.43	0.51	0.58	0.65
250	0.27	0.36	0.45	0.54	0.63	0.72	0.82
300	0.33	0.43	0.54	0.65	0.76	0.87	0.98
325	0.35	0.47	0.59	0.71	0.82	0.94	1.06
350	0.38	0.51	0.63	0.76	0.89	1.01	1.14
400	0.43	0.58	0.72	0.87	1.01	1.16	1.30

This initial table indicates that, based on our cost assumptions, TS and OSI machines may be cost effective when the price for AN fertilizer exceeds £225 and £200/t respectively. However, for the TH to be cost-effective AN would need to be >£350/t.

Other potential cost savings

If grass cut for silage is still contaminated with slurry, this can reduce silage intake. If total animal energy intake is to be maintained additional concentrate feed will be needed. For example if, on a 100 cow dairy unit silage DM intake was reduced by 2 kg DM/head per day as a result of poor silage fermentation for a full 180 day winter, in the region of 41 tonnes of extra concentrate would be needed to replace the energy not provided by the silage. Assuming a concentrate straight such as wheat feed was purchased to supply the lost energy from silage, 41 tonnes would cost £131/tonne (March 09) or £5371. Based on a dairy cow producing c. 80 L slurry per day from excreta and parlour washings then this is equivalent to c. £3.70 m^{-3} slurry, much more than the cost of reduced-NH_3 slurry spreading. However, such savings should not be assumed for all users and this may be regarded as a maximum potential benefit.

So too with odour control (see Appendix 1 below). The majority of farmers have no need to reduce odours and hence they have nothing to gain from the reduction in odour emissions that may be achieved by reduced-NH_3 slurry spreading. However, for those who are vulnerable to complaints and liable to fines for non-compliance the avoidance of such fines could be worth up to c. £10.00 m^{-3}, depending on the size of farm and hence volume of slurry to be spread.

Reported experience of UK farmers. Results of survey and interviews carried out by Creedy Associates.

Practicalities and costs of using low ammonia emission techniques in the application of livestock manures to land

The aim of this project was to obtain a current view of farmers` experiences with reduced-NH_3 emission spreading techniques for livestock manures and to assess the costs.

Farmers` experiences.

Information was gathered from conducting telephone interviews with farmers, contractors and machinery suppliers. Farmers included some that had participated in MAFF project WA0710 Ammonia Pilot Farms. Creedy also drew on historical feedback from farmers during manure management workshops provided by Creedy Associates and on extensive day-to-day advisory contact with farmers.

Since farmers do not keep sufficiently accurate and detailed records on manure management, costs were based largely on standard values and on the farm business expertise of John Morgan (Creedy Associates).

Results

1.1 Farmers` experiences.

Most of the information gathered in this section relates to use of reduced-NH_3 emission machines for slurry application. Although many farmers incorporate solid manure (and slurry on arable land) into the soil, there was little evidence that many do this soon enough after spreading to have a significant impact on NH_3 emissions. Similarly, so called 'soft' measures do not appear to be commonly used to reduce NH_3 emissions. Some farmers are, in fact, reluctant to spread in the evening because of a greatly likelihood of complaints about odour when neighbours are home.

As to be expected, farmers` experiences and views varied widely from having no interest or intention of employing the machines, to having tried and dismissed a machine to being very enthusiastic and using on a regular basis. In the time available, it was not possible to identify the reasons for this wide variation although it did appear that the more progressive, younger farmers were keener on using the machines. No doubt soil type, topography, current management, proximity of contractor/machine supplier and local advice play a part. However, the responses were much more positive than we had expected! The main conclusions are:

1. There has been a large increase in the uptake of the machines over the past year or two. This seems to have arisen from pressure from farmers rather than 'hard sell' from contractors or suppliers.

2. The main reason for use is savings in fertilizer, especially with recent increases in N prices, smaller and more accurate application (especially on growing cereals), less contamination of grass for grazing (application between grazings) and silage and odour reduction (especially on pig farms) in specific locations.

3. In general, capital cost of ownership is too high for individual farmers and most use contractors. Pig farmers appear to be more likely to own a machine than cattle farmers. It is conjectured that this may be due to the greater need of pig farmers to control odour. More highly skilled labour is needed than for splashplate. Of particular interest, a contractor in Dorset invested about £0.5M in a complete 'Terrigator' injector set up and applies about 140,000 m^3 slurry /year to a wide range of crops often at relatively low, but accurate, application rates. Some slurry is exported from livestock (pig) to arable farms with the latter receiving slurry for free but paying for transport and injection.

4. The machines are generally reliable and most problems/breakdowns can be fixed fairly readily. Macerators do block but this did not appear to be seen as a real problem. There are issues with using thick slurries or those contaminated with stones, plastic etc.

5. There was insufficient information to rate machines according to popularity. However, the evidence indicates that shallow injectors are popular for use on grassland unless conditions are such that there is poor soil penetration (esp. very heavy or stony soils) or soils are too wet resulting in damage to the sward. Soil

compaction and damage to gateways and headlands were also mentioned. Trailing shoes overcome some of these problems, and may be increasing in popularity for grass, although new injectors are adjustable to allow slurry to be placed on the surface. Injectors can apply greater application rates than TH but some farmers claim the former encourages weed growth along the slot. Trailing hoses/dribble bars are more common on arable land for growing crops and can be used on crops up to 15 cm high but extra storage is needed to apply from March to May. Application to growing crops may increase with extended closed periods for spreading in NVZs. No one type of machine is suitable for all circumstances and, on some farms, it would not be possible to use any of the machines due to soil type, slope etc.

6. Contractors appear to charge 20-30% more for application with reduced-emission machines than for splashplate. Costs (and how they were calculated) for the former varied between less than £1 to over £2 m^{-3} applied. A reasonable average would be £1.40 m^{-3}. Thus the additional contractor's charge for these machines over splashplate is estimated to be between 28 and 42p m^{-3}. This study estimated the value of extra N for TH, TS and OSI to be 0.24, 0.38 and 0.47p, respectively. At current high N fertilizer prices, there would be a small cost benefit over SP solely on savings on purchased N in most circumstances.

1.2. Ammonia Pilot Farm project

Re-contacting farmers who participated in the project gave an opportunity to gather experience from farmers who owned and operated reduced-emission machines over the longer term. The experiences of these farmers are summarised below:

1. A dairy farmer on a gritty loam over clay soil (Somerset) with high rainfall gave up on his 10 m^3 tanker-mounted disc injector mainly due to problems of soil compaction, damage to gateways and headlands and damage to grass swards. There were also difficulties with soil penetration in dry weather and problems with blockages. He now applies mechanically-separated slurry, that infiltrates into the soil very quickly, with a TS (contractor operated) to grassland and TH to growing cereals. Separated solids are composted with FYM and spread on stubbles with incorporation within 1 or 2 days.

This farmer also installed covers on 2 circular steel slurry stores. In both instances there was re-occurring damage to the stores, most recently following heavy snow fall and high winds so he would not cover this type of store again.

2. In contrast, another dairy farmer on heavy clay soil (Gloucestershire) has successfully used his 7 m^3 disc injector for the past 11 years. He makes the point that he maintains it well because he could not afford to buy another. He sites damage to gateways and headlands and occasional blockages together with high maintenance costs as problems. Much improved utilisation of slurry and lack of contamination of grazed grass have encouraged him to convert to organic.

3. A third dairy farmer on clay/loam soils (Cheshire) still operates his 10 m^3 tanker-mounted 4 m wide injector and has not experienced problems with the flexible cover on his circular steel slurry store. The latter reduces volume of slurry to be spread by 17%. About 50% of the slurry is injected into grass for silage and grazing saving about £10,000/year on fertilizer. The rest is spread via umbilical splashplate prior to sowing maize. Maintenance costs have been high for the amount the machine

is used and he could not afford to buy another machine. There are problems with accessibility to same fields and with blockages.

4. A dairy/arable/poultry farmer on mixed light and medium heavy loams (Cheshire) continues to use his 12 m wide TH mounted on a 11.3 m^3 tanker. Dairy slurry liquid (from weeping wall store) is applied to grassland for grazing throughout the season, after cutting for silage and to growing cereals and claims to save £15,000/year in fertilizer costs. Splashplate is used for spreading on cereal and maize stubbles. In addition to savings on fertilizer, the advantages of TH include flexibility to apply to crops as and when required, accurate placement on crop and odour reduction. No operating problems have been encountered with using weeping wall liquid but repairs/replacement parts (macerator blades, hoses) have cost £3000 over the 11 years of operation. The machine also requires a very large tractor (200 hp) to pull it. Even so, the farmer is very pleased with the machine and says it has made a significant, positive impact on his business.

5. A pig farmer on a heavy clay soil in the Midlands gave up on both an umbilical disc injector and a TS due to soil compaction and high operating costs. Soil penetration was also a problem with the injector. He now successfully uses a TH machine to apply to growing crops and considers this to be the only option on his soils. The flexible cover on his above ground concrete store has proved successful.

Another pig farmer still uses his 7 m^3 tanker with 4 m wide disc injector on hilly loam/silt soil (Cornwall) to apply about 85% of his slurry to both grass and arable land. Odour control, fertilizer savings and lack of crop contamination are seen as advantages on this farm. He claims to have saved £23,000 on purchased fertilizer over 8 years. He cites high maintenance cost as a disadvantage and, even though machine had driven rear axle, there are problems on steep slopes. Could not have afforded to purchase without subsidy from the project.

6. A third pig farmer on heavy, seasonally waterlogged clay soil in Cornwall continues to use his 4.2 m wide injector mounted on an 8.4 m^3 tanker to apply mechanically-separated slurry. 85% is applied to grassland and 15% to arable saving about £17,500/year on N fertilizer. In addition, odour control is of great benefit together with flexibility and timeliness of application. High capital and operating cost are disadvantages but soil compaction, damage to gateways/headlands no worse than vacuum tanker and splashplate. Only 50% of slurry is applied via injector (an umbilical splashplate is used for the rest) because ground conditions are unsuitable at some times of the year.

The main conclusions from this part of the project are:

- All the farmers are still using reduced-NH_3 emission machines after 10 – 11 years, albeit one has stopped using an injector in favour of a TH, and most still have their original machine.
- Most claim that the machine has had a positive impact on their business, especially in terms of saving on fertilizer costs, flexibility in when and where to apply slurry accurately and according to crop requirements and odour reduction. It is not always clear whether or not savings in fertilizer are entirely due to the machine or could have been achieved by more considered

use of splashplate spreading. There is no doubt that the machine encourages, and makes it easier, for farmers to use slurry more effectively.

- Most could not afford to replace the machine nor could have afforded to initially purchase without subsidy from the project.
- All claim maintenance costs to be relatively high but, in general, resolved mechanical problems. None had accurate costs, some assume maintenance to be 4% capital. Most did not think running costs were significantly more than tanker and splashplate because time for filling tanker and transport to field, that accounted for large proportion of total time, were the same. Unfolding the boom added some time to TH machines.
- Many farmers were not able to use the machine to apply all the slurry produced on their farm and often used SP for a proportion. This was due to difficult soil conditions (too wet or too dry at times of the year, stony or steeply sloping land, some slurry too thick or containing stones etc, inaccessibility of some fields.

Annex. Basis for UK cost estimation

Creedy Associates (John Morgan and Brian Pain)

Costs of machines

Introduction

As with most machine-based operations on farm, the running costs of the tractor pulling the implement, is a considerable element of the overall cost. This section of the review aims to outline the key elements that have been taken into account when working out the running costs of livestock manure spreading equipment. The annual running costs of a suitable tractor are reviewed alongside those associated with reduced-NH_3 emission spreading equipment such as TH, TS and OSI machines as well as cultivation equipment required to incorporate solid manures. Finally an attempt has been made to identify and provide examples of financial savings made possible by the co-benefits of reduced-NH_3 emission spreading of liquid and solid organic manures.

Tractor running costs

Depreciation

A non-cash payment, depreciation is an estimate of the decreasing value of an asset over time. In theory this deprecation, if set aside in a reserve fund, should be sufficient to replace the asset as and when the time comes.

Depreciation occurs for three reasons, obsolescence, gradual deterioration with age and wear and tear as a result of the tractors use. While the first two reasons are time-related and are largely age-related, wear and tear is a result of its use and is directly linked to the hours a tractor works during a year. If the first two reasons predominate then depreciation tends to be more of a fixed cost. If the tractor does many hours the wear and tear associated with this use becomes the key element of its depreciation over time and in effect makes deprecation more of a variable cost (rises proportionately as hours worked increases) than a fixed one.

Depreciation tends to be calculated either via the straight line or diminishing balance methods. The straight line method of calculating depreciation divides the difference between the purchase price and anticipated sale price or scrap value over the years the machine is owned. The diminishing balance method deducts a constant percentage of the written down value off the written down value each year. As a result the annual deprecation in monetary terms reduces each year reflecting the inherent residual value that any tractor is likely to have regardless of its age.

While the straight line method of calculating depreciation is very simple its major flaw is that it takes no account of the workrate of the machine. The calculated straight line depreciation on a tractor working 1000 hours per year would be the same as one working 250 hours a year which would be clearly wrong bearing in mind the reduced wear and tear on the second machine. As a consequence of the inherent weakness in the straight line method the diminishing balance method is used particularly where tractors are used for a large number of hours each year.

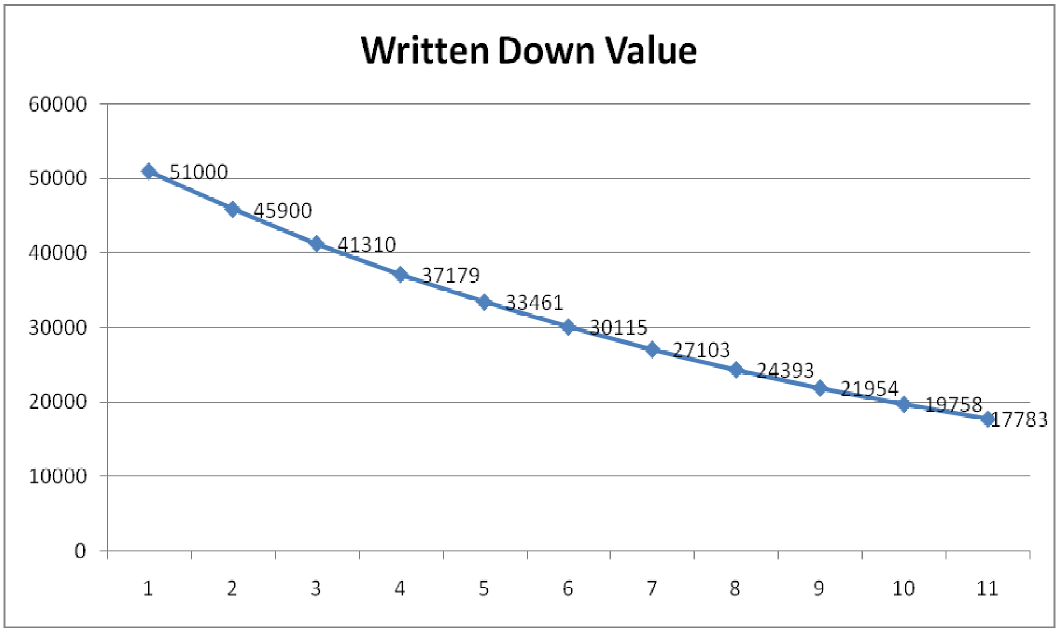
Typically 35 – 40% of a machines original purchase price is achieved when sold after 10 years.

Effect of annual work rate.

As noted earlier, while the rate of depreciation is not directly linked to hours worked there is a close link between the two. As a consequence the more hours a machine works the less the depreciation per hour. This reducing rate of depreciation needs to be balanced by the likely increase in repairs and maintenance cost as the hours worked increases.

Interest on capital

The capital invested in the ownership of a machine either results in lost interest, if purchase money has been taken from reserves, or actual interest payments if capital is borrowed. This lost or extra interest payment should be taken in to account when working out the cost of running a machine. When working out the interest payment associated with a machine the average interest paid over the life of the machine is used and is therefore calculated on the average capital invested. Typically interest is calculated on half the initial capital cost on the basis that the machine is being written off over the time and the deprecation money is being invested and earning interest in preparation for the machines replacement. The interest rate charged on this capital will inevitably depend on the personal situation of the machines owner and the interest rates at the time. Whether interest is being lost, as a result of money from reserves being used to finance a machine, or paid as a result of borrowed finance the rates paid are to a large extent linked to the Bank of England base rate. The low Bank of England rates at present mean that the interest element of machinery running cost is relatively small.



Appendix figure 1 The annual depreciation (diminishing balance method) on a £51,000 four- wheel drive tractor over a 10 year period.

The annual interest charge on a £51,000 tractor would be based on an average capital invested figure of £25,500. Based on the current Bank of England base rate this capital could be secured at a rate in the region of 3 – 6% depending on circumstance. Taking an average rate of 4.5% the interest on the tractor would be £1150/year. As a truly fixed cost the annual interest charge would be diluted or concentrated directly depending on the hours worked in a year.

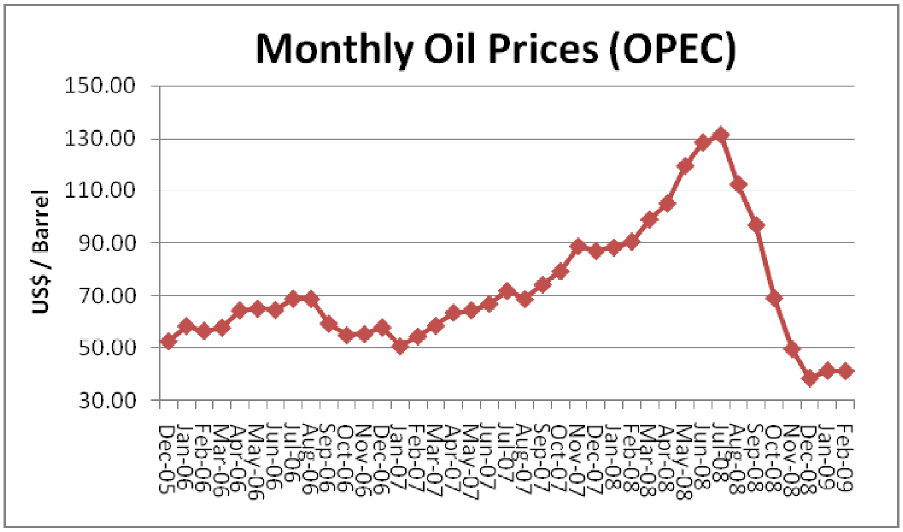
Insurance

Insurance on machines equates to approximately 2% of the average capital value of the machine. The individual farm or contractor "no claims" records have the biggest impact on the actual farmer or contractor rate.

The annual insurance cost of a £51,000 (purchase price) tractor (average capital value £25,500) would be £510. Like interest on capital, insurance costs are fixed and as a consequence would be diluted or concentrated depending on the hours worked.

Fuel

Fuel costs of a tractor are truly variable being a consequence of the hours worked by the machine multiplied by the fuel price per hour. Average fuel consumption of between 18 -25 litres/working hour are quoted for 100 – 180 Horse Power tractors. While fuel consumption is known, the dramatic variation in fuel prices over the last year make predicting fuel costs per litre very difficult. Prices gathered in early March 09 suggest a price per litre is in the region of 38 p. Using this figure, fuel costs per hour of between £6.84 and £9.5 have been calculated as typical.



Annex figure 2. OPEC Oil prices US$/barrel over last 38 months. Source Dairy Co

Repairs

While it is tempting to assume that repair costs rise or fall directly in proportion to the hours the machine works like other variable costs, certain repair costs are in fact related to the machines age. Examples of such fixed costs would be battery life. This point made, repair and maintenance costs while not directly linked to workrate are very closely associated with the amount of work undertaken and for practical reasons repair costs tend to be linked to hours worked. Repair costs for tractors are typically assumed to be in the region of 8% of the initial capital purchase price of the machine. For the £51,000, 1000 hour, example tractor repairs and maintenance costs have been calculated at £4080/year or £4.08/hour.

Labour

Labour costs, be they paid by the farmer direct or via contractor, have remained relatively static in recent years. Hourly rates of £9 - 10/hr are typical for tractor drivers and foreman/supervisors respectively. The relatively slower work rate of the reduced-NH_3 emission spreaders will inevitably increase the cost per hour of using this equipment. Interestingly while there is a difference in the output of the machinery in the field, when spreading with a tanker-based system, most of the time taken is a result of the travel to and from the field. Even with slower application rates of band spreaders compared to surface spreading, the overall increase in work rate is relatively small. Annex table 1 taken from a DARD technical note, Alternative Spreading Systems, shows the difference in number of tanker loads over an 8 hour period between two different spreading systems with system B being based around a lower output spreader.

Annex Table 1. Slurry tanker loads per eight hours at two different work rates in the field

	Travel time to field from slurry store	Time to spread slurry in field	Travel time to slurry store from field	Time to fill tanker at slurry store	Efficiency	Tanker loads per 8 hours
A	4 mins	4 mins	4 mins	4 mins	80%	24
B	4 mins	6 mins	4 mins	4 mins	80%	22
Difference A-B		+50%				-9%

Source: Derived from Lenehan 2004

When fitted to umbilical systems the reduction in work rate compared to splash plates will be more marked, however work rates are so quick with umbilical systems that very high application rates per hour are possible with any applicator.

Spreading machinery running costs

Depreciation

In addition to the tractor required to spread slurry or solid manure the actual spreading machine will also have significant running costs. The three, obsolescence, gradual deterioration with age and wear and tear elements of machinery depreciation will apply. The obsolescence element has been considerable in the past, particularly for band slurry spreading machines, as the release of new improved machines makes their predecessors obsolete earlier than may be anticipated for more mature types of equipment e.g. ploughs.

Typical depreciation rates would be in the region of 15% of the initial purchase price. As with many machines initial annual depreciation would be greater than this but late in the machines life rates would decrease. Assuming an initial capital cost of a tanker plus band spreader of £28,000, See Annex table 2 below, deprecation would typically be £4200/year. It is assumed that the machine is sold after 6 years of use at 10% of its initial purchase price.

Repair and maintenance costs

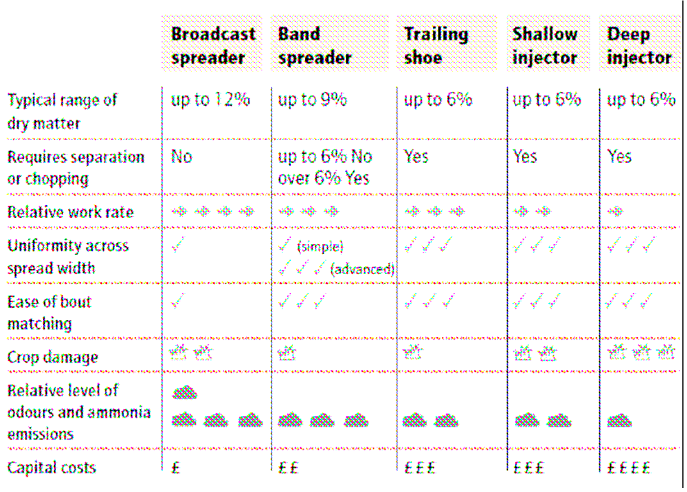
Repair costs associated with machinery that is attached to the back of a power unit such as a tractor, tends to be directly linked to the number of hours worked. As the hours of work increase so will the repair and maintenance costs and vice versa.

Machines that require direct soil to machine contact such as injectors will inevitably have much higher repair and maintenance costs that those that do not. Repair costs of individual farm machines over a long enough time to come up with genuine averages are very rarely kept. Budgeting estimates of 7% of initial purchase price are quoted for the first 200 hours of use with an additional 2% of purchase cost per 100 hours above this 200 hour base for machines with limited soil to machine contact. Annual repair costs in the region of 13% of the initial purchase price should therefore be budgeted on machines that do 500+ hours. Assuming an initial capital cost of a tanker plus band spreader of £28,000 repairs and maintenance costs would therefore typically be £3640/yr.

Interest on Capital

The capital cost of reduced-NH_3 emission machinery will depend on size of machinery as well as manufacturer. Annex table 2 taken from Managing Livestock Manures 'Spreading Systems for Slurries and Solid Manures' booklet shows the relative capital cost of different types of spreaders.

Annex Table 2. An estimate of the relative capital costs of different types of slurry spreader



	Broadcast spreader	**Band spreader**	**Trailing shoe**	**Shallow injector**	**Deep injector**
Typical range of dry matter	up to 12%	up to 9%	up to 6%	up to 6%	up to 6%
Requires separation or chopping	No	up to 6% No over 6% Yes	Yes	Yes	Yes
Relative work rate	✣ ✣ ✣ ✣	✣ ✣ ✣	✣ ✣ ✣	✣ ✣	✣
Uniformity across spread width	✓	✓ (simple) ✓ ✓ ✓ (advanced)	✓ ✓ ✓	✓ ✓ ✓	✓ ✓ ✓
Ease of bout matching	✓	✓ ✓ ✓	✓ ✓ ✓	✓ ✓ ✓	✓ ✓ ✓
Crop damage	🌱 🌱	🌱	🌱	🌱 🌱	🌱 🌱 🌱
Relative level of odours and ammonia emissions	☁ ☁ ☁ ☁	☁ ☁ ☁	☁ ☁	☁ ☁	☁
Capital costs	£	££	£££	£££	££££

It should be noted that the above, while a useful example of previous, qualitative, assessments, is not entirely consistent with the findings of this review.

The above table only provides very general guidance for dry matter. In the Netherlands pig slurry is typically 10% DM and is spread by injector. Problems may arise from straw or silage getting into the slurry , but most of these machines have macerators and the Defra pilot study (see below), indicated that the macerators were pretty robust. There may also be loading problems with thick slurry as well as pumping problems for umbilical systems.

Quoted prices for the OSI, TS and TH machines range between £14,000 and £41,000. These costs are for the application unit only. Using the same logic re interest rates as is set out for the tractor above i.e. an assumed interest rate on the average capital outstanding, the annual interest rate for a £28,000, (average capital value £14,000) machine would be £630.

Annex table 3. Quoted prices for a range of tanker and umbilical mounted band spreaders as at February 2009

Machine	Type	Maker	Price (£)
Shallow Injection	Tanker 5.2 m	Major	31,900
Shallow Injection	Tanker 6.4 m	Major	33,000
Shallow injection	double disc 6 m	Samson	28,000
Shallow injection	to mount on tanker, 4 m	Spreadwise	14,000
Shallow injection	umbilical, 4 m	Spreadwise	14,500
Trailing shoe	Tanker 5.2 m	Major	35,200
Trailing shoe	Tanker 6.0 m	Major	36,300
Trailing shoe	10,000 L tanker, 7 m	Schuitemaker	41,000
Trailing shoe	tanker, 7.5 m	Hi-Spec	33,000
Trailing shoe	umbilical, 6 m	Tramspread/Joskin	13,500
Trailing shoe	6 m, to fit on 11,000 L tanker	Joskin	28,000

Combined Tractor and Band Spreader Running Costs

Taking all the individual cost elements outlined and explained above it is now possible to estimate the costs of running a tractor and band spreading machine annually, hourly and per unit of volume of slurry spread. The costs of running such a combination are set out in Annex table 4.

Annex table 4. Combined running costs per hour for a 150-180 HP £51,000 initial purchase price tractor (1000 h/yr) plus £28,000 tanker based band spreader running for 500 hours per year

Tractor Running Costs	Annual Cost (£)	Hourly rate assuming 1000 hours (£)	m^3 rate Assuming 27 m^3 spread per hour (£)
Tractor Depreciation (Diminishing balance over 10 years)	3500	3.50	0.13
Interest on Capital	1150	1.15	0.04
Insurance	510	0.51	0.02
Fuel (38 ppl)	8170	8.17	0.30
Repairs and maintenance	4080	4.08	0.15
Labour	9500	9.5	0.35
Total Tractor Costs	26910	26.91	1.0
Band spreader running costs	Annual Cost (£)	Hourly rate assuming 500 hours (£)	m^3 rate assuming 27 m^3 spread per hour (£)
Band spreader depreciation	4200	8.4	0.31
Band spreader repairs (average of all three types)	3640	7.28	0.27
Interest on capital	630	1.26	0.05
Insurance	280	0.56	0.02
Band spreader costs	8750	17.5	0.65
Total Package		44.41	1.65

We considered it is impossible to produce accurate costs for every type of machine without setting up a project to track costs in a standard way over a long term period of time. Issues will arise with respect to machines produced by different manufacturers and interactions with soil type, maintenance and workrates.

The costs assume a 6 year write-off with a final sale price of 10% of the purchase price. While interest rates are currently very low, this will only reduce costs per m^3 by a very small amount. We have assumed that the depreciation money would be set aside to replace the machine after 6 years. As a consequence we have not included a capital repayment element in my costs.

Difference between splash plate machines and reduced-NH_3 emission spreaders.
The key differences when calculating the direct differences in cost between band spreaders and splash plates are:

- Slower work rate of band spreaders and therefore higher tractor costs per unit of slurry spread.
- Lower repair costs associated with splash plate machinery due to less soil/machine contact and less moving parts.

These differences have been used to calculate the spreading costs via a splash plate tanker.

Annex table 5. Annual running costs of splash plate applicator

	Annual running costs (£)	Cost per hour (£)	Cost per m^3 Broadcast***
Tractor	26910	26.91	0.90
Spreader Depreciation	*1800	3.6	0.12
Splash plate repairs	**1200	2.4	0.08
Interest on capital	270	0.54	0.018
Insurance	120	0.24	0.008
Spreader cost	3390	6.78	0.23
Total package		33.69	1.13

*assumes purchase price of tanker of £12,000, **assumed 10% repair cost for tanker, ***30 m^3/h spread rate assumed 9% greater work rate.

As expected the costs per annually, per hour and per unit of slurry spread are considerably less when using a splash plate machine. A typical 50 m^3 application of slurry via a band spreader would cost £80. The same slurry applied via a splash plate would cost £49.5. The difference of £30.5 needs to be made up with tangible fertiliser nitrogen savings and or the additional “add on” benefits associated with reduced-emission machinery.

Cost of rapid incorporation
It might be argued that there are no inherent extra costs associated with rapid incorporation of solid manures in most circumstances. Incorporation of manures will usually occur at some stage post spreading. The key issue is the time between spreading and incorporation. However, in the UK, manures are often spread to arable land over the winter in the period between harvest of cereals and planting of spring-sown crops such as sugarbeet and potatoes. Normal practice is for the manures to remain on the soil surface until cultivation prior to planting in March or April. Hence if manures are to be incorporated soon after spreading this is likely to introduce an additional cultivation, since in the interval between ploughing subsequent soil settlement and weed growth might requires another cultivation before seedbed establishment. Even for manures applied in late summer or early autumn, shortly before planting autumn-sown crops, there is an issue with respect to logistics.

Logistics
The primary challenge associated with incorporation within 24 h of spreading is logistics. Practically many farmers find it difficult to have spreading and

incorporation machinery on site at the appropriate time. For the one-man-band type farming operation rapid incorporation relies on the farmer regularly swapping machines on his tractor which can waste significant quantities of time and slow down work rates. For larger operations liaisons with farm workers and contractors is needed to ensure required machines are on site at the same time. In addition, work rates of the incorporation and spreading machinery need to be matched to keep all units working at optimum speeds. Matching work rates is not simple particularly bearing in mind the different travelling times between different blocks of land for spreaders and different work rates of cultivation machinery based on soil type, machinery size etc.

To avoid the challenging logistics identified above an extra pass of an incorporation machine could be planned for. Use of such an approach would ensure maximum work rates of all other machines and labour units associated with manure application. Tractor costs for such an operation would be similar to those identified for the band spreading machines. Incorporation would be typically via a surface cultivator. The running costs of which are shown in Annex table 6.

Annex table 6. Annual and hourly based incorporation costs for a £12000 cultivator working 200 h per year.

	Annual running costs (£)	Cost per hour (£)	Cost per ha*	Cost per m^3/tonne**
Tractor	26910	26.91	15.4	0.31
Cultivator depreciation (15%)	1800	9	5.14	0.10
Cultivator repairs and maintenance (14% of purchase price)	1680	8.4	4.8	0.10
Interest on capital	270	1.35	0.77	0.02
Insurance	120	0.6	0.34	0.01
Total Cultivator cost	2790	19.95	11.4	0.23
Total package		46.86	26.77	0.54

Annual work rate of 1000 hrs for tractor and 200 hours for cultivator * assumed work rate of 1.75 ha/hr
**Assumed application rate of 50 m3/ 50 tonnes/ha

It would be very difficult to come up with a robust set of assumptions re opportunity cost savings or loss resulting from such a small change in the interval between spreading and incorporation.

Ground truthing of costs

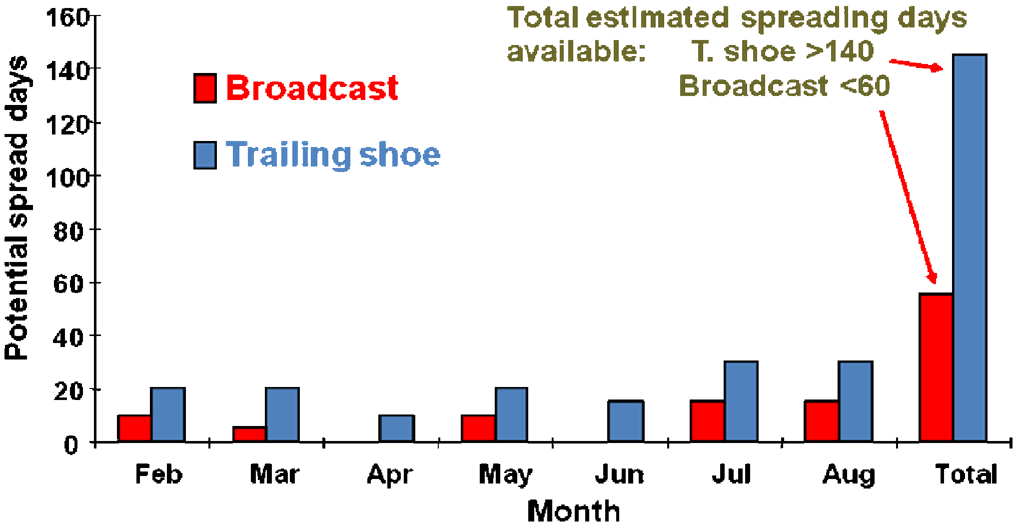
The above costs have been based on a combination of standard cost estimates, plus farmer and author experience. As a general rule farmers rarely calculate reliable costs of machinery operation and therefore generating information from this source alone would be difficult and potentially inaccurate. Contractors will in many cases attempt to calculate tractor and machine running costs and will use these to set rates charged to clients. Where possible these contractor costs have been used to ground truth the above costs or running machines. Further work in this ground truthing via contractors area would further improve the accuracy of the costings.

Additional benefits of band spreading

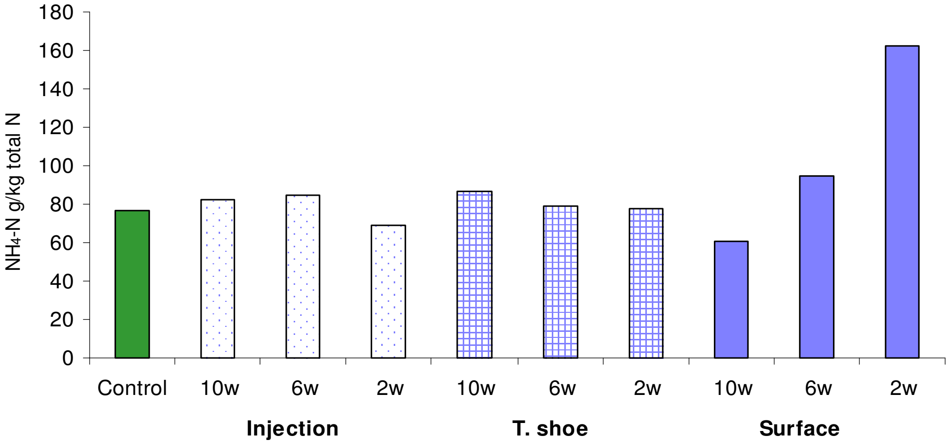
Benefits of increased spreading window

The use of injection, TH and TS application machines aims to place slurry in to or very close to the soil surface and in so doing dramatically reduce the surface contamination of the crops on to which slurry has been spread. This reduced surface contamination cuts down herbage grazing rejection levels as well as the risk of contaminating subsequent silage or hay crops with harmful bacteria which can result in poor silage fermentation. As a result slurry can be spread much closer to a subsequent grazing or forage cut. Farmer experience of using a TS application on grassland has highlighted the importance of this increased spreading time flexibility.

Work in carried out in 2001 and reported in 2002 (Williams and Chambers, 2002) illustrated that the number of available spreading days was doubled when TS machinery was used on a large dairy farm in Worcestershire compared to traditionally broadcasting. The main reason for the increased number of spreading days was less sward contamination reduced spreading drift and odour nuisance also played a part. The use of the TS equipment allowed grazing within a few days as opposed to the 3-4 weeks that would otherwise have been the case. This ability to use fields relatively quickly post spreading with such machines has been cited by farmers as a significant advantage.



Annex figure 3. Number of available spreading days when dairy slurry broadcast or spread via a trailing shoe (Dairy Farm Worcs)



Annex figure 4. Effects of slurry application on 1st cut silage NH_4-N content (IGER 1999, Laws et al., 2003)

Experiments that quantified the NH_4-N content of silages made following slurry spreading via band and surface spreading were carried out on two UK sites in 1998/99 (Laws et al. 2003). Ammonium-N content levels in a grass silage are often used as one of the indicators of silage fermentation quality. Ammonium-N concentrations below 100g/kg total N usually indicate well-fermented silage. The work and Appendix figure 4 shows that silage quality has the potential to be compromised if slurry is surface spread relatively close to cutting time and that this risk is all but eliminated if band spreading techniques are used.

High Ammonium-N rates primarily reduce the intake potential of silage. If total animal energy intake is to be maintained additional concentrate feed will be needed. For example if, on a 100 cow dairy unit silage DM intake was reduced by 2 kg DM/head per day as a result of poor silage fermentation for a full 180 day winter, in the region of 41 tonnes of extra concentrate would be needed to replace the energy not provided by the silage. Assuming a concentrate straight such as wheat feed was purchased to supply the lost energy from silage, 41 tonnes would cost £131/tonne (March 09) or £5371.

The increased number of spreading days associated with reduced-NH_3 emission spreaders provides more opportunities for farmers to spread on *more* of their land. By being able to spread on more of their land, slurry spreading at target application rates is more realistic and less purchased fertiliser will be needed. Knowing that he can spread slurry safely, without overly risking the fermentation quality of his first cut silage, in March, enables a farmer to target early January/February applications of slurry on grazing grass which historically received a compound fertilizer.

It is difficult to quantify the value, if any, of additional days of grazing. The same yield of grass will be grown during growing season whatever the number days of grazing available, so no extra food will be produced. In theory having more spreading days should mean less slurry storage is needed. That said the NVZ requirement means that most farmers will have to have 5 months winter storage and therefore should have plenty of surplus storage in the spring and summer in most cases.

Accurate application rates

A key strength of the reduced-NH_3 emission spreading machinery is the ability to apply slurry evenly across a fixed bout width and therefore much more accurately than broadcasting. Such an attribute is very important particularly in current financial circumstances where the cost of fertilizer is forcing/encouraging farmers to make maximum use of their slurries to replace purchased nutrients.

When using reduced-NH_3 emission spreading machinery bout width is simply the width of the boom or injector toolbar. When using splash plates to broadcast slurry achieving event spreading rates is more difficult, bout widths need to overlap.

Such improvements in accuracy of application increases the number of target crops onto which slurry can be applied as a replacement to other fertilisers. The target crop list for applying slurry with reduced-NH_3 emission spreaders is considerable with many arable field crops being added to the traditional targets such as grassland.

Although we have made our estimates of cost savings on the basis of additional N conserved by reducing emissions of NH_3, there is also an issue, which cannot be readily quantified, of improved farmer confidence due to the accurate bout width and resultant accurate application rates onto the soil surface in a growing a crop in the ability of manures to supply P and K as well as N. Because a farmer can be confident of application rates he is potentially better able to replace historic bagged fertiliser.

If such spreading accuracy is combined with known quality of slurry, increased proportions of the total crop N requirements can be confidently applied to crops via slurry. Historically over-reliance on the N supplied via broadcast slurry had the potential to cause over- or under-application and consequential problems such as lodging crops (too much N) or under-performing crops (too little N). To avoid such problems the advice has been to supply a maximum of 50-60% of the crops N requirement from organic manures. The improved accuracy associated with reduced-NH_3 emission spreaders could allow the 50-60% figure to be increased to say 60-70% and as consequence reduced the manufactured fertilizer needed for a crop by a similar amount. For example, a typical wheat crop receiving 220 kg ha^{-1} of N, supplying 10% more of the N requirement via slurry will reduce the purchased fertilizer bill by 22 kg ha^{-1} or at current fertiliser prices (£0.77 kgN) £16.94 ha^{-1}.

The improved accuracy and fixed bout width is increasing the popularity of slurry application to arable crops in the spring. The inputs to these crops are often applied via fixed tramlines within the field. Matching bout width of slurry spreading machines with existing tramlines makes very good sense and allows for spring top dressing of crops with valuable N, phosphate (P_2O_5) and potash (K_2O).

Fixed bout widths also allows farmers to spread up to legal (Cross Compliance and NVZ) field margin limits with confidence. The unpredictability of splash plate spreading patterns inevitably means that to be on the safe side drivers keep further away form ditches, watercourses, hedges and well/boreholes than they are legally required to do so. Use of reduced-NH_3 emission spreaders allows them to spread up to the legal boundary of the fields thereby increasing the area on which manures can be spread.

Odour reductions

The close proximity of commercial agriculture to members of the non farming general public who often have very different views as to what is acceptable both visually and nasally has always been a challenge to livestock farmers. At best this difference of opinion has resulted in limiting the available spreading days on fields located close to dwellings to days when weather conditions are suitable or on new crop establishment when rapid incorporation of manures pre-establishment, limits the odour.

Reduced-NH_3 emission spreaders reduce the odour associated with slurry spreading considerably. Injection of slurry results in the biggest reduction being followed by TS and TH machines respectively. The reduction in odour emissions allows farmers to spread slurry on more fields than would have otherwise been the case. The ability to do so will result in direct fertilizer savings on these fields as the bulk of crop needs can be supplied via slurries.

To value the potential benefits of reduced odours following the application of manures is also difficult. Suggestions have been made with respect to property prices and other such externalities. However, external costs are outside the remit of this review and will not be referred to again. For most farmers there is no potential financial benefit since they can operate without the need to control odour.

For those who are required to avoid nuisance the only potential gain is the avoidance of being fined for breaking the law. For example, in the UK, under the Environmental Protection Act 1990, domestic and commercial odours are investigated by local authorities (where applicable, district councils rather than county councils). This means that there may be some variation in the approach taken between different authorities. Section 79 of the Environmental Protection Act 1990 lists all issues that can be dealt with as a statutory nuisance. The odour needs to be considered to be a Statutory Nuisance from an Environmental Health Officer's professional opinion. Obtaining data on the potential scale of fines was also difficult. Annex table 7 below lists the range of fines in countries from which such data could be readily extracted. In Japan a custodial sentence of up to a year may be imposed instead of a fine. West Vancouver has recently adopted amendments to its nuisance bylaw that will allow the district to fine odour-generating businesses up to $10,000 for failing to eliminate offending odours.

Annex table 7. Potential fines for causing nuisance by offensive odours (£)

Country	Maximum
UK	20,000
Japan	*7000
Canada	5500

*1 M ¥

In the UK at least the majority of complaints arise following the application of pig manures. A 2000 finishing pig unit will produce *c.* 3000 m^3 undiluted slurry per year. Hence the maximum fine could be equivalent to *c.* £7.00 m^{-3}, much more than the additional cost of application.

Appendix 3, Impact of reduced-NH_3 emission application techniques on emissions of N_2O

This section summarizes the results of work which has measured the impact of reduced-NH_3 emission application techniques on emissions of N_2O, without taking measurements of NH_3. These results are then discussed together with those of studies reported in the section on NH_3 abatement which measured both NH_3 and N_2O.

Measurements of nitrous oxide only

Thorman et al., 2007, FYM

FYM was collected form cattle and pigs housed on different amounts of straw. The FYM had been stored for 12 months. Pig FYM was spread in late March, cattle FYM in July. Both manures were either left on the surface or incorporated by plough within 4 h, and in the case of cattle FYM incorporation within 4 h by disc was also evaluated.

Emissions were measured for 2-3 months. From pig FYM emissions of N_2O were always greater when manure was ploughed in immediately, but only significantly so ($P < 0.05$) for fresh FYM. Conversely, emissions from cattle FYM were always greatest from the surface application, but in no case was the difference significant. The two experiments were conducted at different sites with differences in soil and weather conditions. The authors concluded that the apparent differences between manures with respect to emissions of N_2O was most likely a consequence of those environmental differences than due to differences in the manure properties.

Perälä et al., 2006

Nitrous oxide emissions were measured after slurry was injected or incorporated after application by TH. There was no comparison with surface-applied slurry, so the results in Appendix 1 are N_2O-N as % of N applied over the 5 month measuring period. In contrast to some other reports, N_2O-N emissions from injected slurry and fertilizer-N were significantly less than from slurry alone. The smallest N_2O-N emissions were from slurry incorporated with fertilizer-N. The greatest N_2O-N emissions were observed at a medium moisture content which allows both nitrification and denitrification to occur. However, the month after application was drier than average (*c.* 50% of long-term average) and this may have influenced the results.

Vallejo et al., 2005

These workers simulated injection to 5 cm around a lysimeter. The measurement period covered 7 months. There was no significant difference between surface application and injection for emissions of either N_2O or NO expressed as g m^{-2}. Both the denitrification rate and N_2O emission correlated very significantly with water-soluble carbon (WSC). The lack of difference in, N_2O emissions was attributed to the WSC being the same for surface-applied and injection treatments.

Velthof et al. (2003)

Velthof et al. (2003) summarised earlier work on the impacts of manure application on N_2O emissions as suggesting that while some studies showed no clear effect of application technique from livestock slurries on N_2O emissions, other studies had indicated increased N_2O emission from slurry injection. They 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.

Velthof et al. (2003) measured N_2O emissions in an incubation study from a range of manures including cattle and pig slurry and layer manure. A sandy soil was chosen and a mixture of topsoil and subsoil used. The reason given for such a mixture was that the authors wished to avoid large background emissions of N_2O that might have arisen from using topsoil only. Manures were thoroughly mixed with the soil. There were only comparisons with manure left on the surface for pig slurry. Emissions of N_2O were measured for 98 days. No NO_3 was measured in any of the manures. In comparison with N_2O emissions from mineral fertilizer (ammonium nitrate (AN) and ammonium sulphate (AS)) there were larger fluxes from all the manures on day 1 but smaller emissions on days 2, 3 and 4. Emissions from AN and AS were remarkably similar on each of those first 4 days, suggesting nitrification took place immediately and denitrification a day later. After an initial flux up to day 15, N_2O emissions from manures subsided but then peaked again between days 60 and 90 following addition of water

Emissions were greatest when pig manure was placed at 5 cm ($P <0,05$), least when placed at 10 cm ($P < 0.05$) and intermediate for surface application, thorough mixing and placement at 5 cm. *These results suggest that while injection to 5 cm might increase emissions of N_2O, deeper injection might reduce them.*

The impacts of manure addition on N_2O emissions may also be affected by soil organic matter (SOM) content, texture and pH. They suggested that the effect of the added C in manures on denitrification and N_2O emissions would be greatest in soils with little SOM, since a mechanism of N_2O emission following manure application can be denitrification of soil nitrate fuelled by the readily-metabolizable carbon added in manures. In soil volatile fatty acids (VFA) are metabolized within a few days by soil bacteria, increasing denitrification and/or N immobilization (Kirchmann and Lundvall, 1993, cited in Velthof et al., 2003). Pig manures usually have greater VFA contents than cattle manures (Kirchmann and Lundvall, 1993). 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 (Chadwick et al., 2000, cited in Velthof et al., 2003).

The conclusions that can be drawn from this limited data are as follows. While it might be expected that reducing emissions of NH_3, by conserving N in soil and adding a readily metabolizable source of C, has the potential to increase emissions of N_2O, such increases are not always measured. There are a number of reasons for this: injection or incorporation by increasing the length of the diffusion path from the site of denitrification to the soil surface may lead to a greater proportion of denitrified N being emitted as N_2; the subsequent soil moisture status and hence aeration may not be suitable for increased N_2O production; in soils already well-supplied with both readily metabolizable C and mineral N any increase in N_2O emission may be too small to have a significant effect.

Solid manure incorporation

Mkhabela et al., 2008

Not really a study of incorporation per se, rather a comparison of conventional and zero tillage. Manures incorporated, 'soon after spreading'. N_2O emissions measured for a full year from FYM, 2 months after slurry. Incorporating manure reduced emissions of both NH_3 and N_2O, although there were no control plots to measure background emissions of N_2O. Greater denitrification and N_2O production under NT was considered to be in part due to the presence of greater amounts of available-C under NT and greater aeration under CT created by tillage.

Rohde and Karlsson, 2002
Compared NH_3-N emissions from broiler manure left on the soil surface or incorporated after 4h by harrow.

Conclusions
There are not enough field studies reporting both NH_3-N emissions and N_2O emissions measured over 12 months to draw firm conclusions. The available data suggest a different pattern of results for slurry and FYM:

- Following application of slurry by reduced-NH_3 emissions spreading techniques emissions were usually greater than when manures were surface-applied, although differences were not always significant.

- When solid manures are rapidly incorporated N_2O emissions have often been less than from surface application, in some cases significantly less.

In an incubation N_2O study emissions were greatest when pig manure was placed at 5 cm ($P < 0{,}05$), least when placed at 10 cm ($P < 0.05$) and intermediate for surface application, thorough mixing and placement at 5 cm. *These results suggest that while injection to 5 cm might increase emissions of N_2O, deeper injection might reduce them.*

The addition of labile C in manures has been proposed as a mechanism for increasing emissions of N_2O by more than would be expected as a result of the additional N entering the soil as a result of NH_3 abatement. There are a number of reasons why reduced-NH_3 emission application techniques would not always lead to greater emissions of N_2O: injection or incorporation by increasing the length of the diffusion path from the site of denitrification to the soil surface may lead to a greater proportion of denitrified N being emitted as N_2; injection and incorporation would also increase the length of the diffusion path for N_2O produced by nitrification; the subsequent soil moisture status and hence aeration may not be suitable for increased N_2O production; in soils already well-supplied with both readily metabolizable C and mineral N any increase in N_2O emission may be too small to have a significant effect. It has been suggested that the effect of the added C in manures on denitrification and N_2O emissions would be greatest in soils with little SOM.

While it is likely that the use of these methods will, by increasing the amount of manure-N that enters the soil, increase direct emissions of N_2O, indirect emissions will be reduced. Concerns over increasing emissions of N_2O should not be a barrier to the adoption of reduced- NH_3 emission spreading techniques. In a modelling study of the impacts of NH_3 abatement measures, on nitrate (NO_3^-) leaching and N_2O emissions using the NARSES model, Webb et al. (2007) found that the increase in N_2O emissions was never more than 2% of the NH_3-N conserved. In total N_2O emissions were little changed by the adoption of NH_3 abatement techniques. Some NH_3 abatement methods also decrease emissions of both NO_3^- and N_2O. Thus it is possible to formulate approaches to reducing emissions of NH_3 without axiomatically causing large increases in emissions of either NO_3^- or N_2O.

Slurry supplies metabolizable-C which can be used as a substrate for nitrification and denitrifcation leading to an immediate increase in emissions of N_2O. Concentrations of metabolizable-C in litter-based manures are smaller, often as a result of leaching of soluble-C during manure storage, and hence additions of these manures provide less stimulus to microbial activity than additions of slurries.

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