An Inventory of Methods to Control Ammonia Emissions from Agriculture

Ammonia Mitigation User Manual

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INTRODUCTION

Emissions of ammonia to the atmosphere are of concern because of the damaging effects of subsequent deposition to sensitive ecosystems through eutrophication and soil acidification and, increasingly, because of the role that atmospheric ammonia has in the formation of fine particulates which have human health implications. Some of the ammonia emitted from a source can be transported long distances, crossing international boundaries, before deposition, which has led to the formulation of international legislation[1,2]. Under this legislation, the UK is required to ensure that total ammonia emissions are below the agreed emission ceiling (currently set at 297 kt by 2010, but new targets are being negotiated for 2020). However, much of the emission may be deposited locally (within 1 km of the source), increasing the importance of closely located significant sources in the consideration of protection of sensitive habitats.

A large body of research has been funded by Defra aimed at assessing potential methods for mitigating ammonia emissions from agricultural sources (for further details see Defra Project report ES0127 “Defra Research in Agriculture and Environmental Protection, 1990-2005”), which represent by far the major source of UK ammonia emissions (>85% of total) [3]. Non-agricultural ammonia emissions arise from a relatively large number of minor sources. In consequence, there has been much less emphasis to date in terms of providing robust estimates of emission from each individual source or assessing potential mitigation methods. Wastewater treatment plants represent the most significant non-agricultural source, for which an improved knowledge of current emissions, treatment activities and mitigation potential would be beneficial. This document therefore focuses only on mitigation methods for the agricultural sector.

The primary purpose of this document is to provide information on the range of potential mitigation methods available to aid the formulation of strategies and policies aimed both at meeting national ammonia ceiling targets and local protection of sensitive habitats. This document is not intended as an on-farm implementation guide, but provides an overview of the mitigation methods available, which can then be researched in more detail for farm-specific purposes if required.

A total of 25 potential mitigation methods are described in this Ammonia Mitigation User Manual, of which 20 are considered to be immediately applicable within the industry (Table 1a), 3 require more development in terms of a route to industry (Table 1b) and 2 are speculative, requiring further research to confirm effectiveness and applicability (Table 1c). The list of methods is not exhaustive, but is considered to represent those which are potentially applicable to the UK. There are a number of manure and feed additives which have not been included in this list as the evidence for their effectiveness is weak or inconclusive. However, two which might be worth future consideration in the UK are the use of aluminium sulphate (or aluminium chloride) which is an accepted mitigation measure within broiler housing in the United States[4], and in-house acidification of pig slurry which has

[1] UNECE Gothenburg Protocol (1999) http://www.unece.org/env/lrtap/full%20text/1999%20Multi.E.Amended.2005.pdf
[2] National Emissions Ceilings Directive (2001) http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2001:309:0022:0030:EN:PDF
[3] National Atmospheric Emissions Inventory Report ‘UK Emissions of Air Pollutants 1970 to 2006’, http://www.naei.org.uk/reports.php
[4] Choi, I. H., and Moore, P. A. (2008). Effects of liquid aluminium chloride additions to poultry litter on broiler performance, ammonia emissions, soluble phosphorus, total volatile fatty acids, and nitrogen contents of litter. Poultry Science 87, 1955-1963.

been applied to a limited number of farms in Denmark[5]. These methods are not currently included in the Integrated Pollution Prevention and Control Reference Document on Best Available Techniques for Intensive Rearing of Poultry and Pigs (BREF document)[6] and further review and research would be required to assess effectiveness and applicability to the UK pig and poultry sectors.

In the methods descriptions section, methods have been grouped according to the following categories:

- Livestock diet
- Livestock housing
- Manure storage
- Manure application to land
- Fertiliser use

The methods are not presented in any order of effectiveness (although some discussion of cost-effectiveness and order of implementation for each sector is given with summary tables 3a-3e). Each method is given a number and a brief title that can be used in tables and for reference. This is followed by a description of the method and its application, arranged into ten sections:

Description: A description of the actions to be taken to implement the method.

Rationale: The broad reason for adopting the method as a means of reducing ammonia emission.

Mechanism of action: A more detailed description of the processes involved and how the method achieves a reduction in ammonia emission.

Potential for applying the method: An assessment of the farming systems, regions, soils and crops to which the method is most applicable.

Current implementation: The degree to which the method has already been adopted within the industry or sector. This will influence the overall impact of full adoption of a method on the ammonia mitigation which might be expected.

Practicability: An assessment of how easy the method is to adopt, how it may impact on other farming practices and possible resistance to uptake. Additionally, a **score** is given as an indication of how readily the mitigation method might be implemented:

1 = tried and tested, ready for industry adoption
2 = potential method, development route to industry required
3 = speculative method, further research and route to industry required and/or not practical

Costs: Estimates are presented of how much it would cost to implement the method, taking into account annual running costs and an annual charge for any capital investment required derived by amortising the required investment over the anticipated write-off period at an interest rate of 7%. Costs are presented per head of livestock or per cubic metre/tonne of manure, whichever is the most appropriate. Costs are primarily derived from a report by

[5] Kai, P., Pedersen, P., Jensen, J. E., Hansen, M. N., and Sommer, S. G. (2008). A whole-farm assessment of the efficacy of slurry acidification in reducing ammonia emissions. European Journal of Agronomy 28, 148-154.
[6] European Commission 2003. Integrated Pollution Prevention and Control Reference document on best available techniques for intensive rearing of poultry and pigs.

Martin Ryan[7], the publication by Webb *et al*[8] and the 'Diffuse Water Pollution to Agriculture User Manual'[9].

Effectiveness: Estimates are presented of the ammonia emission reduction efficiency of the method with, for some methods, factors influencing the effectiveness. Estimates of the effectiveness of the method in reducing emission from a particular sector are also presented, taking account of the potential for application and current implementation, based on the Inventory of Ammonia Emissions from UK Agriculture, 2006[10]. Reduction efficiencies are as compared to UK 'standard practice', for which the emission factors are given in the Inventory of Ammonia Emissions from UK Agriculture, 2006. It is important to note that estimated reductions in emission are through the implementation of the single method in question. Reductions achieved through implementation of combinations of methods are not necessarily additive and alternative methods for a given emission source may be mutually exclusive.

Other benefits or risk of pollution swapping: This section provides a largely qualitative assessment of how the ammonia mitigation method may influence other pollutant losses. Some mitigation methods may have knock-on effects on ammonia emissions from 'downstream' management activities. This is illustrated in Fig. 1, which shows the flow of nitrogen from livestock feed input to manure application to land, through the management stages of livestock housing and manure storage (with additional direct inputs to land through fertiliser applications and grazing livestock). Dietary manipulation to reduce N excretion will reduce N losses by ammonia or other pathways (such as denitrification and nitrate leaching) from all subsequent sources. However, a mitigation method which reduces ammonia emission from livestock housing has the potential to increase ammonia (and other N) emissions from manure storage and land application, as the N retained at housing flows through the system increasing the available N at later stages. It is therefore important that a holistic approach is taken regarding mitigation to ensure that maximum benefits are achieved. Other manuals have been produced detailing potential mitigation methods specific to diffuse pollution to water from agriculture[9] and greenhouse gas emissions from agriculture[11]. Additionally, ongoing work (within Defra project WQ0106) seeks to bring together all key mitigation methods for a range of pollutants in order to provide a comprehensive overview of the potential for win-win scenarios or pollution swapping.

Key references: Key reports and/or papers where further information regarding the method can be found.

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[7] Ammonia Emission Abatement Measures; Unit cost of measures for Agriculture. 2004. Prepared by M Ryan, Rural Development Service.

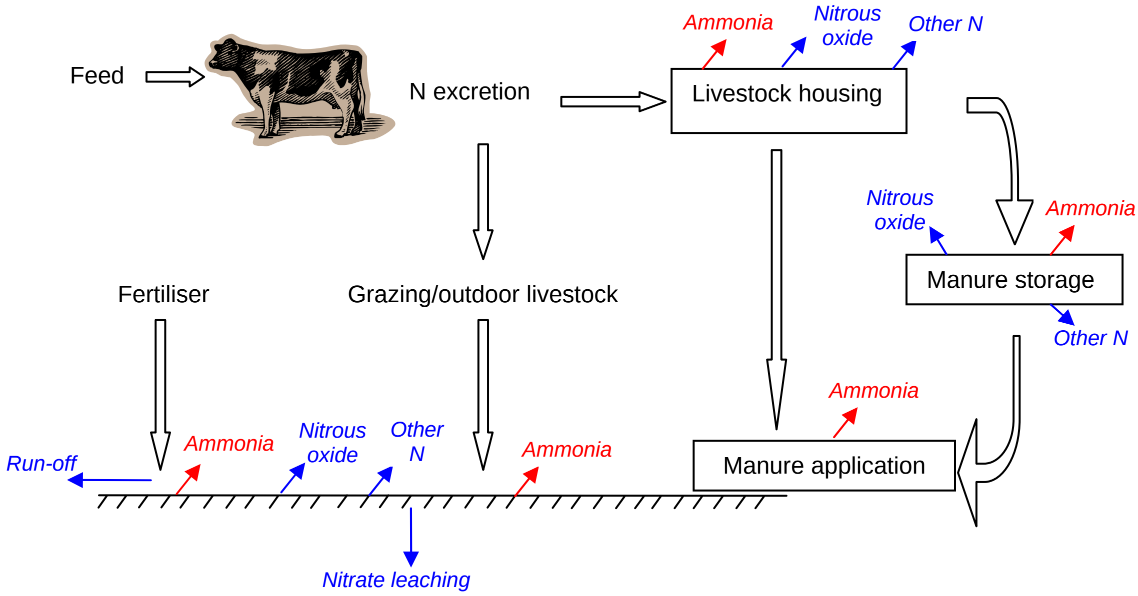
[8] Webb, J., Ryan, M., Anthony, S.G., Brewer, A., Laws, J., Aller, M.F., Misselbrook, T.H. 2006. Cost-effective means of reducing ammonia emissions from UK agriculture using the NARSES model. Atmospheric Environment 40, 7222-7233.

[9] Cuttle, S.P., Haygarth, P.M., Chadwick, D.R., Newell-Price, P., Harris, D., Shepherd, M.A., Chambers, B.J., Humphrey, R. 2006. An inventory of measures to control diffuse water pollution from agriculture. Report to Defra, project ES0203.

[10] Misselbrook, T.H., Chadwick, D.R., Chambers, B.J., Smith, K.A., Williams, J., Demmers, T.G.M. 2007. Inventory of ammonia emissions from UK agriculture 2006. Report to Defra (Project AC0102).

[11] Moorby, J.M., Chadwick, D.R., Scholefield, D., Chambers, B.J., Williams, J.R. 2007. A review of research to identify best practice for reducing greenhouse gases from agriculture and land management. Reprot to Defra as part of project AC0206.

Figure 1 – N flows and losses through the livestock production system



Described methods in relation to existing legislation

This manual describes methods which can be used specifically to mitigate ammonia emissions from specific sources within agriculture. However, existing regulations relating to minimising diffuse pollution from agriculture may already require some of the methods to be implemented, or may conflict with some of the methods listed within this document. Two pieces of legislation which are particularly relevant in this respect are that relating to Nitrate Vulnerable Zones (NVZ) and Pollution Prevention and Control (PPC), further details of both of which can be found on the Environment Agency web-site[12,13] or in Defra publications[14,15].

Farms operating within a NVZ have to comply with regulations regarding the timing and amounts of manure applied to land, which are dependent on soil type and cropping, and are aimed at minimising nitrate leaching losses. One of the main effects is a requirement to increase manure storage capacity and a move from autumn/winter to spring/summer application timings. Both of these effects will to some extent result in increased ammonia emissions – larger surface area of storage from which emissions can occur and manure applications under hotter, dryer conditions enhancing ammonia loss. Adoption of methods to mitigate emissions from these sources (e.g. Methods 16-18 for manure storage and 20-22 for manure application) should be encouraged. Conversely, Methods 20-22, aimed at reducing ammonia emissions from manure applications pose a risk of increased nitrate leaching. It is important therefore that these methods are used at appropriate times, with agronomically appropriate manure application rates.

Large pig and poultry farms are required under the Environmental Permitting Regime legislation to use best available techniques (BAT) to minimise ammonia emissions. Guidance notes (BREF document) list a large number of potential housing systems which would qualify as BAT. However, in this User Manual a full list of all potential housing designs has not been included. Rather, the general principles relating to the means by which ammonia emission reduction is achieved, which can then be applied to individual systems in a variety of ways, have been listed. These include frequent manure removal (Methods 3, 6 and 7), improved

[12] http://www.netregs.gov.uk/netregs/sectors/1736703/1736798/1742497/
[13] http://www.environment-agency.gov.uk/commondata/acrobat/ippc_comply_0406_1397535.pdf
[14] Guidelines for Farmers in NVZs – England. Defra booklet PB5505, July 2006
[15] Manure Planning in NVZs – England. Defra booklet PB5504, July 2002.

floor design (Method 4), direct filtering of exhaust air (Method 5) and poultry manure drying (Method 8). All methods listed for manure storage and application would equally qualify as BAT.

Summary Tables

This section provides an overview of the potential mitigation methods which are described in this manual (Table 1), their current implementation, applicability, reduction efficiency and costs (Table 2). In addition, information per livestock sector is presented (Table 3: Dairy, Beef, Pig, Laying hens, Other poultry, Fertiliser), giving an overview of the potential impact of each method on each sector. In these sector tables, those methods which could be readily implemented (i.e. with a practicability score of 1) are listed first, in descending order of potential feasible reduction. Less certain methods (*i.e.* with practicability scores of 2 or 3) are listed below the dashed line in each table.

Table 1: Methods to reduce ammonia emissions

Table 1a: Methods immediately applicable to UK agriculture

Category	No.	Method
Livestock diet	2	Adopt phase feeding of livestock
Livestock housing	3	Frequent removal of slurry from below slatted-floor storage in pig housing
	4	Part slatted-floor design for pig housing
	5	Install air-scrubbers or biotrickling filters to mechanically ventilated pig housing
	6	Convert caged laying hen housing from deep-pit storage to belt manure removal
	7	More frequent manure removal from laying hen housing with belt clean systems
	8	In-house poultry manure drying
	9	Increase scraping frequency in dairy cow cubicle housing
	10	Conversion of slurry-based to solid manure management systems for cattle
	12	Extend the grazing season for cattle
	14	Washing down of dairy cow collecting yards
Manure storage	16	Install covers on slurry stores
	17	Allow cattle slurry stores to develop a natural crust
	18	Cover solid manure stores with sheeting
	19	Store FYM prior to land application
Manure application	20	Use slurry band spreading application techniques
	21	Use slurry injection application technique
	22	Rapid soil incorporation of manure following land application
Fertiliser use	23	Replace urea fertiliser with another nitrogen form (e.g. ammonium nitrate)
	25	Integrate fertiliser and manure nitrogen supply

Table 1b: Methods potentially applicable to UK agriculture

Category	No.	Method
Livestock diet	1	Reduce dietary N intake
Livestock housing	11	Additional targeted straw bedding for cattle housing
Fertiliser use	24	Incorporate a urease inhibitor with urea-based fertilisers

Table 1c: Speculative methods potentially applicable to UK agriculture

Category	No.	Method
Livestock housing	13	Outwintering of cattle on woodchip stand-off pads
	15	Establish tree shelter belts around livestock housing facilities

Table 2: Summary of mitigation methods: applicability, current implementation, reduction efficiency and costs

Source	Method	Sector	Practicability score[†]	Applicability[‡] %	Current implementation %	Reduction efficiency %	Annual unit cost* £	Maximum feasible reduction kt NH_3
Livestock diet	1	Cattle, Pig, Poultry	2/3	50-100	0	20?	Up to 45 [a]	16?
	2	Cattle, Pig	1	100	c. 100	10-30	0.65-4.30[a]	<1
Livestock housing	3	Pig	1	100	0	25	8.50[a]	3
	4	Pig	1	100	0	20-50	7.10[a]	3-4
	5	Pig	1	New build only	0	70-95	17[a]	0-1
	6	Poultry	1	New build only	50	50	?	0-1
	7	Poultry	1	100	50	50	0.02[a]	0.5
	8	Poultry	1	100	<5	25-50	0.02-0.50[a]	3
	9	Cattle	1	100	<10	20	1.10[b]	1.5
	10	Cattle	1	100	34 dairy, 82 beef	25-30	122[a]	16
	11	Cattle	2	100	?0	50?	25[a]	4.5
	12	Cattle	1	50?	40?	1-2	-	<1
	13	Cattle	3	100	<1	?	10-20[a]	?
	14	Cattle	1	100	<5	90	30-40[a]	5
	15	Pig, Poultry	3	100	?	5-10	?	?
Manure storage	16	Pig	1	100	<1	40-80	0.35-1.10[b]	1.6
	17	Cattle	1	100	80	50	0.2[b]	1
	18	Cattle, Pig, Poultry	1	100	0	15-90	0.6[b]	3
	19	Cattle, Pig	1	100	70	30	2-3[b]	5
Manure application	20	Cattle , Pig	1	100	3 cattle, 13 pig	30-60	1.40-1.60[b]	18
	21	Cattle, Pig	1	70 grassland, 10 arable	1 cattle, 11 pig	70-90	2.80[b]	14
	22	Cattle, Pig, Poultry	1	50-90	<10	60-85	0.40-5.00[b]	13
Fertiliser use	23	All	1	100	-	90	-	16
	24	All	2	100	0	40-70	-	11
	25	All	2	100	?	?	-	?

[†]Practicability score: 1, immediate take-up; 2, some further development; 3, speculative
[‡]Applicability is specific to the source being mitigated e.g., 100% applicability for Method 4 means it is 100% applicable to *__slurry-based__* pig housing, not all pig housing
* Unit cost: a, per animal place; b, per m^3 slurry or tonne FYM/poultry manure (fresh weight)
** Applies also to manure deriving from housed sheep, horses, deer, etc.

Table 3: Potential impact of mitigation methods by livestock sector

Table 3a: Dairy (sector total emission of 84.5 kt NH_3, 2006 inventory)

Method	Description	Potential reduction kt NH_3	Reduction as % of sector total
20	Use slurry band spreading application	13.3	16
10	Convert slurry systems to straw-based	11.7	14
21	Use slurry injection application	10.1	12
14	Wash dairy cow collecting yards	5	6
22	Rapid incorporation of applied manure	1.9	2
9	Increased scraping in cubicle house	1.5	2
19	Store all FYM for >3 months	1.0	1
17	Allow slurry stores to form natural crust	0.8	1
18	Cover FYM stores with sheeting	0.2	<1
12	Extend the grazing period	<1	<1
Less certain methods:			
1	Reduced dietary N intake	11	13
11	Increased, targeted bedding	1.5	2
13	Out-winter on woodchip corrals	?	?

Table 3b: Beef (sector total emission of 64.4 kt NH_3, 2006 inventory)

Method	Description	Potential reduction kt NH_3	Reduction as % of sector total
20	Use slurry band spreading application	4.1	6
10	Convert slurry systems to straw-based	4.0	6
21	Use slurry injection application	3.3	5
19	Store all FYM for >3 months	2.6	4
22	Rapid incorporation of applied manure	2.3	4
18	Cover FYM stores with sheeting	1.0	2
17	Allow slurry stores to form natural crust	0.2	<1
12	Extend the grazing period	<1	<1
Less certain methods:			
11	Increased, targeted bedding	3.0	5
13	Out-winter on woodchip corrals	?	?

Reduced emission slurry spreading techniques (Methods 20 and 21) give some of the maximum reductions of any single method for the cattle sectors (Tables 3a and 3b) and, combined with rapid incorporation of manure applied to arable land (Method 22), represent the most sensible first options in trying to achieve reductions from these sectors. Almost all cattle housing is naturally ventilated, with limited options for reducing emissions. The conversion of slurry-based to straw-based systems presents one option, with potentially large reductions in emission, but would require significant structural changes to management systems and a greatly increased demand for straw bedding (which may not be able to be met), making this a less viable option. Outwintering of stock on woodchip corrals may offer an alternative housing reduction option and ongoing research will yield more quantitative information for this option in the near future. Manure storage options are also limited; with most existing slurry stores developing a crust the potential for further reduction (by crusting or covering) is small. Storing of FYM as opposed to spreading directly from the house, combined with covering of the heaps offers some potential reductions although further work is required regarding the practicalities of covering manure heaps. Dietary N reduction can potentially give large reductions in emission and ongoing research aims to provide potential solutions for uptake, although the difficulties of achieving this with largely forage-based diets are not to be underestimated.

Table 3c: Pig (sector total emission of 26.6 kt NH_3, 2006 inventory)

Method	Description	Potential reduction kt NH_3	Reduction as % of sector total
4	Part-slatted floor design	3.5	13
3	Frequent slurry removal	3	11
22	Rapid incorporation of applied manure	2.7	10
16	Fit slurry store tank covers	1.6	6
19	Store all FYM for >3 months	1.4	5
20	Use slurry band spreading application	1.0	4
18	Cover FYM stores with sheeting	0.5	2
21	Use slurry injection application	0.5	2
2	Phase feeding	<1	<1
Less certain methods:			
1	Improved livestock diet	5	19
15	Tree belts around housing	<1	<1

For the pig sector, the largest potential reductions in emission are given by Methods applicable to housing (Methods 3 and 4, Table 3c). Implementation of these methods might rely on replacement of existing housing as it reaches the end of its useful lifetime with purpose-built facilities. More immediate impact can probably be achieved through implementation of Methods associated with land spreading (Methods 20, 21 and 22) and slurry storage (Method 16).

For the poultry sector, the largest potential reductions in emission are also given by Methods applicable to housing (Methods 6, 7 and 8, Tables 3d and 3e) and rapid incorporation of applied manure (Method 22). As mentioned above, the use of aluminium sulphate as a bedding additive within broiler systems has been used for some years in the United States and the potential for use in the UK should be considered.

Table 3d: Laying hen (sector total emission of 9.6 kt NH_3, 2006 inventory)

Method	Description	Potential reduction kt NH_3	Reduction as % of sector total
6	Convert deep-pit to belt clean systems	1	10
8	In-house manure drying	1	10
22	Rapid incorporation of applied manure	0.7	7
7	Twice-weekly manure removal on belts	0.5	5
18	Cover FYM stores with sheeting	0.2	2
Less certain methods:			
15	Tree belts around housing	<1	<1

Table 3e: Broilers and other poultry (sector total emission of 28.3 kt NH_3, 2006 inventory)

Method	Description	Potential reduction kt NH_3	Reduction as % of sector total
22	Rapid incorporation of applied manure	5.0	18
8	In-house manure drying	1.8	6
18	Cover FYM stores with sheeting	0.8	3
Less certain methods:			
15	Tree belts around housing	<1	<1

For fertiliser use, replacement of urea or urea ammonium nitrate fertilisers with ammonium nitrate or other N form would give significant reduction in emission. However, usage of the different fertiliser types is largely driven by unit cost and manipulation of the relative proportions used may be difficult to achieve through policy measures without breaching free trade agreements. Better integration of manure and fertiliser N supply is being achieved to some extent through NVZ legislation and also because of increasing fertiliser prices. However, it is difficult to predict the overall impact of this on national emission totals.

Table 3f: Fertiliser use (sector total emission of 32.6 kt NH_3, 2006 inventory)

Method	Description	Potential reduction kt NH_3	Reduction as % of sector total
23	Replace urea/UAN with another N form	16.4	50
25	Integrate manure and fertiliser N supply	?	?
Less certain methods:			
24	Include urease inhibitor with urea/UAN	11.4	35

DETAILS OF METHODS

1. Reduce dietary N intake

Description: Adjust the composition of livestock diets to reduce the total intake of N per unit of production.

Rationale: Avoiding excess N in the diet and/or making dietary N more available allows the concentration of N in the diet to be reduced without adversely affecting animal performance. Both reduce the amount of N excreted, thereby reducing the potential for ammonia volatilisation losses throughout the whole livestock and manure management continuum.

Mechanism of action: Farm animals are often fed diets with higher than recommended N content, partly as a safeguard against a loss of production arising from a deficit, and partly through the use of N-rich ingredients being used as a source of essential amino acids in least-cost feed formulations (when these are less expensive than synthetic amino acids). In practice, however, surplus N is not utilised by the animal and will be excreted. Most of the surplus N intake will be excreted in the urine, in the form most susceptible to ammonia volatilisation. Reducing the crude protein content of the diet, while ensuring that the requirement for essential amino acids is met, will limit the amount excreted, particularly in urine (from which ammonia emissions predominantly derive), without affecting animal performance. Excretion can also be reduced by changing the composition of the diet to increase the proportion of dietary N utilised by the animal; for example, by optimising the balance of N to carbohydrate in ruminant diets or by reducing the proportion of rumen-degradable protein. In ruminants and non-ruminants, feeding a ration that supplies amino acids in the ideal proportions required for protein synthesis will reduce the amount of ‘surplus’ amino acids that remain unutilised and contribute to N excretion (commercial rations formulated on a least-cost basis will often supply many amino acids in surplus while ensuring that sufficient of the essential amino acids are present).

Potential for applying the method: Benefits will most readily be realised on indoor pig and dairy units (where feedstock components can be manipulated). The greatest challenges exist on cattle farms feeding a largely forage diet (although developments in plant breeding to produce forages aimed at improving N utilisation by ruminants continue). There is limited scope for further reducing the N content of poultry diets without reducing output. There are concerns that reducing nutrient inputs may also have adverse effects on reproductive performance or carcase quality. Clear guidance is required on appropriate crude protein contents in diets for different livestock types.

Practicability: The extent to which this method can be applied depends on the proportion of farms currently feeding excess N (many pig and dairy farms may already be implementing the method to varying degrees). Precise formulation of diets requires accurate analytical data about the chemical composition of the feedstuffs, which may not be readily available for forages. Within the dairy sector there is already a focus on lowering total diet crude protein content, optimising protein:energy balance in the rumen and supplying adequate metabolisable protein. Reducing the crude protein content of the diet to 14% may be a significant challenge in areas relying on grass silage. There is limited applicability for the method in the beef cattle and sheep sectors.

Practicability Score: 1 for pigs and poultry; 2 for dairy cows

Current implementation: Current implementation of reduced crude protein diets supplemented by synthetic amino acids is considered to be non-existent in cattle sectors and, while many least-cost pig diets will contain synthetic amino acids, total crude protein content is not often considered a constraint in ration formulation.

Cost: For dairy cows, costs will depend on the extent to which protein is being oversupplied, and it may be possible to make cost savings. However, switching from a standard dairy cake and supplementing with soya could cost up to £45 per cow per year. For pigs, a slight loss in production together with an increased cost of diet formulation gives an approximate annual cost of £17.50 per sow. For broilers, small reductions in N input are estimated to cost £0.008 per bird.

Effectiveness: The effectiveness of this method will vary according to the reduction in crude protein intake by the animal and the level of production achieved. Based on limited laboratory studies and controlled feeding trials, it is estimated that reductions in ammonia emission of up to 20% might be achieved through strict control of dietary N intake. This could result in potential reductions of up to 5 kt and 11 kt NH_3 for the UK pig and dairy sectors, respectively (assuming reductions in N excretion for the housed period only for dairy cows).

Other benefits or risk of pollution swapping: Reducing the amount of N excreted, particularly the more readily available N in urine, will reduce the potential for all forms of diffuse N pollution (ammonium-N in surface drainflow/run-off, nitrate leaching, nitrous oxide emission). Thus, if estimated maximum reductions are achieved in N excretion, then these pollutant pathways may also be reduced by up to 20%. Impacts on methane emissions from ruminants will depend on the changes in diet composition and digestibility (see Defra project AC0206).

Key references:

Dourmad, J.Y., Jondreville, C. (2007). Impact of nutrition on nitrogen, phosphorus, Cu and Zn in pig manure on emissions of ammonia and odours. *Livestock Science* 112, 192-198.

Misselbrook, T. H., Powell, J. M., Broderick, G. A., and Grabber, J. H. (2005). Dietary manipulation in dairy cattle: laboratory experiments to assess the influence on ammonia emissions. *Journal of Dairy Science* 88, 1765-1777.

Misselbrook, T. H., Chadwick, D. R., Pain, B. F., and Headon, D. M. (1998). Dietary manipulation as a means of decreasing N losses and methane emissions and improving herbage N uptake following application of pig slurry to grassland. *Journal of Agricultural Science* 130, 183-191.

Defra project AC0206 ‘A review of research to identify best practice for reducing greenhouse gases from agriculture and land management’

2. Adopt phase feeding of livestock

Description:

- Manage livestock in groups, divided on the basis of their individual feed requirements.
- Feed the groups separately with rations matched to the optimum N (and P) requirements of the animals within each group (phase feeding).

Rationale: Phase feeding allows more precise matching of the ration to the individual animal's nutritional requirements. Nutrients are utilised more efficiently and less of the dietary N is excreted, thereby reducing the N content of manures. This reduces the amount of N available for loss via ammonia emission from the point of excretion onwards (*i.e.* during livestock housing, manure storage and following land spreading

Mechanism of action: Livestock at different growth stages or stages of the reproductive or lactation cycle have different optimum feed requirements. However, because of limited labour and housing facilities, livestock with different feed requirements are often grouped together and receive the same ration. As a result, some stock will receive higher levels of N (and P) than they can utilise efficiently and will excrete the surplus (see Method 1). Greater division and grouping of livestock on the basis of their feed requirements allows more precise formulation of individual rations. This will reduce N (and P) surpluses in the diet and reduce the amounts excreted.

Potential for applying the method: The measure is applicable to all livestock systems except those based primarily on grazing (e.g. beef cattle and sheep).

Current implementation: Phase feeding is currently widely practiced in the poultry and pig sectors. However, the number of steps or 'phases' used vary, depending on the number of buildings and feeding facilities available on a particular unit. More detailed survey data are required to assess the level of implementation. In the dairy sector, in-parlour feeding of concentrates to lactating dairy cows according to production level is widely practiced.

Practicability: The method is most suited to larger units, where there would be greater numbers of animals in the individual feeding groups. Feeders are now available which can deliver differing diets to individual animals within the same building. However, in reality, the industry is unlikely to move beyond a limited number of feeding phases because of the increasing complexity and costs, without necessarily improving performance.

Practicability Score: 1 for pigs and poultry, 2 for dairy cattle

Cost: For pigs, the cost of implementing an additional feeding phase is estimated at £0.65 per pig place (based on provision of an additional feed-bin and associated auger and pipe). For dairy cattle, the fitting of transponders and in-parlour feeders is estimated at £4.30 per cow.

Effectiveness: For growing pigs, reductions in ammonia emissions deriving from phase feeding are estimated at between 10 and 30% when compared with a single diet throughout the entire growing period. However, the practice is already commonly adopted and the implementation of a greater number of phases within the pig industry is unlikely, so total further reductions in emission which might be achieved through further implementation are minimal (perhaps up to 1 kt NH_3). For dairy cattle, where a large part of the diet is likely to be forage based, emission reductions are likely to be difficult to deliver practically.

Other benefits or risk of pollution swapping: Reducing the amount of N excreted will reduce the potential for diffuse losses to water (ammonium-N in surface drainflow/run-off and nitrate leaching) and for gaseous emissions of nitrous oxide. If phase feeding also reduced P intake, there would be additional benefits of reducing diffuse losses of P to water.

Key references:

Defra project WA0309 'Phase feeding of pigs to reduce nutrient pollution'

Dourmad, J.Y., Jondreville, C. (2007). Impact of nutrition on nitrogen, phosphorus, Cu and Zn in pig manure on emissions of ammonia and odours. Livestock Science 112, 192-198.

3. Frequent removal of slurry from below slatted-floor storage in pig housing

Description: Frequent removal of slurry from below slatted-floor storage pits to an outside, covered store, by vacuum removal systems operated at least twice per week. This replaces the system whereby slurry is stored beneath the slats for typically 1-6 months.

Rationale: Ammonia emissions from a slatted-floor pig house derive both from manure deposited onto the slat surfaces and also from the slurry in the below slatted-floort storage area. Frequent removal of the beneath-slat source will reduce the overall ammonia emission from the pig house. Removal to a covered store (see Method 16) will prevent further emissions during slurry storage offsetting the reduction achieved in the housing phase.

Mechanism of action: This method relies on the removal of a source of ammonia emission from the pig house.

Potential for applying the method: This method could be applied to all slatted-floor pig housing, subject to sufficient outside storage capacity being available.

Current implementation: Low

Practicability: This method is most suited to purpose-built new installations. For new-build, this method could be combined with Method 4 to reduce the emitting surface area. There may be considerable reluctance to the retro-fitting of pig housing (and costs would rule it out in most cases) and there is a requirement for additional covered storage capacity.

Practicability Score: 1 (technology exists, but can only be fully implemented in new buildings)

Cost: £8.50 per pig place per annum for finishing pig accommodation, based on increased costs of housing construction, increased running costs and the provision of a slurry storage tank (covered).

Effectiveness: This method is estimated to give a 25% reduction in emissions from pig housing (based on the EC BREF document), although more experimental evidence is required to provide a robust reduction value. A key factor for the success of this method is that the slurry should be removed completely each time (twice per week), otherwise an emitting surface will still be present. Also, that ammonia emissions from outdoor slurry storage (generally under cooler conditions than within the house) are not further increased, which can be controlled by using a store cover (see Method 16). Assuming the method to be applied to all currently slurry-based finishing pig housing (with covered storage included as part of the method), total reduction from the UK pig industry would be approximately 3 kt NH_3.

Other benefits or risk of pollution swapping: Reducing ammonia emissions from the pig house will result in a greater ammonium-N content of the slurry going to storage. Potentially, therefore, emissions from slurry storage and land spreading will be greater unless mitigation methods are employed. An increase in the readily available N content of the slurry at spreading will also increase the potential for pollution via other N losses (*e.g.* in drainflow/run-off, nitrate leaching and nitrous oxide emission). This method may also be associated with a reduction in the in-house concentrations of hydrogen sulphide and other odorants.

Key references:

BREF document: European Commission 2003. Integrated Pollution Prevention and Control Reference document on best available techniques for intensive rearing of poultry and pigs.

4. Part-slatted floor design for pig housing

Description: A part-slatted floor is used (rather than fully-slatted), ideally with a domed solid floor area and with sloping sided below slatted-floor slurry storage.

Rationale: This method aims to reduce the overall emitting surface area of slurry.

Mechanism of action: Ammonia emissions from pig housing derive from the fouled floor/slat area and from the surface of the below slatted-floor slurry storage. Providing a solid floor lying area and a slatted floor dunging area can reduce emissions compared with a fully-slatted design. A 50:50 void:floor area (compared with traditional 20:80) can further reduce the fouled floor area. Also, a domed lying area will encourage any urine deposited in that area to quickly drain to the below-slat storage. The ventilation airflow direction is critical to the success of this system. Incoming airflow should be drawn downwards to the central lying area and then horizontally across the slatted surface. This encourages pigs to lie in the lying area and dung over the slatted area, and also results in very little air mixing above the slurry surface below the slats.

Potential for applying the method: This method is potentially applicable to all slurry-based pig housing, provided the appropriate ventilation system is also present or installed.

Current implementation: Low

Practicability: This method is most suited to larger units and to purpose-built new installations. For new-build, this method could be combined with Method 3 and the adoption of sloping sided below slat storage to reduce the emitting surface area. However, the practicality of retro-fitting would depend on current building design and would not be possible for many older buildings.

Practicability Score: 1, but air flow control and animal behaviour aspects are critical to the success of this method

Cost: £7.10 per pig place per annum, including cost of additional outside slurry storage (with cover).

Effectiveness: Emission reductions of between 20-50% from the house have been achieved when compared with a conventional fully-slatted system. Building ventilation design is critical to the effectiveness, as discussed above. If applied to all currently slurry-based pig housing, reductions in emission from the UK pig sector would be between 3 – 4 kt NH_3.

Other benefits or risk of pollution swapping: Reducing ammonia emissions from the pig house will result in a greater ammonium-N content of the slurry going to storage. Potentially, therefore, emissions from slurry storage and land spreading will be greater unless mitigation methods are employed. An increase in the readily available N content of the slurry at spreading will also increase the potential for pollution via other N losses (*e.g.* in drainflow/run-off, nitrate leaching, nitrous oxide emission). This method may be associated with a reduction in the in-house concentrations of hydrogen sulphide and other odorants.

Key references:

Defra project WA0720 ‘Demonstrating opportunities for reducing ammonia emissions from pig housing’

Chambers, B. and Nicholson, F. (2005). Emissions from pigs and ppoultry farms. Society of Chemistry and Industry – Symposium on Ammonia; Approaches, National Emission Ceiling Targets, London, March 2005 [Abstract]

5. Install air scrubbers or biotrickling filters to mechanically-ventilated pig housing

Description: Exhaust air from mechanically-ventilated pig housing is treated by acid scrubbers or biotrickling filters to remove ammonia.

Rationale: While this method does not reduce the ammonia emission from floor/slurry surfaces within the house, it removes ammonia from the exhaust air-stream, thereby reducing the emission from the house to the wider environment.

Mechanism of action: Ammonia is very readily absorbed by low pH (acid) solutions. Acid scrubbers mainly apply sulphuric acid in their recirculation water to bind ammonia, as ammonium sulphate. Nitrogen is removed from the system by controlled discharge of the recirculation water. In biotrickling filters, ammonia is converted to nitrate through bacterial action of the biomass held on the synthetic supporting material (organic materials tend to have a short lifetime) and in the recirculation water. As with acid scrubbers, nitrogen is removed from the system by controlled discharge of the recirculation water.

Potential for applying the method: This method is most suited to exhaust-ventilated pig housing, although the very high conversion costs are likely to restrict application to new build only. High dust loading in poultry housing complicate reliable long-term functioning of current designs.

Current implementation: Zero

Practicability: The requirement for specific ventilation designs to treat the exhaust air restricts the practical application of this method to newly purpose-built facilities. Current waste regulations may restrict the use of the wastewater, which potentially has a fertiliser replacement value.

Practicability Score: 1 (for new purpose-built pig housing only)

Cost: £17 per pig place per annum, based on data from the Netherlands.

Effectiveness: Where used in the Netherlands, Germany and Denmark, reduction efficiencies of 70-95% in the animal house have been cited. However, as the method can only be implemented in new purpose-built facilities, adoption will be slow. Assuming a life expectancy of pig buildings of 20 years, 5% will be replaced per year. If all of the replacements adopted this method, then potential reduction from the UK pig sector would be *c.*1 kt NH_3 over the next 10 years.

Other benefits or risk of pollution swapping: Treatment of the exhaust air will also remove other air pollutants (e.g. particulates, odorants). The discharge water from the air scrubber or biotrickling filter could be used as an inorganic fertiliser, subject to waste regulations, although subsequent N losses from such use could arise.

Key references:

Aarnink, A.J.A., van Hattum, T., Hol, A., Zhao, Y. (2007). Reduction of fine dust emission by combi-scrubber of Big Dutchman. Report No. 66, Animal Sciences Group Wageningen, NL. ISSN 1570-8616

6. Convert caged laying hen housing from deep-pit storage to belt manure removal

Description: In a deep-pit system, manure from laying hens drops to a pit below the tiers of cages where it is commonly stored for a number of months prior to removal. This is replaced by a series of belts below each tier of cages that retain the manure dropped by the hens, which is then removed from the house (usually on a weekly basis) by mechanically running the belts.

Rationale: Ammonia emissions from a deep-pit laying hen house derive from the accumulated manure in the deep-pit storage area. With a belt removal system (operating on weekly manure removal) much of the ammonia emission from a given quantity of manure will occur after the manure has been removed from the house i.e. during storage in a heap where temperatures and emitting surface area per tonne of manure are lower.

Mechanism of action: Birds excrete excess nitrogen as uric acid (readily available N) and organically bound N. The hydrolysis of uric acid to ammonia is generally more prolonged than the rapid hydrolysis of urea, so significant emissions of ammonia may take one or more days to develop (depending also on temperature and moisture content). Therefore, compared with a deep-pit system where the accumulation of manure will result in a continuous high emission rate, emissions will be substantially less from a (weekly) belt clean system.

Potential for applying the method: The method would potentially be applicable to all deep-pit laying hen systems.

Current implementation: Approximately 50% of caged laying hens are housed in systems with belt-removal of manure and 50% on traditional deep-pit systems.

Practicability: The practicalities of conversion will depend on individual building design and age. In many cases, a new build might be more appropriate.

Practicability Score: 1 (for new purpose-built layer housing only)

Cost: No data available

Effectiveness: Ammonia emissions from laying hen houses with belt clean systems are approximately 50% less than those from deep-pit laying hen houses, based on UK measurements. Conversion of all remaining deep-pit housing to belt removal would reduce ammonia emissions from UK laying hens by just over 1 kt NH_3.

Other benefits or risk of pollution swapping: Air quality (ammonia and other odorant concentrations) within the house should be improved by conversion to a belt cleaning system with weekly manure removal. The lower ammonia emissions from the house would be offset to some extent by greater emissions during manure storage and/or application to land; however, these would not negate the overall benefits of belt clean compared with deep pit systems.

Key references:

Nicholson, F. A., Chambers, B.J., and Walker, A. W. (2004). Ammonia emissions from broiler litter and laying hen manure management systems. *Biosystems Engineering* 89, 175-185.

Defra project WA0651 ‘Ammonia fluxes within broiler litter and layer manure management systems’

7. Increase the frequency of manure removal from laying hen housing with belt clean systems

Description: Laying hen houses with belt clean systems typically operate weekly manure removal. This method increases the frequency of manure removal to twice weekly.

Rationale: This method relies on the rapid removal of manure from the laying hen house, prior to the peak rate of ammonia emission from the manure.

Mechanism of action: Birds excrete excess nitrogen as uric acid (readily available N) and organically bound N. The hydrolysis of uric acid to ammonia is generally more prolonged than the rapid hydrolysis of urea, so significant emissions of ammonia may take one or more days to develop (depending also on temperature and moisture content). For a weekly manure removal system, measurements have shown that ammonia emissions can increase substantially on the last two days prior to manure removal. Twice weekly removal of manure on the belts will therefore remove the emitting source prior to the peak emission rate for much of the manure. Limited further reduction in emission is likely to be achieved by daily removal.

Potential for applying the method: The method can be applied to all laying hen houses with belt systems for manure removal.

Current implementation: Estimated to be 50%.

Practicability: There should be few or no practical reasons why this method could not be adopted in laying hen houses incorporating belt clean manure removal systems. Some farmers may wish to spread the manure directly following each removal event, which could increase manure application costs by a small amount.

Practicability Score: 1

Cost: £0.02 per bird place per annum, based on increased running costs.

Effectiveness: This method has been shown to reduce emissions by *c.*50% compared with weekly manure removal. Daily removal was shown to give little additional benefit in terms of emission reduction. If adopted by the remaining 50% of laying hen houses with belt clean systems, the reduction in ammonia emission from UK laying hens would be *c.*0.5 kt NH_3.

Other benefits or risk of pollution swapping: In addition to reducing ammonia emissions from the house, this method will also improve air quality (lower ammonia and potentially other odorant concentration) within the house. The greater N content of the manure going to storage increases the potential for ammonia and other N losses (*e.g.* drainflow/surface run-off, nitrate leaching, nitrous oxide emission) at storage and land spreading.

Key references:

Nicholson, F. A., Chambers, B. J., and Walker, A. W. (2004). Ammonia emissions from broiler litter and laying hen manure management systems. *Biosystems Engineering* 89, 175-185.

Defra project WA0651 'Ammonia fluxes within broiler litter and layer manure management systems'

8. In-house poultry manure drying

Description: Installation of ventilation/drying systems to reduce the moisture content of laying hen manure (in deep-pit or on belts) or poultry litter within the house.

Rationale: Drying will inhibit hydrolysis of the uric acid (readily available N) content of the manure, slowing the formation of ammonium and thereby reducing ammonia emission.

Mechanism of action: Birds excrete excess nitrogen as uric acid (readily available N), which is subsequently converted to ammonium-N by hydrolysis. Drying the manure or litter to achieve a dry matter content of 60-80% will greatly reduce the rate of hydrolysis.

Potential for applying the method: Applicable to all poultry housing systems.

Current implementation: Not well known. Some new belt clean systems may include drying technologies.

Practicability: Laying hen houses with belt clean systems should have few practical problems installing drying systems. Depending on building design, it may also be possible to retro-fit deep-pit drying systems in some houses. The practicalities of installing drying systems in litter-based housing (*e.g.* broilers) will depend on existing building design and age.

Practicability Score: 1

Cost: For deep-pit laying hen housing, belt-removal layer housing, perchery layer housing and broiler housing costs have been estimated at £0.02, £0.50, £0.20 and £0.06 per bird place per annum, respectively.

Effectiveness: The effectiveness of this method will depend on the design of the ventilation system and the resulting speed of drying and moisture content of the manure/litter. Emission reductions in excess of 50% may be achieved from housing with very effective drying, but expectations of reductions in the range 25-50% are perhaps more reasonable. Taking a conservative mean reduction of 30%, overall reductions in emission from UK laying hen and other poultry sectors of *c.*1 and 1.8 kt NH_3, respectively, would be achieved.

Other benefits or risk of pollution swapping: Increased ventilation within the house may result in increased dust concentrations. The greater N content of the manure increases the potential for ammonia and other N losses (*e.g.* drainflow/ surface run-off, nitrate leaching, nitrous oxide emission) at storage and land spreading.

Key references:

Defra project WA0638 'Low cost aerobic stabilisation of poultry layer manure'

Smith, K.A., Jackson, D.R. and Metcalfe, J.P. (2001). Low cost aerobic stabilisation of poultry layer manure. In: Sustainable Handling and Utilisation of Livestock Manure from Animals to Plants, Proceedings of NJF Seminar No 320 (Eds. Rom, H.B. and Sorenesen, C.G.), Danish Institute of Agricultural Sciences Report No 21, Animal Husbandry.

9. Increased scraping frequency in dairy cow cubicle housing

Description: Increase the number of times that the cubicle passages are scraped from twice per day to three or more times per day.

Rationale: More frequent removal of urine and faeces from the cubicle passage floor reduces the amount of time that ammonia emission from a given quantity of excreta will occur, thereby reducing the overall potential for emission.

Mechanism of action: Ammonia emissions from the cubicle house derive predominantly from urine, following hydrolysis of the urea content to ammonium through action of the ubiquitous enzyme urease. More frequent removal of urine and faeces by scraping will increase the proportion of urine removed from the floor surface prior to hydrolysis and also leave a smaller 'pool' of material from which emission is occurring at any one time. A build up of dung on the floor impedes the natural drainage of urine, so more frequent removal will also increase the volume of urine reaching the slurry store by natural drainage (particularly with a sloping floor), thereby reducing emission from the cubicle house.

Potential for applying the method: The method is applicable to all dairy cow cubicle houses, but best suited to those with a sloping floor to assist rapid drainage of urine. A proportion of houses are fitted with automatic scraper belts, which may already operate a frequent scraping system.

Current implementation: Probably <10%.

Practicability: For tractor-scraped systems, increasing the frequency of scraping will require labour that might otherwise be employed elsewhere on the farm. There should be no practical limitations to operating automatic scraper systems in a more frequent removal mode. There may be reluctance to retro-fit automatic scraper systems to existing dairy cow cubicle houses.

Practicability Score: 1

Cost: The additional cost of increasing scraping frequency from two to four times per day, based on a tractor-scraper system, is estimated as £1.10 per m^3 of slurry.

Effectiveness: A reduction in ammonia emission from cubicle houses of 20% is estimated from such an increase in scraping frequency (to 4 times daily). Further increases in scraping frequency may not greatly improve effectiveness, as scraping will leave a thin layer of emitting material across the entire floor area. Assuming a 10% current implementation, the maximum reduction which could be achieved by implementing this method in the UK dairy sector is *c.*1.5 kt NH_3.

Other benefits or risk of pollution swapping: Reducing ammonia emissions from the dairy cow cubicle house will result in a greater ammonium-N content of the slurry going to storage. Potentially, therefore, emissions from slurry storage and land spreading will be greater unless mitigation methods are employed. An increase in the readily available N content of the slurry at spreading will also increase the potential for pollution via other N losses (*e.g.* drainflow/surface run-off, nitrate leaching, nitrous oxide emission).

Key references:

Braam, C. R., Ketelaars, J., and Smits, M. C. J. (1997). Effects of floor design and floor cleaning on ammonia emission from cubicle houses for dairy cows. *Netherlands Journal of Agricultural Science* 45, 49-64.

10. Conversion of slurry-based to solid manure management systems for cattle

Description: Change from a system where the manure from housed cattle is collected as liquid slurry to one where the cattle are kept on a bed of straw to produce solid farm yard manure (FYM).

Rationale: Straw use will encourage bacterial immobilisation of readily available nitrogen, resulting in a lower potential for ammonia emission. In addition, the presence of a straw layer will reduce air movement, and hence volatilisation, from urine which has infiltrated below the surface layer of the bedding.

Mechanism of action: The use of straw as a bedding material provides a physical barrier to ammonia volatilisation from urine as it will infiltrate readily into lower layers of the bedding. Also, the mixing of cattle excreta (urine/faeces) with the straw bedding encourages microbial immobilisation of the readily available nitrogen (deriving primarily from urine deposition), reducing the pool from which ammonia volatilisation might occur. Further losses of readily available nitrogen *via* denitrification (*i.e.* dinitrogen, nitric oxide and nitrous oxide), particularly during manure storage, result in a manure with substantially less readily available N (typically in the range 10-25% of total N) at land application than from a slurry-based management system.

Potential for applying the method: This method is potentially applicable to all cattle farms which currently handle all or part of their manure as liquid slurry. Studies have shown that for pigs, emissions from straw-bedded housing can be greater than from slurry-based, slatted floor systems, because of pig behaviour in moving the straw bedding to preferential lying areas.

Current implementation: 34% of dairy cows and heifers and 82% of other cattle are kept on solid manure management systems.

Practicability: Solid manure systems require a source of suitable bedding material and are less suited to regions where little straw is produced. There are significant additional labour requirements associated with the management of straw based cattle housing. Also, solid manure is less easily handled than liquid slurry. Dairy cow cubicle housing would not be suitable as straw-bedded loose housing, so substantial changes to buildings would have to be made. There may be reluctance to move to a solid manure management system for dairy cows due to animal hygiene and milk quality issues.

Practicability Score: 1 (taking no account of costs and animal welfare issues)

Cost: Additional costs would be incurred through provision of additional floor area per cow ($2m^2$), straw bedding costs and additional labour requirements for manure management. These are estimated at £122 per cow per annum.

Effectiveness: At a whole systems level (losses from housing, manure storage and land application), a solid manure management system is associated with ammonia emissions *c.*30% lower than those from a slurry-based management system. Emissions from housing are *c.*25% lower. If all slurry-based cattle systems were to convert to solid manure management, there would be reductions in emissions of 11.7 and 4.0 kt NH_3 from the UK dairy and beef sectors, respectively. However, due to the high costs of conversion, a significant move from the current situation is unlikely, particularly in areas where straw availability is limited.

Other benefits or risk of pollution swapping: Solid manures are more easily stored than slurries and present less risk of pollutant loss to water when spread (*i.e.* in drainflow/surface run-off, nitrate leaching). Methane emissions are lower from solid manure systems. Nitrous oxide emissions are somewhat greater from solid manure than from slurry systems during storage, but are lower following land spreading (because of their lower readily available N content). Overall, nitrous oxide emissions would decrease on changing from a slurry-based to solid manure management system. Farm yard manure has a lower available N content at spreading than slurry and therefore a lower fertiliser replacement value. If farmers were fully accounting for manure nutrients in their fertiliser plan, then this method might be associated with an increase in mineral N fertiliser use (to offset the lower amount being applied as manure), and with it the associated risk of N losses.

Key references:

Defra project WA0632 ‘Ammonia fluxes within solid and liquid manure management systems’

Defra project CC0234 ‘Nitrous oxide emissions from slurry-based and straw-based animal production systems’

Defra project WT0706 ‘Benefits and pollution swapping: cross-cutting issues for Catchment Sensitive Farming Policy’

Chambers, B.J., Williams, J.R., Cooke, S.D., Kay, R.M., Chadwick, D.R. and Balsdon, S.L. (2003). Ammonia losses from contrasting cattle and pig manure management systems. In: Agriculture, Waste and the Environment (Eds. I. McTaggart and L. Gairns), The Scottish Agricultural College, pp19-25

11. Additional targeted straw bedding for cattle housing

Description: Adding 25% extra straw bedding to the cattle house, and targeting the additional straw to wetter/dirtier areas of the house.

Rationale: Solid manure management systems are associated with lower ammonia emissions than slurry-based systems for cattle (as noted in Method 10). Increasing the straw bedding allocation in such systems will enhance physical and microbiological effects leading to further emission reduction.

Mechanism of action: As noted in Method 10, straw bedding reduces ammonia emissions from cattle housing by providing a physical barrier between urine (which has infiltrated into the bedding) and the air above the bedding, and by encouraging microbial immobilisation of readily available nitrogen. Adding 25% additional straw above standard practice (by typically 8 kg per head per day for dairy cows) enhances these effects, achieving further reductions in emission, particularly when the additional straw is specifically targeted to the wettest/dirtiest areas of the house (e.g. around water or feeding troughs). Limited further reductions can be achieved by even more additional bedding, but there is a risk that too much bedding can cause the litter temperature to rise (due to greater aeration and associated oxygen supply) and actually lead to an increase in ammonia emissions.

Potential for applying the method: The method is applicable to all cattle farms where a solid manure handling approach is used.

Current implementation: It is assumed that there is a low level of current implementation of ‘additional, targeted’ straw-use, beyond normal use rates to meet animal welfare needs, as straw is expensive to buy and handle.

Practicability: This method requires buying, storing and handling additional straw. Greater quantities of manure will also be generated, which will need storing and spreading, and there may be a requirement to remove manure from the building on more occasions over the housed period if the bedding depth becomes too great.

Practicability Score: 2 (Validation of experimental results at the commercial scale are required)

Cost: The cost of additional straw is estimated at £25 per cow per annum.

Effectiveness: Using 25% additional straw has been shown to give a *c*.50% reduction in ammonia emissions from cattle housing. Using extra bedding above this level gives little benefit in terms of further emission reduction. Implementation of this method would give potential emission reductions of 1.5 and 3.0 kt NH_3 from the UK dairy and beef sectors, respectively.

Other benefits or risk of pollution swapping: Assuming that much of the ammonia emission reduction during housing is because of microbial immobilisation of ammonium-N, the potential for increased emissions at the storage and land spreading stages is low.

Key references:

Defra project AM0103 ‘Evaluation of targeted or additional straw use as a means of reducing ammonia emissions from buildings for housing pigs and cattle’

12. Extend the grazing season for cattle

Description: Where soil conditions allow, the grazing season is extended in the spring and in the autumn (and even throughout the winter under very favourable soil conditions).

Rationale: Urine deposition by cattle at grazing rapidly infiltrates into the soil and is therefore associated with low ammonia emissions. This compares with the high emissions associated with urine depositions to concrete floors within cattle housing and the associated emissions from the storage and spreading of manure deriving from housing livestock.

Mechanism of action: When cattle are grazing at pasture, excretal returns (urine and faeces) are deposited directly on the field. Ammonia emissions derive predominantly from the urea content of the urine, which must first be hydrolysed to ammonium before emission can occur. Urine will generally rapidly infiltrate into the grazed pasture and hydrolysis will occur within the soil. The soil will present a physical (by reducing air movement) and chemical (by binding ammonium) barrier to emission, greatly reducing emissions compared with that from urine deposition to a concrete floor in cattle housing.

Potential for applying the method: This method can be applied to all cattle farms where cattle are housed for at least some periods when soil conditions for grazing are still favourable.

Current implementation: The Farm Practices Survey Report (2005) indicates that on at least 10% of dairy holdings young stock and dry cows are outdoors from early April to the end of December, and that 50% are outdoors from mid-April until the end of October.

Practicability: This method is unlikely to be favoured by high output dairy farmers who like to closely control herd nutrition. However, split herds may be operated, where low yielders, dry cows and followers are managed on an outdoor grazing system, while high yielders are housed. Farmers may also be unwilling to risk soil compaction and sward damage that can be associated with grazing under marginal conditions.

Practicability Score: 1 (though will be limited by soil types and weather conditions)

Cost: This method will be at least cost-neutral and probably result in cost savings, unless construction of new tracks is required.

Effectiveness: The overall reduction in emissions achieved at the farm level will depend on the duration of the extended grazing period and whether cattle are grazed 24 hours per day for this period or just a few hours per day. One month of extended 24 hours grazing can reduce emissions from a typical dairy farm by *c.*10%. If cattle only graze for 4 hours per day for this extra month, then the reduction in emission falls to 1-2% because of the emissions associated with housing, manure storage and land spreading for the remaining housed period of each day.

Other benefits or risk of pollution swapping: Extended grazing (particularly if 24 hours per day) will reduce the amount of manure storage and handling required. However, urine deposition in the field will increase nitrous oxide emissions and the potential for nitrate leaching. There will be an increased risk of poaching, sediment loss and potential for phosphorus and pathogen transfer to surface water systems. The use of this method conflicts directly with Method 14 of the Diffuse Pollution to Water User Manual, which describes *reducing* the length of the grazing season to reduce the risk of water pollution. For this reason, Method 13 (outwintering of cattle on woodchip stand-off pads) is likely to present a better option than Method 12 in most cases.

Key references:

Webb, J., Anthony, S. G., Brown, L., Lyons-Visser, H., Ross, C., Cottrill, B., Johnson, P., and Scholefield, D. (2005). The impact of increasing the length of the cattle grazing season on emissions of ammonia and nitrous oxide and on nitrate leaching in England and Wales. *Agriculture Ecosystems & Environment* 105, 307-321.

13. Outwintering of cattle on woodchip stand-off pads

Description: Purpose built woodchip pads (including an impermeable liner and drainage collection system) with feeding area, as an alternative to winter housing for cattle.

Rationale: Ammonia emissions from urine deposition on a woodchip standoff pad are likely to be substantially lower than those on a concrete yard or within a cattle house, because of rapid infiltration into the woodchip matrix.

Mechanism of action: Rapid infiltration of urine deposition into the woodchip media of stand-off pads will greatly increase the physical barrier to volatilisation of ammonia, in a similar way to bedding material in livestock housing (Methods 10 and 11) and soil when cattle are at grazing (Method 12). There may also be some direct adsorption of ammonia to the woodchip media and potential for microbial immobilisation from the development of a bacterial community within the media. Additionally, drainage from the stand-off pad will lower in N content and dry matter when compared with cattle slurry from housing, and so the potential for ammonia emissions following application is likely to be lower than for housed systems, because of more rapid infiltration of the lower dry matter/N content material into the soil.

Potential for applying the method: This method is applicable to all dairy and beef farms, where cattle are housed or kept on concrete yards for at least part of the year.

Current implementation: Minimal (<1% dairy and beef holdings)

Practicability: Farmers are unlikely to replace current cattle housing facilities with stand-off pads, but may install them where they are expanding cattle numbers and have insufficient housing, or where they currently outwinter a proportion of their cattle on sacrifice fields. As yet, there are a number of uncertainties regarding the management of the woodchip bed (replacement frequency, utilisation) and until further guidelines are available, the method may not be widely adopted.

Practicability Score: 2

Cost: Depending on design and requirements, but likely to be in the range £10 - £20 per head per annum.

Effectiveness: To date, there are no direct measurement data of the effectiveness of woodchip stand-off pads in reducing ammonia emissions in comparison with cattle housing, although it is generally accepted that emissions are likely to be lower. Effectiveness is likely to depend on the make-up and management of the woodchip bed, the stocking density and the climate.

Other benefits or risk of pollution swapping: Providing that the stand-off pad is lined and drainage is collected, there is no increased risk of water pollution when compared with conventional housing systems. No measurement data exist on nitrous oxide or methane emissions from stand-off pads.

Key references:

Smith, K.A., Agostini, F.A. and Laws, J.A. (2005) Survey of woodchip corrals and stand-off pads in England and Wales: Construction, Operation and Management Practices and Potential Environmental Impacts. Report 45pp.

14. Washing down of dairy cow collecting yards

Description: Dairy cows are 'collected' on concrete yard areas prior to milking. Such areas are usually scraped at least once per day to remove excreta. This method involves pressure washing (or hosing and brushing) of the yards immediately following dairy cow use to more effectively remove the excreta.

Rationale: Urine deposited on the collecting yard surface by dairy cattle is a major source of ammonia emissions. Reducing the quantity of urine on the yard surface and the time it remains there will reduce ammonia emissions.

Mechanism of action: The urea content of urine is rapidly hydrolysed to form ammonium-N by the enzyme urease, which is present in the faecal deposits of the dairy cows. Excreta are typically removed from dairy cow collecting yards once per day (following the morning milking event) by scraping (with either a hand or tractor-mounted scraper). Scraping has been estimated to remove 60% of the material from the yard surface, but leaves a film of material remaining from which emission will continue. Removal of excreta by pressure washing or by hosing and brushing, immediately following each milking event, will remove a greater proportion of the material on the yard surface (>90%) and remove the material prior to urea hydrolysis.

Potential for applying the method: The method can be applied to all collecting yards used by dairy cows.

Current implementation: Data from Defra project WA0523 (Survey element of Defrta project WA0516; Run-off and emissions from hard standings) indicated that <5% of dairy cow collecting yards were cleaned by washing.

Practicability: The main practical issue relating to this method is the extra labour involved in cleaning the yard (2-3 times per day) and the extra volume of slurry that will be produced from the added water use. The method is unlikely to be adopted if it will require extra slurry or dirty water storage capacity to be installed.

Practicability Score: 1

Cost: Costs for yard washing will be of the order of £30 - £40 per cow per year, based on a 100 cow herd and 15 minutes per day per cleaning. This does not include costs of any additional slurry storage capacity which may be required or additional costs of slurry application.

Effectiveness: Pressure washing of the yard immediately after removal of the cows can give a reduction in emissions from the collecting yard of *c.*90% compared with scraping once per day. Implementing this method on the 95% of dairy cow collecting yards not currently using it would reduce emissions from the UK dairy sector by *c.*5 kt NH_3.

Other benefits or risk of pollution swapping: Depending on the volume of water used and the manure management system, this method may result in significantly more slurry/dirty water to be managed, which may increase the risk of application at inappropriate times. However, the slurry will be more lowser in dry matter, which is likely to result in lower ammonia emissions following land application.

Key references:

Misselbrook, T. H., Pain, B. F., and Headon, D. M. (1998). Estimates of ammonia emission from dairy cow collecting yards. *Journal of Agricultural Engineering Research* 71, 127-135.
Misselbrook, T. H., Webb, J., and Gilhespy, S. L. (2006). Ammonia emissions from outdoor concrete yards used by livestock - quantification and mitigation. *Atmospheric Environment* 40, 6752-6763.

15. Establish tree shelter belts around livestock housing and slurry storage facilities

Description: Plant tree shelter belts around livestock housing facilities and slurry lagoons

Rationale: The tree shelter belt will disrupt air flow around the building or slurry lagoon, reducing the emission rate to some extent, and will also directly recapture a proportion of the ammonia emitted from the source.

Mechanism of action: Planting of tree shelter belts upwind and downwind of livestock housing or slurry lagoons will reduce ammonia emissions beyond the farm boundary in two ways. Firstly, the shelter belt will result in a lower wind speed directly above and around the building or lagoon, increasing the time taken for emitted ammonia to be transported away in the free air stream, and thereby increasing the resistance to further emission. Secondly, the trees will recapture a proportion of the emitted ammonia both directly though cuticular uptake and also indirectly by increased deposition.

Potential for applying the method: The method could potentially be applied to all livestock housing facilities, including the manure storage/slurry lagoon areas.

Current implementation: Visual screening of pig and poultry units with tree belts is not uncommon, but current implementation is unknown.

Practicability: A shelter belt of sufficient height to be effective will take a number of years to establish. More guidance is required on species type, planting density and location in order to avoid damaging effects on building foundations or store integrity.

Practicability Score: 3

Cost: Approx. £400 per ha planted. Costs per animal place will depend on the ratio of the relative sizes of the shelterbelt and livestock unit.

Effectiveness: The effectiveness of this method in reducing ammonia emissions from livestock housing will depend on the height and canopy density of the shelter belt and the prevailing environmental conditions. With careful design of tree belts, it is thought that ‘recapture’ efficiencies of 5-10% of emitted ammonia can be achieved.

Other benefits or risk of pollution swapping: Tree belts around buildings can offer additional benefits including visual screening, enhanced biodiversity (particularly in areas of intensive agriculture) and carbon sequestration. However, there may be a number of disbenefits, including loss of the land from agricultural production, harbouring of pests and weeds, shading of adjacent farmland and potentially enhanced emissions of nitrous oxide from the recaptured ammonium-N.

Key references:

Dragosits, U., Theobald, M. R., Place, C. J., ApSimon, H. M., and Sutton, M. A. (2006). The potential for spatial planning at the landscape level to mitigate the effects of atmospheric ammonia deposition. *Environmental Science & Policy* 9, 626-638.

Defra project WA0719 ‘Impact of vegetation and/or other on-farm features on net ammonia emissions from livestock farms.’

16. Install covers to slurry stores

Description: Open slurry stores (tanks or lagoons) are fitted with a cover (a rigid cover with a vent or a floating flexible cover).

Rationale: Covering the slurry store limits any ammonia generated at the slurry surface to be emitted to the atmosphere.

Mechanism of action: Ammonia will freely volatilise from a slurry store surface (the rate depending on factors such as ammonium-N concentration, pH, temperature and air movement), and will be replenished in the surface layer from lower levels in the store. Natural air movement above the store (i.e. wind) ensures that the emitted ammonia is removed from above the store, being continually replaced by air with a lower ammonia concentration. By placing a cover above the slurry surface and preventing the removal of emitted ammonia by advection, a higher ammonia concentration will soon develop in the enclosed airspace. This higher concentration will inhibit further ammonia emission from the slurry, so the overall emission rate will decline. Most covers include some vents (to prevent a build up of methane), so emission will not stop entirely, but will be greatly reduced compared with a situation of free air movement above the slurry store.

Potential for applying the method: This method could be applied to all open slurry stores. There may be little benefit in applying the method to cattle slurry stores, where natural crusts often develop and give effective ammonia emission reduction (see Method 17). Therefore the method is most relevant to the pig sector. Little benefit will be gained from covering of very dilute slurry stores, so separate storage of slurry and dirty water is recommended with the slurry store being covered. The two waste streams may be brought back together at spreading if that suits the farm-specific manure management system.

Current implementation: Minimal (<1%); some covers have been fitted where odour from stores has created a nuisance and some in high rainfall areas deliberately to exclude rainwater.

Practicability: Rigid covers are applicable to concrete or steel tanks, but may not be suitable for all existing stores (e.g. where the existing store has insufficient structural support for a rigid cover). Plastic floating covers are applicable to tanks and small earth-banked lagoons, but become increasingly difficult to fit and manage on larger lagoons. ‘Low technology’ floating covers (*e.g.* oil-based liquids, chopped straw, peat, bark, LECA balls) may be applicable to concrete or steel tanks, but the solid-based materials are probably not suitable on earth-banked lagoons, where wind drift can cause problems with retaining a complete surface cover. Consideration needs to be given as to how the cover impacts on store filling, mixing and emptying.

Practicability Score: 1 (3 for oil-based and other solid materials)

Cost: Rigid tank cover, £1.10 per m^3 slurry; flexible lagoon cover, £0.50 per m^3 slurry; flexible tank cover, £0.35 per m^3 slurry.

Effectiveness: A rigid store cover has been shown to reduce emissions from slurry storage by 80%, plastic sheeting cover by 60% and ‘low technology’ floating covers by 40%. Implementing this method in the UK pig sector, with rigid covers fitted to tanks and plastic sheeting to lagoons, would give a reduction in emissions of 1.6 kt NH_3.

Other benefits or risk of pollution swapping: A rigid cover will exclude rainfall from slurry stores and particularly in high rainfall areas this can lead to a significant reduction in the quantity of slurry to be spread, however, the higher dry matter of the slurry may result in greater ammonia emissions after spreading. Plastic sheet covers on earth-banked lagoons can also exclude rainfall, although the water has to be regularly pumped from the lagoon cover. A cover will also significantly reduce odours arising from slurry storage. Reducing ammonia emissions from slurry storage will result in a greater readily available N content of the slurry being applied to land, and will therefore result in a small increase in the potential for N losses following application (*i.e.* ammonia and nitrous oxide emissions to air, N in surface run-off/drainflow and nitrate leaching).

Key references:

Chambers, B. and Nicholson, F. (2005). Emissions from pig and poultry farming. Society of Chemistry and Industry – Symposium on Ammonia: Approaching National Emission Ceilings Targets, London, May 2005 [abstract]

Portejoie, S., Martinez, J., Guiziou, F., and Coste, C. M. (2003). Effect of covering pig slurry stores on the ammonia emission processes. *Bioresource Technology* 87, 199-207.

Scotford, I. M., and Williams, A. G. (2001). Practicalities, costs and effectiveness of a floating plastic cover to reduce ammonia emissions from a pig slurry lagoon. *Journal of Agricultural Engineering Research* 80, 273-281.

Sommer, S. G., Christensen, B. T., Nielsen, N. E., and Schjorring, J. K. (1993). Ammonia volatilization during storage of cattle and pig slurry - effect of surface cover. *Journal of Agricultural Science* 121, 63-71.

Defra project AM0102 ‘Modelling and measurement of ammonia emissions from ammonia mitigation pilot farms’

17. Allow cattle slurry stores to develop a natural crust

Description: A surface crust composed of fibres and bedding material present in the slurry which develops on cattle slurry stores and is retained intact for the majority of the year.

Rationale: The developed surface crust acts as a physical barrier between the ammonium-N in slurry and the free air above the crust.

Mechanism of action: Fibres from undigested plant material and cattle house bedding within the slurry float to the surface of the slurry store, aided by uprising methane bubbles produced by bacterial action within the slurry. Thereafter, evaporative forces due to wind and solar radiation cause the crust to dry, increasing its strength and integrity. The greatly increased viscosity of the surface layer greatly increases the time taken for ammonium at the surface emitting layer to be replenished from deeper within the slurry store.

Potential for applying the method: The method is applicable to all slurry stores with the potential to form a crust. In the UK, this tends to be cattle slurry stores, although there may be circumstances in which cattle slurry stores do not form a crust (*e.g.* where they contain very dilute slurries).

Current implementation: Estimated at 80%.

Practicability: Management of the slurry store in order to maintain an effective crust is critical to the success of this method. Regular agitation is therefore not an option, unless it can be achieved without breaking the crust. Some top filling slurry stores may not form a complete crust. If the crust becomes too thick and solid, then tank emptying may become difficult; for this reason it is recommended that the crust is completely broken up during tank emptying at least once per year. Crusting will not occur following slurry separation.

Practicability Score: 1

Cost: Probably cost-neutral. Where additional stirring may be required prior to spreading to enable efficient slurry homogenisation, a cost of £0.20 per m^3 slurry has been estimated.

Effectiveness: Effectiveness is variable, depending on crust thickness and integrity, but a mean reduction efficiency of 50% compared with non-crusted slurry stores has been estimated. If this method could be successfully implemented on the remaining 20% of cattle slurry stores, reductions in emissions from the UK dairy and beef sectors would be 0.8 and 0.2 kt NH_3, respectively.

Other benefits or risk of pollution swapping: Crust formation will reduce odour emissions from slurry storage. Also, there is evidence that methane emissions are reduced due to microbial oxidation of methane as it passes through the slurry crust. However, a crust also results in nitrous oxide emissions from slurry storage (negligible from non-crusted stores) through nitrification and denitrification of ammonium in the surface crust. However, reducing ammonia emissions from slurry storage will result in a greater readily available N content of the slurry being applied to land and therefore a small increased potential for N losses following application (*i.e.* ammonia and nitrous oxide emissions to air, N in surface run-off/drainflow and nitrate leaching).

Key references:

Misselbrook, T. H., Brookman, S. K. E., Smith, K. A., Cumby, T. R., Williams, A. G., and McCrory, D. F. (2005). Crusting of stored dairy slurry to abate ammonia emissions: pilot-scale studies. *Journal of Environmental Quality* 34, 411-419.

Petersen, S. O., Amon, B., and Gattinger, A. (2005). Methane oxidation in slurry storage surface crusts. *Journal of Environmental Quality* 34, 455-461.

Smith K., Cumby, T. Lapworth J. Misselbrook T.H. and Williams A. (2007) Natural crusting of slurry storage as an abatement measure for ammonia emissions on dairy farms. *Biosystems Engineering* 97, 464-471.

Sommer, S. G., Petersen, S. O., and Sogaard, H. T. (2000). Greenhouse gas emission from stored livestock slurry. *Journal of Environmental Quality* 29, 744-751.

18. Cover solid manure stores with polythene sheeting

Description: The solid manure heap is covered with heavy duty polythene sheeting, in a similar manner to a silage clamp.

Rationale: The polythene sheeting provides a physical barrier preventing the release of ammonia from the manure heap to the air.

Mechanism of action: Ammonia will volatilise from the ammonium-N content of the manure heap and will diffuse through the heap into the free air stream above. Covering the heap with polythene sheeting provides a physical barrier which the ammonia gas cannot pass through. The cover prevents the advection of volatilised ammonia away from the heap, so a high ammonia concentration develops in the air spaces within the heap and between the heap and cover. This high concentration will inhibit further emissions from the manure, so the overall emission rate will decline very rapidly.

Potential for applying the method: The method could be applied to all solid manures that are stored in heaps. The method is most effective in situations where the manure will subsequently be rapidly incorporated into the soil following land application (see also Methods 19 and 22).

Current implementation: Minimal (<1%). Some layer manure heaps are covered for odour/fly nuisance control.

Practicability: Heaps should be sited and shaped to minimise their overall surface area and hence the amount of polythene required for covering. Heaps are unlikely to be as compact as silage heaps, so additional health and safety considerations are required concerning walking on heaps. This method may not be well suited to management systems that involve regular addition of manure to heaps (e.g. daily, twice weekly), where there would be a continual need for sheet removal and replacement and is therefore most suited to clearance operations following livestock removal from housing (e.g. at cattle turn-out, at the end of a broiler crop).

Practicability Score: 1

Cost: Costs of sheeting plus labour required to cover the heap are estimated at £0.60 per tonne of solid manure.

Effectiveness: Experimental studies have shown a large range in the effectiveness of this method (from 14 – 89% reduction), with a mean reduction efficiency of 65% from stored solid manure. Assuming 100% potential implementation, reductions in emissions from the UK dairy, beef, pig, layer and other poultry sectors would be 0.2, 1.0, 0.5, 0.2 and 0.8 kt NH_3, respectively.

Other benefits or risk of pollution swapping: The covering of solid manure heaps has been shown to reduce nitrous oxide emissions during storage. Covering may reduce the aeration within the heap and therefore the composting activity. This may result in less die-off of weed seeds and pathogens during storage, and less overall volume reduction. Covering prevents rainfall leaching nutrients from the heap and results in more nitrogen and potassium (in particular) being retained in the heap, with potential agronomic benefits following land application. However, the greater readily available nitrogen content at spreading means that, if manure is not rapidly incorporated into the soil (see Method 22), increased ammonia losses following spreading can offset reductions achieved during storage.

Key references:

Chadwick, D. R. (2005). Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering. *Atmospheric Environment* 39, 787-799.

Chadwick, D.R., Matthews, R.A., Nicholson, R.J., Chambers, B.J. and Boyles, L.O. (2002). Management practices to reduce ammonia emissions from pig and cattle manure stores. In: Proceedings of the 10th International Conference of the FAO RAMIRAN Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture (Eds. J. Venglovsky and G. Greserova), pp219-223.

Defra project WA0716 'Management techniques to reduce ammonia emissions from solid manures'

Sagoo, E., Williams, J.R., Chambers, B.J., Boyles, L., Matthews, R. and Chadwick, D.R. (2004). Integrated management practices to minimise losses and maximise crop nitrogen values of broiler litter. In: Proceedings of the 11th International Conference of the FAO RAMIRAN Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture (Eds. Bernal, M.P., Moral, R., Clemente, R. and Paredes, C.), Vol. 1, pp249-252.

19. Store farmyard manure (FYM) prior to land application

Description: Remove farmyard manure (FYM) from straw-bedded cattle, pig and horse housing and create storage heaps (uncovered) where FYM will be stored for a period of at least 3 months prior to land application.

Rationale: Ammonia emissions from the storage and spreading of FYM will overall be less than that from the spreading of 'fresh' FYM directly from the animal house, because of N transformations and some additional N losses which occur during FYM storage.

Mechanism of action: This method relies on reducing the quantity of readily available nitrogen in the FYM at the time of spreading and thereby reducing the potential for ammonia loss at that stage, such that emissions from storage and spreading are less than that from the spreading of 'fresh' FYM. During open-air storage of the FYM, there will be losses via ammonia volatilisation, but readily available nitrogen will also be immobilised in straw and lost via denitrification (following a nitrification stage), the products of which are the gases nitrous oxide, nitric oxide and dinitrogen (the ratio in which these gases are produced will depend upon conditions in the FYM heap).

Potential for applying the method: This method could be applied to all FYM produced from pigs, cattle and horses managed on a straw-based system. However, it will most effectively be applied in situations where the FYM is not rapidly incorporated into the soil following land application, *i.e.* it is left on the surface. Spreading 'fresh' manure direct from the animal house, or sheeting manure during storage (Method 18) prior to land application are the most appropriate management strategies for situations where the manure is to be rapidly incorporated into the soil following field application (Method 22).

Current implementation: Approximately 70% of cattle and pig FYM is currently stored in heaps, the remainder being spread directly (*i.e.* 'fresh') from the house.

Practicability: Few practical barriers exist to implementing this Method, although it is important that any leachate from FYM heaps is managed appropriately and not allowed to pollute surface or ground water.

Practicability Score: 1

Cost: The additional cost of 'double handling' the FYM, compared with spreading directly (*i.e.* 'fresh') from the house, is estimated at £2-3 per tonne of FYM.

Effectiveness: Experimental studies have shown a wide range in the effectiveness of this method at reducing ammonia emissions compared with the surface spreading of 'fresh' FYM, depending on the relative rates of gaseous losses during storage and the extent to which other nitrogen transformations occur (mineralisation/immobilisation). Overall, the data indicate a mean reduction efficiency of *c.*30% where stored FYM (compared with 'fresh') is not incorporated into the soil following land application. Applying this method to all cattle and pig FYM that is not currently stored prior to land spreading would result in emission reductions of 1.0, 2.6 and 1.4 kt NH_3 from the UK dairy, beef and pig sectors, respectively.

Other benefits or risk of pollution swapping: Storage will result in significant reductions in the amount of FYM that has to be spread. However, storing FYM will result in increased emissions of nitrous oxide and methane (although the magnitude is uncertain), and uncontained leachate from FYM heaps represents a pollution risk to surface and ground waters. Stored FYM has a lower available N content than FYM spread directly from the house. If farmers were fully accounting for manure nutrients in their fertiliser plan, then this method might be associated with an increase in mineral N fertiliser use (to offset the lower amount being applied as manure), and with it the associated risk of N losses.

Key references:

Chadwick, D.R., Matthews, R.A., Nicholson, R.J., Chambers, B.J. and Boyles, L.O. (2002). Management practices to reduce ammonia emissions from pig and cattle manure stores. In: Proceedings of the 10th International Conference of the FAO RAMIRAN Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture (Eds. J. Venglovsky and G. Greserova), pp219-223.

Defra project WA0716 ‘Management techniques to reduce ammonia emissions from solid manures’

Sagoo, E., Williams, J.R., Chambers, B.J., Boyles, L., Matthews, R. and Chadwick, D.R. (2004). Integrated management practices to minimise losses and maximise crop nitrogen values of broiler litter. In: Proceedings of the 11th International Conference of the FAO RAMIRAN Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture (Eds. Bernal, M.P., Moral, R., Clemente, R. and Paredes, C.), Vol. 1, pp249-252.

20. Use slurry band spreading application techniques

Description: Slurry is applied to land in a series of narrow bands (typically 5-10 cm width at a spacing of 20-30 cm) via trailing hoses mounted on a boom. For applications with *trailing hose* equipment, the slurry is delivered via trailing hoses just above the soil surface. For applications with *trailing shoe* equipment, slurry is delivered just behind a forward facing 'shoe', which ensures that the slurry is delivered directly to the soil surface below the sward/crop canopy.

Rationale: Ammonia volatilisation occurs from the surface of the applied slurry, therefore reducing the overall surface area of slurry by application in narrow bands will lead to a reduction in ammonia emissions (provided that slurry infiltration into the soil is not delayed by the increased hydraulic loading rate into slurry bands compared with broadcast spreading). In addition, if the slurry is placed beneath the crop canopy, the canopy will provide a physical barrier, also reducing the rate of loss.

Mechanism of action:

Trailing hose – Slurry is placed in narrow bands above the soil surface via trailing hoses. As ammonia volatilisation occurs from the slurry surface, applying the same volume of slurry in narrow bands rather than as an overall (broadcast) surface cover will reduce the surface area to volume ratio of the applied slurry, reducing the area from which emission can occur. Band spreading will result in a thicker layer of slurry on the soil surface, for a given volume of slurry applied, thereby increasing the hydraulic loading rate per unit area, which may impede the infiltration of slurry into the soil. Some combinations of slurry composition (usually high dry matter content) and soil and climatic conditions can result in the slurry bands remaining on the soil surface and continuing to emit ammonia for an extended period of time. When applied to taller crops, slurry will be delivered below the canopy, which will reduce air movement and temperatures at the emitting surface, thereby reducing emissions. Applications to a shorter crop will not benefit from this effect and coating of crop leaves with slurry may also occur.

Trailing shoe – Slurry is placed in narrow bands onto the soil surface beneath the grass canopy. The presence of a canopy results in a greatly reduced air movement and temperature at the soil surface, so emissions from slurry placed there will be lower than for slurry placed onto the crop canopy. The taller and denser the canopy, the greater this effect will be.

Potential for applying the method: This method is applicable for all slurry applications to grassland (trailing shoe) or arable crops (trailing hose).

Current implementation: An estimated 3% of cattle and 13% of pig slurry is currently applied in bands using trailing hose/shoe equipment (Defra Farm Practices Surveys).

Practicability: Band spreading slurry application is generally a slower operation (with lower application rates) than conventional surface broadcast application, so there may be issues of labour availability. Many trailing hose slurry applicators have a boom width of less than 24m (although 24m booms are now available), so for cereal crops with tramline spacings of greater width than the applicator boom width, slurry application will require travelling on the crop between tramlines, which may result in some crop damage depending on growth stage at the time of application. On sloping land, the higher centre of gravity and additional width of some machines increases the risk of tipping over.

Practicability Score: 1

Cost: Additional costs compared with conventional broadcast (splashplate) application are estimated at £1.40 and £1.60 per m^3 slurry applied for trailing hose and trailing shoe equipment, respectively.

Effectiveness: Variability in the effectiveness of these application techniques at reducing emissions can be large (0-90% reduction compared with surface broadcast), depending on soil conditions, crop height and density, slurry characteristics (particularly dry matter content) and machine performance. Mean reduction efficiencies for slurry spreading are estimated at 30% for trailing hose and trailing shoe equipment when the grass is short and 60% for trailing shoe equipment when the grass is longer (>10 cm). Implementation of this method, involving trailing shoe application to grassland and trailing hose to arable crops, would result in reductions in emissions of 13.3, 4.1 and 1.0 kt NH_3 for the UK dairy, beef and pig sectors, respectively.

Other benefits or risk of pollution swapping: Applying slurry beneath the crop canopy (grassland or arable) avoids contamination of the crop with slurry. For grassland, this reduces the required period between slurry application and grazing or silage harvest, extending the window of opportunity for slurry application. For arable crops, this extends the window for slurry application later into the spring when crop height normally excludes conventional surface broadcast slurry application (because of risk of crop damage and contamination) at a time when applied slurry can still be agronomically useful. Trailing shoe and trailing hose slurry application equipment also delivers a much more uniform rate of slurry across the entire application width in comparison with conventional broadcast application and will be unaffected by wind. Reducing ammonia emissions from the applied slurry increases the potential for nitrogen losses via nitrate leaching or nitrous oxide emissions, depending on time and rate of application. If within a Nitrate Vulnerable Zone, it is important to comply with spreading restrictions as defined under NVZ legislation. Generally, if applied at an agronomically suitable time (e.g. spring.summer) and rate, the risks of pollution swapping will be minimal.

Key references:

Defra project ES0114 ‘Integrating slurry management strategies to minimise nitrogen losses - application rates and method (Slurry-NR)’

Defra project ES0115 ‘Optimising slurry application timings to minimise nitrogen losses: OPTI-N’

Defra project KT0106 ‘MANNER Policy Support Model (MANNER-PSM)’

Defra project NT2001 ‘Improved manure management – nutrient demonstration farms’

Misselbrook, T. H., Smith, K. A., Johnson, R. A., and Pain, B. F. (2002). Slurry application techniques to reduce ammonia emissions: Results of some UK field-scale experiments. *Biosystems Engineering* 81, 313-321.

Smith, K. A., Jackson, D. R., Misselbrook, T. H., Pain, B. F., and Johnson, R. A. (2000). Reduction of ammonia emission by slurry application techniques. *Journal of Agricultural Engineering Research* 77, 277-287.

Williams, J.R., Chambers, B.J., Smith, K.A., Misselbrook, T.H. and Chadwick, D.R. (2000). Integration of farm manure nitrogen supply within commercial farming systems. In: Proceedings of the Ninth International Conference of the FAO ESCORENA Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture: Technology Transfer - RAMIRAN 2000 (Ed. F. Sangiorgi), University of Milan, pp263-268.

21. Use slurry injection application techniques

Description: Slurry is delivered to the soil, either into shallow slots (5-10 cm depth, at 25-30 cm spacing) which are cut by preceding discs, or much deeper into the soil (*c.*25 cm depth) where slurry placement is behind a tine.

Rationale: Ammonia volatilisation occurs from the surface of applied slurry, therefore reducing (for open slot shallow injection) or eliminating (for closed slot deep injection) the overall surface area of applied slurry will greatly reduce ammonia emissions.

Mechanism of action: Placing slurry into narrow open slots, via shallow injection, greatly reduces the exposed slurry surface area. Placing slurry deeper into the soil behind cultivation tines, as with deep injection, essentially eliminates the exposed slurry surface area. Diffusion of any ammonia present within the soil pore spaces to the surface is very much slower than emission directly from the soil surface. The 'free' ammonium content of the slurry placed within the soil will also be reduced through direct adsorption to clay particles and through the action of nitrifying bacteria, further reducing the potential for ammonia emission.

Potential for applying the method: Shallow injection is suitable for grassland where field slopes or stoniness are not limiting (estimated to rule out approx. 30% of agricultural land) and for arable land prior to crop establishment. Deep injection is suitable for arable land prior to crop establishment. Current deep injector designs are generally not suited to application to growing crops, where crop damage can be great.

Current implementation: An estimated 1% of cattle slurry and 11% of pig slurry is currently applied by shallow injection.

Practicability: Slurry injection will be a slower operation, with lower application rates than conventional surface broadcast application. It will also require higher draught forces, so larger tractors will be required, particularly for deep injection. This may limit the application window, particularly early in the season to grassland. Additionally, injection to grassland under hot and dry conditions can result in significant sward damage.

Practicability Score: 1

Cost: Additional costs of slurry injection, compared with conventional surface broadcast application, are estimated at £2.80 per m^3 of slurry applied.

Effectiveness: Deep injection will generally achieve >90% reduction in emissions compared with surface broadcast application. The effectiveness of shallow injection depends on a number of factors including the application rate (injection slots can be overfilled at high rates) and soil conditions. The mean shallow injection reduction efficiency is estimated as *c.*70%. Assuming implementation of shallow injection for 70% of slurry applied to grassland and deep injection for 10% of slurry applied to arable land (and that the remainder is spread by trailing shoe or trailing hose, respectively), would result in emission reductions of 10.1, 3.3 and 0.5 kt NH_3 from the UK dairy, beef and pig sectors, respectively.

Other benefits or risk of pollution swapping: Slurry injection will greatly reduce odour emissions arising from application. Also, slurry will be applied much more uniformly across the entire application width in comparison with conventional broadcast application. Applying shallow injection (particularly of dilute slurries) on sloping land can result in run-off along the injection slots. With deep injection it is important to avoid slurry application directly into gravel backfill over field drains. Slurry placement into the soil will reduce crop contamination and can to some extent increase the window of spreading opportunity compared with surface broadcast application. Reducing ammonia emissions from the applied slurry increases the potential for nitrogen losses via nitrate leaching or nitrous oxide emissions, depending on time and rate of application. If within a Nitrate Vulnerable Zone, it is important to comply with spreading restrictions as defined under NVZ legislation. Generally, if applied at an agronomically suitable time (*e.g.* spring/summer) and rate, the risk of pollution swapping will be minimal. When slurries are injected, microbial pathogen are protected from ultra-violet radiation and can survive for longer as a result.

Key references:

Defra project ES0114 'Integrating slurry management strategies to minimise nitrogen losses - application rates and method (Slurry-NR)'

Defra project ES0115 'Optimising slurry application timings to minimise nitrogen losses: OPTI-N'

Defra project KT0106 'MANNER Policy Support Model (MANNER-PSM)'

Misselbrook, T. H., Smith, K. A., Johnson, R. A., and Pain, B. F. (2002). Slurry application techniques to reduce ammonia emissions: Results of some UK field-scale experiments. *Biosystems Engineering* **81**, 313-321.

Smith, K. A., Jackson, D. R., Misselbrook, T. H., Pain, B. F., and Johnson, R. A. (2000). Reduction of ammonia emission by slurry application techniques. *Journal of Agricultural Engineering Research* **77**, 277-287.

22. Rapid soil incorporation of manure following field application

Description: Applied slurries or solid manures are rapidly (within 4 hours, the sooner the better) incorporated into the soil by ploughing or with disc or tine cultivation.

Rationale: Manure incorporation into the soil greatly reduces the exposed surface are of the manure from which ammonia emissions can occur.

Mechanism of action: Incorporating the manure into the soil greatly reduces the exposed manure surface. Diffusion of any ammonia present within the soil pore spaces to the surface is very much slower than emission directly from the soil surface. The ‘free’ ammonium content of the slurry placed within the soil will also be reduced through direct adsorption to clay particles and through the action of nitrifying bacteria, further reducing the potential for ammonia emission.

Potential for applying the method: This method is applicable to manure applications to arable land prior to crop establishment, which account for approximately 50, 70 and 90% of applications of slurry (pig and cattle), poultry manure and pig/cattle FYM to arable land, respectively. The method could also be applied to grassland reseeds.

Current implementation: A significant proportion of manure applications to arable land are currently incorporated within 24h of application (*c.*50% of poultry manures and *c.*20% of cattle and pig slurries and FYM). Less than 10% of manure applications to arable land are incorporated within 4 hours.

Practicability: A cultivation operation would generally follow manure application to arable land prior to crop establishment. This method requires that the cultivation operation occurs rapidly after manure application. Immediate incorporation may be impractical due to different work-rates of the manure application and cultivation operations. Rapid incorporation may require additional resources (machinery and labour) or the use of a contractor.

Practicability Score: 1

Cost: In order to achieve rapid incorporation, additional costs for a contractor to carry out the cultivation operation are assumed. Costs per m^3 of slurry of tonne of solid manure will depend on the manure application rate and the cultivation technique employed, but would typically range from £0.40 - £5.00. More details are given in Table 22.1.

Effectiveness: The effectiveness of this method will depend on the time period between manure application and soil incorporation, and also on the cultivation technique employed (see Table 22.1). There is a considerable decrease in the abetment achieved if incorporation is delayed and incorporation as soon as possible after application should be the aim. Assuming that the maximum potential quantities of manure are incorporated by ploughing, within 4 hours of application, and taking into account the current level of implementation, reductions in emissions of 1.9, 2.3, 2.7, 0.7 and 5.0 kt NH_3 would be achieved from the UK dairy, beef, pig, layer and other poultry sectors, respectively.

Reduction in ammonia emissions (% reduction compared with emission from manure left on the soil surface) achieved by rapid soil incorporation of manures on arable land

Manure type	Cultivation method	Timing of incorporation			Cost
		Immediate	Within 4h	Within 24h	£
Cattle and pig slurry	Plough	90	60	30	0.79
	Disc	80	55	25	0.39
	Tine	70	50	25	0.39
Cattle and pig FYM	Plough	90	70	35	1.10
	Disc	70	55	25	0.55
	Tine	30	25	15	0.55
Layer manure	Plough	95	85	55	2.32
	Disc	80	70	50	1.27
	Tine	70	60	40	1.27
Poultry litter	Plough	95	85	55	4.74
	Disc	80	70	50	2.37
	Tine	70	60	40	2.37

Other benefits or risk of pollution swapping: This method will greatly reduce odour emissions following manure application. It will also reduce the risk of mobilisation of manure nutrients and pathogens in surface run-off waters. Reducing ammonia emissions from the applied manure increases the potential for nitrogen losses via nitrate leaching or nitrous oxide emissions, depending on the manure type (risks are greater for slurries and poultry manures), time and rate of application. If within a Nitrate Vulnerable Zone, it is important to comply with spreading restrictions as defined under NVZ legislation. Generally, if applied at an agronomically suitable time (*e.g.* in spring) and rate, the risk of pollution swapping will be minimal. If the rapid cultivation policy damages soil structure, this may compromise crop yields and result in applied inorganic fertiliser and organic manure N being poorly utilised by crops and at risk of leaching over the next winter drainage period. When manures are incorporated, microbial pathogens are protected from ultra-violet radiation and may survive for longer in the soil. However, as they are mixed throughout the soil matrix, they are less likely to be lost in surface run-off and via drain flow.

Key references:

Defra project ES0116 ‘Field work to validate the manure incorporation volatilization system (MAVIS)’

Defra project NT2001 ‘Improved manure management – nutrient demonstration farms’

Defra project NT2008 ‘Nitrogen value of solid manures – effect of contrasting manure management practices’

Defra project WA0716 ‘Management techniques to reduce ammonia emissions from solid manures’

Huijsmans, J. F. M., and de Mol, R. M. (1999). A model for ammonia volatilization after surface application and subsequent incorporation of manure on arable land. *Journal of Agricultural Engineering Research* **74**, 73-82.

Webb, J., Anthony, S. G., and Yamulki, S. (2006). Validating the MAVIS model for optimizing incorporation of litter-based manures to reduce ammonia emissions. *Transactions of the Asabe* **49**, 1905-1913.

23. Replace urea and urea-based fertilisers with another nitrogen fertiliser form (e.g. ammonium nitrate)

Description: Replace urea or urea-based (*e.g.* urea ammonium nitrate, UAN) fertiliser use with another form of inorganic fertiliser N (*e.g.* ammonium nitrate)

Rationale: Urea and urea-based fertilisers are associated with higher ammonia emissions than other forms of inorganic fertiliser.

Mechanism of action: Following application, urea will undergo hydrolysis to form a mixture ammonium carbonate (the rate of which depends on temperature, moisture and presence of the enzyme urease). This process greatly increases pH around the urea fertiliser granule, leading to a large potential for ammonia emission. This is in contrast to fertiliser forms such as ammonium nitrate, where the ammonium and dissolved ammonia will be in equilibrium at a much lower pH, greatly reducing the potential for ammonia emission.

Potential for applying the method: All currently used urea and urea-based fertilisers could be replaced with ammonium nitrate or other form of N (*e.g.* ammonium phosphate, ammonium sulphate).

Current implementation: Urea and urea-based fertilisers currently (2006 data) account for *c.*16% of all inorganic fertiliser N used in UK agriculture.

Practicability: There should be no practical reasons why urea and urea-based fertilisers cannot be replaced with another fertiliser N type, although such a method may not be enforceable (under World Trade Agreements). Lower costs have been the main reason for urea use.

Practicability Score: 2 (Use of urea cannot be banned under current trade agreements)

Cost: Will depend on the price differential between urea and other fertiliser N types (on a per unit of nitrogen basis). Currently, this method would be at least cost-neutral and probably cost-beneficial as urea is not as agronomically effective as ammonium nitrate.

Effectiveness: Emissions from urea fertiliser applications can vary greatly according to the soil and weather conditions at and following application, but the mean emission factor associated with urea is approximately tenfold greater than that associated with ammonium nitrate. Replacing current urea and UAN use with ammonium nitrate would reduce ammonia emissions from UK agriculture by approximately 16 kt NH_3.

Other benefits or risk of pollution swapping: Reducing ammonia emissions from N fertiliser use will result in a greater proportion of the applied N being available for crop uptake and will potentially reduce the amount of fertiliser N required. Reducing ammonia emissions from applied fertiliser N potentially increases the risk of nitrogen losses *via* nitrate leaching or nitrous oxide emissions. However, provided the fertiliser is applied at an agronomically suitable time and rate, the risk of pollution swapping will be minimal.

Key references:

Defra project NT2605 ‘The behaviour of some different fertiliser-N materials – main experiments’

Harrison, R., and Webb, J. (2001). A review of the effect of N fertilizer type on gaseous emissions. *Advances in Agronomy* **73**, 65-108.

Misselbrook, T.H., Sutton, M.A., and Scholefield, D. (2004). A simple process-based model for estimating ammonia emissions from agricultural land after fertilizer applications. *Soil Use and Management* **20**, 365-372.

24. Incorporate a urease inhibitor with urea fertilisers

Description: Incorporate a urease inhibitor into solid urea, liquid urea/ammonium nitrate (UAN) and liquid urea ammonium sulphate (UAS) solutions

Rationale: Urease inhibitors delay the conversion of urea to ammonium carbonate, allowing applied urea fertiliser to be solubilised and 'washed' into the soil before any significant emissions of ammonia have occurred.

Mechanism of action: Urease inhibitors, such as N-(n-butyl) thiophosphoric triamide (NBPT) or other similar products, slow the hydrolysis of urea by inhibiting the urease enzyme in the soil. Slowing urea hydrolysis allows more time for the urea to be 'washed' into the soil following application and reduces the soil pH increase in close proximity to the applied urea and thereby the potential for ammonia emission.

Potential for applying the method: A urease inhibitor could potentially be incorporated into all urea, UAN and UAS fertilisers applied in the UK.

Current implementation: Nil (product not currently available in the UK).

Practicability: A product including the inhibitor is commonly used in the USA. Other than costs and product registration issues, no barriers to use are envisaged.

Practicability Score: 2 (Commercialisation within the UK would be required – it is understood that a product may be available on the market in the near future, subject to product registration clearance).

Cost: There would be no additional costs associated with the spreading operation as the inhibitor is included within the fertiliser. However, there would be additional cost for the product, for which no data are currently available.

Effectiveness: NBPT has been shown to reduce emissions from solid urea by a mean of 70% and from liquid UAN by a mean of 40% (data from Defra NT26 research programme). Incorporation of NBPT into all applications of urea-based fertiliser types would reduce emissions from UK agriculture by up to 11.4 kt NH_3.

Other benefits or risk of pollution swapping: The Defra NT26 research programme showed evidence of increased efficiency of N use from urea and liquid UAN by crops where NBPT was used, with no evidence of increases in nitrous oxide emission. Provided that urea/UAN is applied at an agronomically suitable time and rate, the risk of pollution swapping will be minimal.

Key references:

Defra project NT2605 'The behaviour of some different fertiliser-N materials – main experiments'

25. Integrate fertiliser and manure nitrogen supply

Description: Use a recognised fertiliser recommendation system (e.g. RB209, PLANET, industry developed nutrient management plans) to plan fertiliser applications to all crops and to take full account of nitrogen supplied by organic manures, adjusting mineral fertiliser N applications accordingly. Use manure analysis to gain a better understanding of nitrogen applications and supply.

Rationale: Robust recommendation systems can be used to provide a good estimate of the amount of nitrogen (and other nutrients) supplied by manure applications. This information can then be used to determine the amount and the ideal timing of additional fertiliser N required by the crop. Fertiliser use statistics suggest that, in most cases, this will result in a reduction in fertiliser N inputs (particularly on arable crops) compared with current practice and a concomitant reduction in ammonia emissions from fertiliser N use (and particularly from urea-based fertilisers).

Mechanism of action: The potential for ammonia emission is reduced at source. Inorganic fertiliser N applications are reduced to no more than is required for optimum economic production levels and to maintain adequate levels in the soil.

Potential for applying the method: Applicable to most intensive grassland (excluding some pure clover swards) and arable systems (excluding land growing peas and beans and land that is organically farmed). The measure is effective wherever inorganic N fertilisers are used to top-up the nitrogen supplied in organic manures. The inclusion of manure N utilisation factors within revisions to the NVZ Action Programme should encourage a shift to better recovery of plant available N from organic manures.

Current implementation: Widely practiced, although full account is not always taken by farmers of manure N supply.

Practicability: The method could easily be implemented via advice, education and guidance. In particular, guidance is required on soil and manure sampling, on-farm analysis of slurries, and interpretation of results.

Practicability Score: 1 The NVZ Action Programme rules require farmers to make full allowance for manure N supply in farm nitrogen management plans.

Cost: Provided that manure nitrogen is used effectively and there are no yield reductions through spreading operations *etc*., this method will commonly result in cost savings through the use of less fertiliser N.

Effectiveness: The effectiveness of this method will be directly in proportion to the reduction in inorganic N fertiliser use. The effectiveness will depend on the type of fertiliser being replaced, with maximum benefits deriving from replacing urea, associated with a high ammonia emissions (see Methods 23 and 24).

Other benefits or risk of pollution swapping: Reducing inorganic fertiliser N inputs will reduce the risk of other associated N losses to water and air (*e.g.* nitrate leaching, surface run-off/drainflow losses, nitrous oxide emissions). When slurry is spread soon after the application of N fertiliser, there is a risk of increased nitrous oxide emissions through the process of denitrification. Current advice is to leave at least 5 days between the application of N fertiliser and slurry.

Key references:

Anon. (2000). Fertiliser Recommendations for Agricultural and Horticultural Crops. Defra Reference Booklet 209, Seventh edition, The Stationery Office, Norwich.

Planning Land Applications of Nutrients for Efficiency and the environmenT (PLANET). Available via Defra website: http://www.defra.gov.uk/farm/environment/land-manage/nutrient/nmu02.htm