WGSR
Informal document no. 20

DRAFT GUIDANCE DOCUMENT FOR PREVENTING AND ABATING AMMONIA EMISSIONS FROM AGRICULTURAL SOURCES

Submitted by the Co-chairs of the Task Force on Reactive Nitrogen

Article 3, paragraph 8 (b) of the 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone requires each Party to "apply, where it considers it appropriate, best available techniques for preventing and reducing ammonia emissions, as listed in guidance document V (EB.AIR/1999/2, part V) adopted by the Executive Body at its seventeenth session (decision 1999/1)", the updated guidance document (ECE/EB.AIR/WG.5/2007/13) and any amendments thereto. In line with the decision of the Executive Body in 2008 to establish a Task Force on Reactive Nitrogen (TFRN) aiming at "*developing technical and scientific information, and options which can be used for strategy development across the UNECE to encourage coordination of air pollution policies on nitrogen in the context of the nitrogen cycle and which may be used by other bodies outside the Convention in consideration of other control measures*" the TFRN has updated the guidance document to provide an amended text. The update includes the results of the workshop on "The Costs of Ammonia abatement and the climate co-benefits" (Paris, 25-27 October 2010), and additional up-dates discussed during the TFRN-6 meeting in Rome in May 2011 and that of the TFRN-7 in St Petersburg (February 27 – March 1 2012).

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SUMMARY

1. The purpose of this document is to provide guidance to the Parties to the Convention in identifying ammonia (NH_3) control measures for reducing emissions from agriculture, as indicated in ANNEX IX of the UNECE Gothenburg protocol.

2. This document summarizes
- the current knowledge of ammonia emission abatement techniques and strategies;
- the scientific and technical background of the techniques and strategies;
- the economic cost of the techniques, in terms of euro per kg of NH_3 abated;
- any limitation and constraint with respect to the applicability of techniques.

3. The document addresses ammonia control measures in the following areas
- Nitrogen management, taking into account the whole nitrogen cycle
- Livestock feeding strategies
- Animal housing techniques
- Manure storage techniques
- Manure application techniques
- Fertilizer application techniques
- Other measures related to agricultural nitrogen
- Measures related to non-agricultural and stationary sources

4. **Nitrogen management** is an integral measure to decrease nitrogen losses. Nitrogen management is based on the premise that decreasing the nitrogen surplus and increasing nitrogen use efficiency contribute to abatement of ammonia emissions. On mixed livestock farms, between 10 to 40% of the nitrogen surplus is related to NH_3 emissions. Nitrogen management also has the premise to identify and prevent pollution swapping between different nitrogen compounds and environmental compartments. Establishing a nitrogen input-output balance at the farm level is a prerequisite to get the basis for optimizing the nitrogen management in an integral way.

5. The cost of establishing a farm nitrogen balance is in the range of 200 to 500 euro per farm per year. (The farm balance refers to an accounting for all nitrogen inputs such as feed, fertilizer etc, and all nitrogen outputs in products). Note that costs associated with education, promotion and start-up are not considered here. The cost of increasing nitrogen use efficiency through improving management are in the range of -1.0 to 1.0 euro per kg nitrogen saved. The possible savings are related to less cost for fertilizer and increased crop quality. The possible costs are related to increased cost for advisory services and soil, crop, feed and manure analyses. The economic cost of possible investments in techniques are not include here, but discussed with the other provisions. Table S1 lists indicative ranges for Nitrogen Use Efficiency (NUE) and the nitrogen surplus of the input-output balance of different farming systems. These ranges serve as rough guidance; they can be made more farm and country specific. Nitrogen use efficiency should be managed in concert with overall nutrient efficiencies and other factors such as pest control.

Table S1. Indicative ranges for target nitrogen (N) surplus and nitrogen use efficiency (NUE) as function of farming system, crop species and animal categories

Farming systems	Species/ categories	NUE, kg/kg	N surplus, kg/ha/yr	Comments
Specialized cropping systems	Arable crops	0.6-0.9	0-50	Cereals have high, root crops low NUE
	Vegetables	0.4-0.8	50-100	Leafy vegetables have low NUE
	Fruits	0.6-0.9	0-50	
Grassland-based ruminant systems	Dairy cattle	0.3-0.5	100-150	High milk yield, high NUE; Low stocking density, low N surplus
	Beef cattle	0.2-0.4	50-150	Veal production, high NUE; 2 year old beef cattle, low NUE
	Sheep & goats	0.2-0.3	50-150	
Mixed crop-animal systems	Dairy cattle	0.4-0.6	50-150	High milk yield, high NUE; Concentrate feeding, high NUE
	Beef cattle	0.3-0.5	50-150	
	Pigs	0.3-0.6	50-150	
	Poultry	0.3-0.6	50-150	
	Other animals	0.3-0.6	50-150	
Landless systems	Dairy cattle	0.8-0.9	n.a.*)	N Output via milk, animals, manure + N-loss ~equals N input; Nsurplus is gaseous N losses from housing and storages.
	Beef cattle	0.8-0.9	n.a.	
	Pigs	0.7-0.9	n.a.	
	Poultry	0.6-0.9	n.a.	
	Other animals	0.7-0.9	n.a.	

*) Not applicable, as these farms have essentially no land. However, the N surplus can be expressed in kg per farm per year. In the case that all animal products, including animal manure and all residues and wastes, are exported, the target N surplus can be between 0 - 1000 kg per farm per year, depending on farm size and gaseous N losses.

6. **Livestock feeding strategies** decrease ammonia emissions from manure in both housing and storage, and following application to land. Livestock feeding strategies are more difficult to apply to grazing animals but emissions from pastures are low and grazing itself is essentially a category 1 measure. Livestock feeding strategies are implemented through (i) phase feeding, (ii) low-protein feeding, with or without supplementation of specific synthetic amino acids and ruminal bypass protein, (iii) increasing the non-starch polysaccharide content of the feed, and (iv) supplementation of pH-lowering substances, such as benzoic acid. Phase feeding is an effective and economically attractive measure even if requiring additional installations. Young animals and high-productive animals require more protein concentration than older, less-productive animals. Combined ammonia emissions for all farm sources decrease roughly by 10% when mean protein content decreases by 10 g per kg (1%) in the diet. The economic cost of the livestock feeding strategies depend on the cost of the feed ingredients and the possibilities of adjusting these ingredients, based on availability, to optimal proportions. The reference here is the mean current practice, which varies a lot across countries and over time. The net costs of livestock feeding strategies depend on the manipulation of the diet and the changes in animal performance. In general, high-protein diets and efficient low-protein diets cost more than diets with medium high protein contents. Both, too high and too low protein contents

in the diet have negative effect on animal performance, although the latter is more evident to producers. The cost of the diet manipulations are in the range of -10 to 10 euro per 1000 kg of feed, depending on market conditions for feed ingredients and the cost of the synthetic amino acids. Hence, in some years there are benefits while in other years there are costs associated with changes in diets. Table S2 summarizes possible target for lowering protein values maintaining production efficiencies for each animal category (see also Appendix 2). Note that the economic costs increase as the ambitions to decrease the mean protein content increase from low to high.

Table S2: Indicative target protein levels (percent) of dry feed with a standard dry matter content of 88%) for housed animals as function of animal category and for different ambition levels. This table summarizes the tables in the main text as well as those in Appendix 2. Note that a decrease of the protein content in the feed by 1% may decrease the total NH_3 emissions from all manure sources by 10%.

Animal type	Mean crude protein content of the animal feed, %[1]		
	Low ambition	Medium ambition	High ambition
Dairy cattle, early lactation (>30kg/day)	17-18	16-17	15-16
Dairy cattle, early lactation (<30kg/day)	16-17	15-16	14-15
Dairy cattle, late lactation	15-16	14-15	12-14
Replacement cattle (young cattle)	14-16	13-14	12-13
Veal	20-22	19-20	17-19
Beef <3 months	17-18	16-17	15-16
Beef >6 months	14-15	13-14	12-13
Sows, gestation	15-16	14-15	13-14
Sows, lactation	17-18	16-17	15-16
Weaner, <10 kg	21-22	20-21	19-20
Piglet, 10-25 kg	19-20	18-19	17-18
Fattening pig 25-50 kg	17-18	16-17	15-16
Fattening pig 50-110 kg	15-16	14-15	13-14
Fattening pigs >110	13-14	12-13	11-12
Chicken, broilers, starter	22-23	21-22	20-21
Chicken, broilers, growers	21-22	20-21	19-20
Chicken, broilers, finishers	20-21	19-20	18-19
Chicken, layers, 18-40 weeks	17-18	16-17	15-16
Chicken, layers, >40 weeks	16-17	15-16	14-15
Turkeys, <4 weeks	26-27	25-26	24-25
Turkeys, 5-8 weeks	24-25	23-24	22-23
Turkeys, 9-12 weeks	21-22	20-21	19-20
Turkeys, 13 -16 weeks	18-19	17-18	16-17
Turkeys, >16 weeks	16-17	15-16	14-15

[1]With adequately balanced and optimal digestible amino acid supply.

7. For **animal housing**, abating ammonia emissions is based on one or more of the following principles:

- Decreasing the surface area fouled by manure;
- Rapid removal of urine; rapid separation of faeces and urine;
- Decreasing of the air velocity and temperature above the manure;
- Reducing the pH and temperature of the manure;
- Drying manure (esp. poultry litter);
- Removing (scrubbing) ammonia from exhaust air; and
- Increased grazing time.

All principles have been applied in category 1 techniques; i.e., scientifically sound and practically proven. Different animal categories require different housing systems and environmental conditions, hence different techniques. Because of their different requirements and housing, there are different provisions according to animal categories. The references used are the most conventional housing systems, without techniques for abating NH_3 emissions. The costs of techniques used to lower ammonia emissions from housings are related to: (i) depreciation of investments, (ii) rent on investments, (iii) energy, (iv) operation and maintenance. In addition to costs, there are benefits related to increasing animal health and performance. These benefits are difficult to quantify and have not always been included in the total cost estimate. The economic costs vary because of different techniques/variants and farms sizes. Table S3 presents an overview of the emission reduction and economic cost for the major animal categories

Table S3. Ammonia emission reduction techniques for animal housing, their emission reduction levels and associated costs.

Category	Minimum emission reduction compared with the reference [a]	Extra Cost (€/kg NH_3-N reduced)
Existing pig and poultry housing on farms with >2,000 fattening pigs or >750 sows or >40,000 poultry	20%	Mean range: 0 to 3 There are also more expensive techniques and approaches
New or largely rebuilt cattle housing [b]	25%	Mean range: 1 to 6 Techniques and approaches still in development
New or largely rebuilt pig housing [b]	25 to 60%, depending on the housing systems	Mean range: 0 to 10
New and largely rebuilt broiler housing [b]	20%	Mean range: 0 to 2
New and largely rebuilt layer housing [b]	30 to 60%, depending on the housing systems	Mean range: 0 to 8
New and largely rebuilt animal housing on farms for animals other than those already listed in this table [b]	0 to 60%, depending on the housing systems	Mean range: 0 to 2

a/ The references are specified further on in the Guidance Document.
b/ Livestock farms with five livestock units or less would be exempt from these requirements.]

8. For **manure storages**, abating ammonia emissions is based on one or more of the following principles (i) decreasing the surface area where emissions can take place, i.e. through covering of the storage, encouraging crusting and increasing depth of storages, (ii) decreasing the source strength of the emitting surface, i.e., through lowering the pH and NH_4 concentration, and (iii) minimizing disturbances such as aeration. All principles have been applied in category 1 techniques; i.e., scientifically sound and practically proven. These principles are generally applicable to slurry storages and manure (dung) storage. However, the practical feasibility of implementing the principles are larger for slurry storages than for manure (dung) storages. The reference here is the uncovered slurry store without crust and uncovered solid manure heap.
The costs of techniques used to lower ammonia emissions from storages are related to (i) depreciation of investments, (ii) rent on investments, and (iii) maintenance. Here, a summary is provided of the total costs, in terms of euro per kg NH_3-N saved (Table S4). In addition to costs, there are benefits related to decreased odour emissions, decreased rain water and increased safety (no open pits); some of these benefits are difficult to quantify and therefore have not been included here. Ranges of costs relate to different techniques/variants and farms size. Note that the cost of the storage system itself are not included in the cost estimates of Table S4. There may be some risk to covers such as increased emissions of toxic gases (H_2S, CO) and methane, and damage from extreme weather. Some covers can only be implemented when new storages are built. Manure processing such as separation, composting and digestion have implications for the total losses during ‘storage’.

Table S4. Ammonia emission reduction techniques for manure storages, their emission reduction levels and associated costs

Techniques	**Emission reduction, %**	**Cost, € per m^3 per year**	**Cost, € per kg NH_3-N saved**
Tight lid	> 80	2 to 8	2 to 4
Plastic cover	> 60	1 to 2	0.5 to 1.5
Floating cover	> 40	1 to 2*)	1 to 2*)

*)not including crust; crusts form naturally on some manures and have no cost, but are difficult to predict.

9. **Low-emission manure application** is based on one or more of the following principles: (i) decreasing the surface area where emissions can take place, i.e. through band application, injection, incorporation; (ii) decreasing the time that emissions can take place, i.e. through rapid incorporation of manure into the soil or immediate irrigation or rapid infiltration; and (iii) decreasing the source strength of the emitting surface, i.e., through lowering the pH and NH_4 concentration of the manure (through dilution). All principles have been applied in category 1 techniques; i.e., scientifically sound and practically proven. These principles are generally applicable to slurry and solid manure application. However, abatement techniques are more applicable and effective for slurry than for solid manures. For solid manure, the most feasible technique is rapid incorporation into the soil and immediate irrigation. The reference here is the broadcast spreading of slurry and solid manure. A fourth principle, applying when volatilization potential is low, such as at low

temperature and wind is considered category 2 because it requires a method of validation. The costs of techniques used to lower ammonia emissions from application are related to:

- depreciation of investments costs of the applicator;
- rent on investments;
- added tractor costs and labor; and
- operation and maintenance.

Here, a summary is provided of the total costs, in terms of euro per kg NH_3-N saved (Table S5). The co-benefits relate to decreased odor emissions and biodiversity loss, and increased palatability of herbage, uniformity of application and consistency of crop response to manure. Some of these benefits are difficult to quantify and therefore have not all been included in the cost estimations. Ranges of costs relate to the NH_4 content of the slurry/manure; the higher the NH_4 content, the lower the abatement cost. Mean costs are likely in the lower half of the range, especially when application is done by contractors, on large farms or with shared equipment.

Table S5. Ammonia emission reduction techniques for manure application, their emission reduction levels and associated costs

Manure type	Application techniques	Emission reduction, %	Cost, € per kg NH_3-N saved
Slurry	Injection	> 60	-0.5 to 1.5
	Shallow injection	> 60	-0.5 to 1.5
	Trailing shoe,	> 30	-0.5 to 1.5
	Band application	> 30	-0.5 to 1.5
	Dilution	> 30	-0.5 to 1
	Management systems	> 30	0 to 2
Solid manure	Direct incorporation	>30	-0.5 to 2

10. For **application of urea and ammonium based fertilizers**, abating emissions is based on one or more of the following principles: (i) decreasing the surface area where emissions can take place, i.e. through band application, injection, incorporation (but note that rapid increase in pH in concentrated bands of urea, especially where there is high crop residue, may lead to high emissions due to rise in pH); (ii) decreasing the time that emissions can take place, i.e. through rapid incorporation of fertilizers into the soil or via irrigation; (iii) decreasing the source strength of the emitting surface, i.e., through urease inhibitors, blending and acidifying substances, and (iv) a ban on its use (as in the case of ammonium (bi)carbonate). All principles have been applied in category 1 techniques; i.e., scientifically sound and practically proven.

The reference here is the broadcast application of the urea- and ammonium based fertilizers.

The costs of techniques used to lower ammonia emissions from fertilizers are related to (i) depreciation of investments costs of the applicator, (ii) rent on investments, (iii) use of heavier tractor and more labor time; and (iv) maintenance. Here, a summary is provided of the total costs, in terms of euro per kg NH_3-N saved (Table S6). The possible benefits relate to decreased fertilizer costs, decreased application costs in a combined seeding and fertilizing system and decreased biodiversity loss. These benefits are difficult to quantify and have not all been included. Ranges of costs relate to the farm size (economics of scale), soil conditions and climate (high emission reduction in relatively dry conditions). Mean costs are likely in the lower half of the range when application is done by contractors or low emitting fertilizers are substituted.

Table S6. Ammonia emission reduction techniques for application of urea and ammonium-based fertilizers, their emission reduction levels and associated costs.

Fertilizer type	**Application techniques**	**Emission reduction, %**	**Cost, € per kg NH_3-N saved**
Urea	Injection	> 80	-0.5 to 1
	Band spreading	> 50[1]	-0.5 to 2
	Urease inhibitors	> 50	-0.5 to 2
	Incorporation	> 30	-0.5 to 2
	Surface spreading with irrigation	> 30	-0.5 to 1
Ammonium carbonate	Ban	~100	-1 to 2
Ammonium-based fertilizers	Injection separately or with seeding	> 80	0 to 4
	Band spreading	> 50	0 to 4
	Incorporation	> 30	0 to 4
	Surface spreading with irrigation	> 30	0 to 4

[1]Surface banding of urea without incorporation may have high emissions where there is high urease activity such as on reduced till with crop residue

I. INTRODUCTION

1. The purpose of this document is to provide guidance to the Parties to the Convention in identifying ammonia (NH_3) control measures for reducing emissions from agricultural sources, taking account of the whole nitrogen cycle. This guidance document will facilitate the implementation of the Basic Obligations of the Protocol mentioned in Article 3, as regards NH_3 emissions, and more specifically will contribute to the effective implementation of the measures listed in Annex IX, and to achieving the national NH_3 emission ceilings listed in Annex II, Table 3 of the Protocol.

2. The document addresses the abatement of NH_3 emissions produced by agricultural sources. Agriculture is the major source of NH_3, chiefly from livestock excreta in livestock housing, during manure storage, processing, treatment and application to land, and from excreta from animals at pasture. Emissions also occur from inorganic nitrogen (N) fertilizers following their application to land and from nitrogen-rich crops and crop residues, including grass silage. Emissions can be reduced through abatement measures in all the above areas but with varying degrees of practicality, efficacy and costs.

3. The first version of the Guidance document (EB.AIR/1999/2) provided general guidance on the abatement of NH_3 emissions. This version was revised in 2007 ECE/EB.AIR/WG.5/2007/13). The current version is further revised and reflects the state of scientific and technological development at the start of 2012.

4. In this document, strategies and techniques for the abatement of NH_3 emissions and N losses are grouped into three categories:

(a) ***Category 1 techniques and strategies***: These are well researched, considered to be practical or potentially practical, and there are quantitative data on their abatement efficiency, at least on the experimental scale;
(b) ***Category 2 techniques and strategies***: These are promising, but research on them is at present inadequate, or it will always be difficult to generally quantify their abatement efficiency. This does not mean that they cannot be used as part of an NH_3 abatement strategy, depending on local circumstances;
(c) ***Category 3 techniques and strategies***: These have not yet been shown to be effective or are likely to be excluded on practical grounds.

5. Based on the available research, Category 1 techniques can be considered as already verified for use in abatement strategies. Category 2 and Category 3 techniques may also be used in abatement strategies. However, for these categories independent verification should be provided by Parties using them in order to demonstrate the reductions in NH_3 emissions that they report. It should be noted that cost of a technique is not considered for the classification. Information on costs is provided to support decisions on the use of the techniques.

6. Separate guidance has also been prepared, at European Union level, under the Integrated Pollution Prevention and Control (IPPC) Directive 2008/1/EC (from November 2011 'Directive on Industrial Emissions' 2010/75/EU) to reduce a range of polluting emissions from large pig and poultry units. The "Reference Document on Best Available Techniques (BAT) for Intensive Rearing of Poultry and Pigs", the BREF (BAT reference) document, may be found at: http://eippcb.jrc.es/reference/irpp.html. The BREF is currently under revision. There is only partial overlap between BAT and the present guidance document, since BAT has only been defined for the pig and poultry sectors, and has not been defined for cattle, sheep or other livestock, nor for the land application of manures or fertilizers. The current document is more inclusive for farms and sectors because it addresses also ammonia emissions from manure and fertilizer application to land and various other sources.

7. Options for NH_3 reduction at the various stages of livestock manure production and handling are interdependent, and combinations of measures are not simply additive in terms of their combined emission reduction. Controlling emissions from applications of manures to land is particularly important, because these are generally a large component of total livestock emissions and because land application is the last stage of manure handling. Without abatement at this stage, much of the benefit of abating during housing and storage which is often more costly may be lost. Likewise, controlling emissions from land application will have less benefit for total farm losses and N use efficiency if large losses occur in barns and storages. Reduction in N excretion rates from livestock has the most direct effect on emissions and has been added to this document. Because of this interdependency, Parties should as far as possible exploit models where the overall mass-flow of ammonia nitrogen is assessed, in order to optimise their abatement strategies. Therefore the whole farm context, including animal feeding, has also been added to this document.

8. Many measures may incur both capital and operational costs (see Table 1). In addition to theoretical calculations based on capital and operating expenditure, actual data on costs (e.g. as charged by contractors) should be used where available. In addition to calculating the direct costs, the benefits of measures should as far as possible be calculated. In many cases, the combined benefits to the farmer (e.g., reduced mineral fertilizer need, improved agronomic flexibility, reduced emissions of other pollutants, less complaints due to odour) may outweigh the costs. Comparison of the net cost to the farmer (i.e. cost minus benefit) with other environmental benefits (e.g., improved air, water quality and soil quality, reduced biodiversity loss, reduced perturbation of climate) is beyond the scope of this document.

9. The costs of the techniques will vary from country to country. It should be noted that, due to economies of scale, some of the abatement techniques may be more cost-effective on large farms than on small farms. This is especially so when an abatement technique requires the purchase of capital equipment, e.g. reduced-emission slurry applicators. In such cases, the unit costs decrease as the volumes of manure increase. A greater cost burden for smaller farms may also be the case for immediate incorporation of manures. Both for slurry application and manure incorporation, the costs for small farms will often

be reduced by spreading the costs of the equipment over several farms through use of contractors with access to suitable equipment, sometimes locally designed and built. Therefore the upper range of costs may also be reduced by focusing mitigation efforts on medium and large farms.

Table 1 (a): Capital costs (capital expenditure (CAPEX))

Consideration	Notes
Capital for fixed equipment or machinery.	Fixed equipment includes building, installations, conversions of buildings, feed storage bins, or manure storage covers. Machinery includes feed distribution augers, field equipment for manure application or equipment for manure treatment, etc.
Labour cost of installation.	Use contract charges if these are normal. If farm staff are normally used to install the conversion, employed staff should be rated at typical hourly rates. Farmers' input should be charged at the opportunity cost.
Grants	Subtract the value of capital grants available to farmers.

CAPEX (new) means the investment costs in new build situations, in contrast with CAPEX (retrofit) meaning rebuilding or renovation of buildings.

Table 1(b): Annual costs (operational expenditure, OPEX): the annual cost associated with the introduction of a technique.

Consideration	Notes
Annualized cost of capital should be calculated over the life of the investment.	Use standard formula. The term will depend on the economic life. Conversions need to take account of remaining life of original facility.
Repairs associated with the investment should be calculated.	A certain percentage of the capital costs.
Changes in labour costs.	Additional hours x cost per hour.
Fuel and energy costs.	Additional power requirements may need to be taken into account.
Changes in livestock performance.	Changes in diets or housing can affect performance, with cost implications.
Cost savings and production benefits.	The introduction of techniques will often result in the saving of costs for the farmer. These should be quantified as far as possible. Separate note should be taken of the avoidance of fines for pollution in costing benefits.

10. Wherever possible, techniques listed in this document are clearly defined and assessed against a "reference" or unabated situation. The "reference" situation, against which percentage emission reduction is calculated, is defined at the beginning of each chapter. In most cases the "reference" is the practice or design that is the most commonly practised technique presently found on commercial farms in the UNECE and is used to construct baseline inventories.

11. When introducing new measures, there is often a cost associated with education, promotion and start-up which are not considered here. In most cases, there are substantial co-benefits arising from the measures, not included in the costing, which will improve the overall wellbeing of farming operations and of the public. An example is reduction of odour, resulting from reduced emissions, which will benefit the public (may even improve tourism) and farmers and their families. The secondary cost savings are also not counted, for example, reduced pollution and energy use from fertilizer manufacturing plants due to better conservation of ammonia on farms. Some measures (e.g. manure injection, covers for FYM, acidification, scrubbing exhaust air) reduce risk of contaminating waterways with N, other nutrients, pathogens and other contaminants.

II. LIVESTOCK PRODUCTION AND DEVELOPMENTS

12. Livestock excreta in livestock housing, during manure storage, processing, treatment and application to land, and from excreta from animals at pasture are the main sources of NH_3 emissions in most UNECE countries. Therefore, it is imperative to explain briefly the livestock sector.

13. The livestock sector is an important contributor to the global food and agricultural economy and to human nutrition and culture, accounting for 40 percent of the value of world agricultural output and providing 10-15 percent of total food calories and one-quarter of dietary protein. In most of the developing country regions it is the fastest growing segment of the agricultural sector. The livestock sector is expected to provide safe and plentiful food for growing urban populations, livelihoods for almost one billion poor producers, enables exploitation of non-arable lands, provides food security against crop failure for subsistence farmers, utilizes food wastes and field losses or residues and even provides fuels, concentrates and re-circulates farm nutrients as well as global public goods related to food security, environmental sustainability and public health (Geers and Madec, 2006; FAO, 2009; Steinfeld et al., 2010).

14. While livestock provides various useful functions to society and the global demand for dairy, meat and egg products continues to increase for the next decades, there is also increasing pressure on (intensive) livestock production systems to become more environmentally friendly. The livestock sector is a major land user globally and has been implicated in deforestation and biodiversity loss (Steinfeld et al., 2006; FAO, 2009; Steinfeld et al., 2010). It is also a main user of fresh water, mainly through animal feed production, while fresh water resources become scarce in some areas. Livestock production is a main source of atmospheric ammonia (NH_3) and the greenhouse gases methane (CH_4) and nitrous oxide (N_2O). The emissions of ammonia mainly originate from the nitrogen in manure of animals. Emissions of NH_3 from livestock production are related to the type, number and genetic potential of the animals, the feeding and management of the animals, and to the technology of animal housing and manure management (Bouwman et al., 1997; Steinfeld et al., 2006; Oenema et al., 2008). Livestock dominate the requirement for reactive nitrogen in Europe. For example, the European Nitrogen Assessment has estimated that 85% of harvested nitrogen goes to feed livestock, while only 15% feeds people directly (Sutton et al., 2011).

15. Livestock production systems can broadly be classified into (i) grazing systems, (ii) mixed systems and (iii) fully confined landless or industrial systems (e.g. Seré and Steinfeld, 1996). Grazing systems are entirely land-based systems, with stocking rates less than one or two livestock unit per ha, depending on grassland productivity. In mixed systems a significant part of the value of production comes from other activities than animal production while part of the animal feed often is imported. Industrial systems have stocking rates greater than 10 livestock units per ha and they depend primarily on outside supplies of feed, energy and other inputs. In industrial systems, 0-10% of the dry matter fed to animals is produced on the farm. Relevant indicators for livestock production systems are animal density in animal units per ha (AU/ha) and kg milk or meat/ha/year. A common

and useful indicator for the pressure on the environment is the total N or P excretion of the livestock per ha per year (e.g., Menzi et al., 2010).

16. In each livestock category, a distinction can be made between conventional and organic farming. Further, there is often a distinction between intensive and extensive systems. Intensive livestock production systems are characterized by a high output of meat, milk, and eggs per unit of agricultural land and per unit of stock (i.e. livestock unit), which usually coincides with a high stocking density per unit of agricultural land. This is generally achieved by high efficiency in converting animal feed into animal products. Because of their capacity to rapidly respond to a growing demand for low-cost animal products, intensive livestock production systems now account for a dominant share of the global pork, poultry meat and egg production (respectively 56, 72 and 61 percent) and a significant share of milk production (Steinfeld et al., 2006; FAO, 2009).

17. Traditionally, most animal products consumed by humans were produced locally using locally produced animal feeds. Increasingly, many animal products consumed by humans in urban areas are produced using animal feeds imported from outside the animal production areas. This holds especially for pig and poultry products. Thereby, areas of animal feed production and pig and poultry production become increasingly disconnected from the site of animal product consumption. This disconnection has been made possible through the development of efficient transport infrastructure and the relatively low price of fossil energy; the shipment of concentrated feed is cheap relative to other production costs. Transportation of meat and egg products has also become cheaper. However, the uncoupling of animal feed production from animal production has major consequences for the proper reuse and management of animal manure (FAO, 2009; Steinfeld et al., 2010 and references therein).

18. Increasingly, production chains are organized and regionally clustered in order to minimize production, processing and delivery costs. Animal feed is the major input to livestock production, followed by labor, energy, water and services. Input costs vary substantially from place to place within countries as well as across countries and continents. Access to technology, labour and know-how is also unevenly distributed, as is the ability to respond to changing environments and to market changes. There are also institutional and cultural patterns that further affect production costs, access to technologies and transaction costs. The combination of these factors determines that livestock production systems become larger, more specialized, and more intensive (FAO, 2009; Steinfeld et al., 2010).

19. Livestock production systems are dynamic systems because of continuous developments and changes in technology, markets, transport and logistics. Increasingly, livestock products become 'global commodities', and livestock production systems are operating in an 'open', highly competitive, global market. These developments are facilitated by the increasing demand for low-cost animal products because of the increasing urban population and the increasing consumption of animal products per capita, although there are large economic, regional and continental differences. The additional demand for livestock products concentrates in urban centers (FAO, 2009; Steinfeld et al., 2010).

20. The rapid developments in livestock production systems have a strong effect on the emissions of NH_3, N_2O and CH_4 from these systems to the atmosphere and of the leaching and runoff of N to waters. Emission abatement strategies have to take such developments into account and to anticipate new developments, so as to make these strategies effective and efficient in the future.

III. NITROGEN MANAGEMENT, TAKING ACCOUNT OF THE WHOLE NITROGEN CYCLE

21. Management is often called the 'fourth production factor', in addition to land, labour and capital (techniques). Its importance for the economic and environmental performances of agricultural is enormous. Management is commonly defined as 'a coherent set of activities to achieve objectives'. Nitrogen management can be defined as '*a coherent set of activities related to the handling and allocation of nitrogen on farms to achieve agronomic and environmental/ecological objectives*' (e.g., Oenema and Pietrzak, 2002). The agronomic objectives relate to crop yield and quality, and animal performance in the context of animal welfare. The environmental/ecological objectives relate to minimizing nitrogen losses from agriculture. 'Taking account of the whole nitrogen cycle' emphasizes the need to consider all aspects of nitrogen cycling, also in 'NH_3 emissions abatement', to circumvent 'pollution swapping'. Although not considered here, other pollutants and impacts must also be avoided. Nitrogen management can be considered as the 'soft-ware' and 'org-ware', while the techniques may be considered as the 'hard-ware' of the nitrogen emissions abatement. Hence, nitrogen management has to be considered in conjunction with the techniques.

22. Nitrogen management varies greatly across the UN-ECE region, and NH_3 emissions will vary accordingly. In general, emissions of nitrogen tend to decrease when:

a. All nitrogen sources on the farm are fully considered in a coherent whole-farm perspective and a whole nitrogen cycle perspective;
b. All nitrogen sources are stored and handled properly;
c. Amounts of nitrogen used are strictly according to the needs of growing plants and animals;
d. Nitrogen sources are used in a timely manner, using the appropriate techniques, in the appropriate amounts and appropriate place;
e. All possible nitrogen loss pathways are considered in a coherent manner.

Supplementary information about 'nitrogen management, taking account of the whole nitrogen cycle' is provided in Appendix 1.

23. *Reference situation*. The reference is a farm situation without nitrogen management planning and without use of nitrogen balances. Because of intrinsic differences in nitrogen cycling, a distinction has to be made between different farming systems, such as:

a. Specialized crop producing farms, further divided into:
    i. arable crops,
    ii. vegetables
    iii. fruits
b. Grassland-based ruminant production farms, further divided into:
    i. dairy cattle
    ii. beef cattle
    iii. sheep and/or goat
    iv. other animals (buffalo, bison, deer, etc)
c. Mixed crop-animal systems, with as dominant animal
    i. dairy cattle

   ii. beef cattle
   iii. pigs
   iv. poultry
   v. other animals
d. Specialized, landless, systems with
   i. dairy cattle
   ii. beef cattle
   iii. pigs,
   iv. poultry
   v. other animals.

Category 1 strategies

24. Implementing effective nitrogen management at farm level is an effective strategy to increase the nitrogen use efficiency and to decrease nitrogen losses. It involves implementing an iterative set (cycle) of common management activities, carried out annually:

a. Analysis of
   i. the nitrogen demands of crops and animals,
   ii. the available nitrogen sources,
   iii. the storage conditions and possible leakages,
   iv. the available techniques, methods, procedures for using nitrogen efficiently
b. Decision making, including:
   i. development of options on the basis of the previous analyses,
   ii. assessment of the consequences of the various options, and
   iii. selecting the best option for achieving both agronomic and environmental targets.
c. Planning, including
   i. working out in broad outline the things that need to be done and measured: when and where and how and with how much.
   ii. making the actual plan, that allocates the available nutrients in a way that maximizes the economic benefit, while minimizing the environmental impact and satisfying environmental limits.
d. Execution, i.e.,
   i. implementation of the nitrogen management plan in practice,
   ii. taking into account actual environmental conditions,
   iii. taking into account best management guidelines and recommendations.
e. Monitoring and control, i.e.
   i. collecting data on yield and nitrogen contents.
   ii. making nitrogen input-output balances
f. Evaluation (verification and control of achievements relative to the set objectives) including:
   i. nitrogen surplus
   ii. nitrogen use efficiency (NUE)

25. The nitrogen input-output balance (also referred to as the farm-gate balance) can be seen as the monitoring tool to help achieve improvement in nitrogen management (e.g. Jarvis et al., 2011). It records at the farm level all nitrogen inputs and all nitrogen outputs in useful products. The difference between total nitrogen inputs and total nitrogen outputs is the nitrogen surplus (Nsurplus), while the ratio between total nitrogen output in useful products and total nitrogen input is a measure of the nitrogen use efficiency (NUE). The Nsurplus is an indicator for the pressure on the environment, and is expressed in terms of nitrogen per ha per year. NUE is an indicator for the efficiency of resources use (how much protein-N in food is produced per unit of input nitrogen) and is expressed in terms of kg per kg (Doberman, 2007). Both, Nsurplus and NUE depend highly on farming systems and management level. Indicative target values can be set for both Nsurplus and NUE, depending again on farming system and management level. In some countries, information about the farm N balance, N surplus and NUE may be seen as confidential ('secret') information

26. Nitrogen input-output balances have been used in research for more than 100 years and also on farms in some countries for more than 10 years now, also as regulatory tool. However, there is less experience with the use of input-output nitrogen balances as a tool to decrease NH_3 emissions specifically. The effectiveness of nitrogen input-output balances to decrease NH_3 emissions is greatest on farms with high livestock density. Constructing nitrogen input-output balances at farm level requires knowledge about bookkeeping in general and about nitrogen inputs and outputs. The experience so far is that these balances are easily understood by farmers and therefore can be used easily in communications and for comparing different farms and their performances. This is especially the case because an improvement in the N balance provides the basis for farmers to reduce costs in the purchase of mineral fertilizers. Similarly, for 'organic' farmers, where mineral fertilizers are not used, improving the nitrogen balance makes better use of nitrogen as a scarce resource on the farm.

27. Nsurplus and NUE depend on farming system and on the agronomic and environmental objectives. Hence, target levels for Nsurplus and NUE are farm-type-specific, and must be considered and evaluated from a regional perspective.

28. The progress in nitrogen management can be evaluated on the basis of changes in Nsurplus and NUE over time, for a specific farm or group of farms. A five-year period should be considered to account for inter-annual variations in weather conditions or incidental losses. Improvement in nitrogen management will be reflected in decreases in Nsurplus and increases in NUE. The improvement in nitrogen management can continue until a level of 'best management practice' has been achieved. This 'best management level' is commonly set by experimental farms or by the upper 5 percentile of practical farms. Hence, the improvement in nitrogen management performance can continue until the farms achieve the level that has been achieved by the upper 5 percentile of practical farms. Farms in Denmark and The Netherlands have been able to achieve decreases in Nsurplus and increases in NUE of the order of 30% in 5-year periods and 50% in 10-year periods (e.g. Mikkelson et al., 2010; Oenema et al., 2011). Further decreases in Nsurplus and

further increases in NUE slow down greatly once a level of 'best management practices' has been achieved.

29. Indicative target levels for Nsurplus and NUE are presented in Table 2. Note, that NUE is related inversely and non-linearly to Nsurplus.

Table 2. Indicative ranges for target Nsurplus and NUE as function of farming system, crop species and animal categories.

Farming systems	**Species/ categories**	**NUE, kg N /kg N**	**Nsurplus, kg/ha/yr**	**Comments**
Specialized cropping systems	Arable crops	0.6-0.9	0-50	Cereals have high NUE; Root crops have low NUE
	Vegetables	0.4-0.8	50-100	Leafy vegetables have low NUE
	Fruits	0.6-0.9	0-50	
Grassland-based	Dairy cattle	0.3-0.5	100-150	High milk yield, high NUE; Low stocking density, low Nsurplus, presence of legumes improves NUE
ruminant systems	Beef cattle	0.2-0.4	50-150	Veal production, high NUE; 2yr old beef cattle, low NUE
	Sheep & goat	0.2-0.3	50-150	
Mixed crop-animal systems	Dairy cattle	0.4-0.6	50-150	High milk yield, high NUE; Concentrate feeding, high NUE
	Beef cattle	0.3-0.5	50-150	
	Pigs	0.3-0.6	50-150	
	Poultry	0.3-0.6	50-150	
	Other animals	0.3-0.6	50-150	
Landless systems	Dairy cattle	0.8-0.9	n.a.*)	N Output via milk, animals and manure ~equals N input; Nsurplus is gaseous N losses from housing and storages.
	Beef cattle	0.8-0.9	n.a.	
	Pigs	0.7-0.9	n.a.	
	Poultry,	0.6-0.9	n.a.	
	Otheranimals	0.7-0.9	n.a.	

*) Not applicable, as these farms have essentially no land. However, the N surplus can be expressed in kg per farm per year. In the case that all animal products, including animal manure and all residues and wastes, are exported, the target N surplus can be between 0 - 1000 kg per farm per year, depending on farm size and gaseous N losses.

30. The indicative costs of making a nitrogen N input-output balance are in the range of 200 to 500 euros per farm per year, depending on the farming system and on the assistance of accountancy and/or advisory services. Note that costs associated with education, promotion and start-up are not considered here. In some countries, data availability may be a constraint for farms in practice, but likely not for 'model farms' and 'pilot farms'. The costs tend to decrease over time (learning effect).

31. The net cost of improving nitrogen management and thereby increasing NUE and decreasing Nsurplus are in the range of -1 to +1 euro per kg N (TFRN Workshop on economic cost of ammonia emission abatement, Paris, October 2010). The net costs are the result of gains through fertilizer savings and increased production performances and gross cost related to sampling and analyses, training and advisory costs.

32. National nitrogen budgets for agriculture provide insight into (i) the nitrogen cost of food production, (ii) nitrogen losses associated with food production at national level and (iii) possible options for improving NUE at national level. National nitrogen budgets when expressed in terms of kg per ha per year also provide a means of comparing agricultural sectors of different UN-ECE countries and assessing progress toward reduced overall losses from national nitrogen cycles. Uniform formats and procedures (on-line) have been established for constructing such national nitrogen budgets. The costs of establishing a nitrogen budget at national level are in the range of 10,000 to 100,000 euro per year, depending on the availability of data statistics. Note that costs associated with education, promotion and start-up are not considered here. In some countries, data availability may be a constraint. A separate guidance document detailing the methods for calculating national nitrogen budgets has been prepared by the Task Force on Reactive Nitrogen (Informal Document 8. CLRTAP Executive Body-30, 30 April - 4 May 2012).

IV. LIVESTOCK FEEDING STRATEGIES

33. Gaseous nitrogen losses from livestock production originate from the feces (dung) and urine excreted by the livestock. The animal feed composition and the feed management has a strong influence on animal performance and on the composition of the dung and urine, and thereby also on the emissions of ammonia (NH_3). This section focuses on feeding strategies to reduce NH_3 emissions. Supplementary information about 'feeding strategies' is provided in Appendix 2.

34. *Reference techniques*. The abatement strategies described in this chapter are not defined and assessed against a uniform "reference" (or unabated or baseline) feeding strategy, because these "reference" feeding strategies are different for different UN-ECE Countries. A distinction has to be made between different animal categories, as animal feed requirements and the resulting nitrogen excretion greatly differ between animal categories.

35. Low-protein animal feeding is one of the most cost-effective and strategic ways of reducing NH_3 emissions. For each percent (absolute value) decrease in protein content of the animal feed, NH_3 emissions from animal housing, manure storage and the application of animal manure to land are decreased by 5 to 15%, depending also on the pH of the urine and dung. Low-protein animal feeding also decreases N_2O emissions, and increases the efficiency of nitrogen use in animal production. Moreover, there are no animal health and animal welfare implications as long as the requirements for all amino acids are met.

36. Low-protein animal feeding is most applicable to housed animals and less for grassland-based systems with grazing animals, because grass is in an early physiological growth stage and thus high in degradable protein, and grassland with leguminous species (e.g. clover and lucerne) have a relatively high protein content. While there are strategies to lower the protein content in herbage (balanced N fertilization, grazing/harvesting the grassland at later physiological growth stage, etc.), as well as in the ration of grassland-based systems (supplemental feeding with low-protein feeds), these strategies are not always fully applicable.

37. The economic cost of animal feeding strategies to lower the NH_3 volatilization potential of the animal excrements through adjusting the crude protein content, depends on the initial animal feed composition and on the prices of the feed ingredients on the market. In general, the economic costs range from -2 to +2 euro per kg NH_3-N saved, i.e. there are potential net gains and potential net costs. Commonly, the economic costs increase when the target for lowering the NH_3 volatilization potential increases. The increasing marginal costs relate in part to the cost of synthetic amino acids supplementation relative to using soya beans. The costs of amino acids supplementation tend to go down. The cost of supplementation of amino acids increases when the target protein content in the animal feed is lowered (see also Appendix 1 and 2).

Category 1 feeding strategies for dairy and beef cattle

38. Lowering crude protein (CP) of ruminant diets is an effective and category 1 strategy for decreasing NH_3 loss. The following guidelines hold (Table 3):

- The average CP content of diets for dairy cattle should not exceed 15 – 16 % in the dry matter (DM) (Broderick, 2003; Svenson, 2003). For beef cattle older than 6 months this could be further reduced to 12 %.
- Phase feeding can be applied in such a way that the CP content of dairy diets is gradually decreased from 16% of DM just before parturition and in early lactation to below 14% in late lactation and the main part of the dry period.
- Phase feeding can also be applied in beef cattle in such a way that the CP content of the diets is gradually decreased from 16 to 12% over time.

Table 3: Indicative target levels for crude protein (CP) content, in % of the dry mass of the ration, and resulting efficiency of cattle N utilisation (NUE), in mass fractions (kg/kg) for cattle (see text and Appendix 2)

Cattle species	CP, %*)	NUE of cattle product kg/kg
Milk + maintenance, early lactation	15-16	0.30
Milk + maintenance, late lactation	12-14	0.25
Non-lactating (dry) dairy cows	13-15	0.10
Veal	17-19	0.45
Cattle <3 months	15-16	0.30
Cattle 3-18 months	13-15	0.15
Cattle >18 months	12	0.05

*) The values presented here can be considered as 'high ambition level'

39. In many parts of the world, cattle production is grassland-based or partly grassland-based. In such systems protein rich grass and grass products form a significant proportion of the diet, and the target values for crude protein noted in Table 3 may be difficult to achieve, given the high CP content of grass from managed grasslands. The CP content of fresh grass in the grazing stage (2000-2500 kg DM per ha) is often in the range of 18 to 20 % (or even higher, especially when legumes are present), the CP content of grass silage often between 16 and 18 % and the CP content of hay between 12 and 15 % (e.g., Whitehead, 2000). In contrast, the CP content of maize silage is only about 7 to 8 %. Hence, grass-based diets often contain a surplus of protein and the magnitude of the resulting high N excretion strongly depends on the proportions of grass, grass silage and hay in the ration and the protein content of these feeds. The protein surplus and the resulting N excretion and NH_3 losses will be highest for grass (or grass-legume)-only summer rations with grazing young, intensively fertilized grass or grass legume mixtures. However, urine excreted by grazing animals typically infiltrates into the soil before substantial NH_3 emissions can occur and overall NH_3 emissions per animal are therefore less for grazing animals than for those housed where the excreta is collected, stored and applied to land.

40. The NH_3 emission reduction achieved by increasing the proportion of the year the cattle spent grazing outdoors will depend on the baseline (emission of ungrazed animals), the time the animals are grazed, and the N fertilizer level of the pasture. The potential to increase grazing is often limited by soil type, topography, farm size and structure (distances), climatic conditions, etc. It should be noted that grazing of animals may increase other forms of N emissions (e.g. nitrate-N leaching and N_2O emissions). However, given the clear and well quantified effect on NH_3 emissions, increasing the period that animals are **grazing all day can be considered as a category 1 strategy** to reduce emissions, but depending on grazing time (see also provisions 52, 184 and 185). The actual abatement potential will depend on the base situation of each animal sector in each country. The effect of changing the period of partial housing (e.g. grazed during daytime only) is less certain and is rated as a category 2 strategy. Changing from a fully housed period to grazing for part of the day is less effective in reducing NH_3 emissions than switching to complete (24 hour) grazing, since buildings and stores remain dirty and continue to emit NH_3. Grazing management (strip grazing, rotational grazing, continuous grazing) is expected to have little additional effect on NH_3 losses and is considered a category 3 strategy.

41. In general, increasing the energy/protein ratio in the diet by using 'older' grass (higher sward surface height, SSH) or swathed forage cereal and/or supplementing grass by high energy feeds (e.g., silage maize) is a category 1 strategy. However, for grassland-based ruminant production systems, the feasibility of these strategies may be limited, as older grass may reduce feeding quality, especially when conditions for growing high energy feeds are poor (e.g. warm climates), and therefore have to be purchased. Hence, full use of the grass production would no longer be guaranteed (under conditions of limited production, e.g. milk quotas or restrictions to the animal density). Hence, improving the energy/protein equilibrium on grassland-based farms with no possibilities of growing high energy feeds is therefore considered a category 2 strategy.

Category 1 feeding strategies for pigs

42. Feeding measures in pig production include phase feeding, formulating diets based on digestible/available nutrients, using low-protein amino acid-supplemented diets, and feed additives/supplements. These are all considered category 1 techniques. Further techniques are currently being investigated (e.g. different feeds for males (boars and castrated males) and females) and might be additionally available in the future.

43. The crude protein content of the pig ration can be reduced if the amino acid supply is optimised through the addition of synthetic amino acids (e.g. lysine, methionine, threonine, tryptophan) or special feed components, using the best available information on "ideal protein' combined with dietary supplementation.

44. A crude protein reduction of 2 to 3 % in the feed can be achieved, depending on pig production category and the current starting point. The resulting range of dietary crude

protein contents is reported in Table 4. The values in the table are indicative target levels and may need to be adapted to local conditions. It has been shown that a decrease of 1 % crude protein in the diet of finishing pigs, results in a 10% lower TAN (total ammonia nitrogen) content of the pig slurry and a 10% lower NH_3 emissions (Canh et al., (1998b).

Table 4: Indicative target crude protein levels in feed for pig rations (Adopted from BREF, 2003; see also text and Appendix 2)

Species	Phases	Crude protein content, % *)
Weaner	< 10 kg	19–21
Piglet	< 25 kg	17–19
Fattening pig	25–50 kg	15–17
	50–110 kg	14–15
	>110 kg	12-13
Sows	Gestation	13–15
	Lactation	15–17

*) With adequately balanced and optimal amino acid supply. The values presented here can be considered as 'medium to high ambition level' (see Appendix 2 for a further specification of target crude protein levels).

Category 1 feeding strategies for poultry

45. For poultry, the potential for reducing N excretion through feeding measures is more limited than for pigs because the conversion efficiency currently achieved on average is already high and the variability within a flock of birds is greater. A crude protein reduction of 1 to 2 % may be achieved depending on the species and the current starting point. The resulting range of dietary crude protein contents is reported in Table 5. The values in the table are indicative target levels, which may need to be adapted to local conditions. Further applied nutrition research is currently being carried out in EU Member States and North America and this may support further possible reductions in the future. A reduction of the crude protein content by 1-2% is a category 1 measure for growers and finishers.

Table 5: Indicative target crude protein levels in feed for poultry (Adopted from BREF-2003; see also text and Appendix 2).

Species	Phases	Crude protein content, % *)
Chicken, broilers	Starter	20–22
	Grower	19–21
	Finisher	18–20
Chicken, layers	18–40 weeks	15.5– 16.5
	40+ weeks	14.5– 15.5
Turkeys	< 4 weeks	24–27
	5–8 weeks	22–24
	9–12 weeks	19 –21
	13+ weeks	16-19
	16+ weeks	14 –17

*) With adequately balanced and optimal amino acid supply. The values presented here can be considered as 'medium to high ambition level' (see Appendix 2 for a further specification of target crude protein levels).

V. LIVESTOCK HOUSING

A. Housing systems for dairy and beef cattle

46. Techniques to reduce NH_3 emissions in cattle housing apply one or more of the following principles:

- Decreasing the surface area fouled by manure;
- Absorption or adsorption by bedding (e.g. by straw);
- Rapid removal of urine; rapid separation of faeces and urine;
- Decreasing of the velocity and temperature of air above the manure except where manure is being dried;
- Reducing the temperature of the manure;
- Decreasing soiled areas in houses and hard standings by increased grazing;

When using measures to abate emission from cattle houses, it is important to minimize loss of the conserved NH_3 during downstream handling of the manure, in storage and spreading, to maximize the benefit from the cost of abatement.

47. Housing systems for cattle vary across the UN/ECE region. While loose housing is most common, dairy cattle are still kept in tied stalls in some countries. In loose housing systems all or part of the excreta is collected in the form of slurry. In systems where solid manure is produced (such as straw-based systems), it may be removed from the house daily or it remain there for up to the whole season, such as in deep litter stables. The system most commonly researched is the "cubicle house" for dairy cows, where NH_3 emissions arise from fouled slatted and/or solid floors and from manure in pits and channels beneath the slats/floor.

Reference System: For cattle housing the cubicle house is taken as reference system (Table 6) Cattle held in tied stalls emit less NH_3 than in loose housing systems, because a smaller floor area is fouled with dung and urine. However, tied systems are not recommended in consideration of animal welfare unless daily exercise periods are applied. The tied housing system is the traditional reference system for maintaining continuity in emission inventories.

48. *Animal welfare considerations* tend to lead to an increase of soiled walking area per animal, increased ventilation, possibly cooler winter temperatures, and overall increase in emissions. Changes in building design to meet the new animal welfare regulations in some countries (e.g. changing from tied stall to cubicle housing) will therefore increase NH_3 emissions unless abatement measures are introduced at the same time to combat this increase. Changes in building or new construction to meet animal welfare requirements present an important opportunity to introduce NH_3 mitigation measures at the same time, thereby reducing the costs of the mitigation measures relative to retrofits.

49. *Solid versus slurry manure systems.* Straw-based systems producing solid manure for cattle are not likely to emit less NH_3 in the animal houses than slurry-based systems. Further, nitrous oxide (N_2O) and di-nitrogen (N_2) losses due to (de)nitrification tend to be larger in litter-based systems than slurry-based systems. While straw-based solid manure can give less NH_3 emission than slurry after surface spreading on fields (e.g., Powel et al., 2008a) slurry provides more opportunity for reduced emissions applicators. The physical separation of faeces (which contains urease) and urine in the housing system reduces hydrolysis of urea resulting in reduced emissions from both housing and manure spreading (Burton, 2007; Fanguiro et al., 2008a, 2008b; Moller et al., 2007). Verification of any NH_3 emission reductions from using solid-manure versus slurry-based systems and from solid-liquid separation should consider all the stages of emission (housing, storage, land application).

Category 1 techniques

50. *The "grooved floor" system* for dairy and beef cattle housing employing “toothed” scrapers running over a grooved floor is a reliable technique to abate NH_3 emissions. Grooves should be equipped with perforations to allow drainage of urine. This results in a clean, low-emission floor surface with good traction for cattle to prevent slipping. Ammonia emission reduction ranges from 25-46% relative to the reference system (Smits, 1998; Swierstra et al., 2001).

51. In houses with traditional slats (either non-sloping, 1% sloping or grooved), optimal barn climatization with roof insulation (RI) and/or automatically controlled natural ventilation (ACNV) can achieve a moderate emission reduction (20%) due to the decreased temperature (especially in summer) and reduced air velocities (Braam et al., 1997a; 1997b; Smits, 1998; Monteny, 2000).

52. Decreasing the amount of animal excrements in animal housing systems through increased grazing is an effective measure to decrease ammonia emissions. Though emissions from grazing will increase, the emissions from animal housing systems decrease much more, provided surfaces in the house are clean while the animals are grazing outside. Total annual emissions (from housing, storage and spreading) from dairy systems may decrease by up to 50% with nearly all-day grazing (Bracher et al., 2012), as compared to animals that are fully confined. While increased grazing is a reliable emission reduction measure for dairy cows, the amount of emission reduction depends on the daily grazing time and the cleanliness of the house and holding area. Grazing is category 1 if the animals are grazed all day or if very little floor area is contaminated with manure each day. Less than 18 grazing hours per day must be considered as category 2 because of the uncertainty in quantifying emissions. In some cases grazing can contribute to increased leaching or increased pathogen and nutrient loading of surface water (see also provisions 40, 184 and 185).

Category 2 techniques

53. *Different improved floor types* based on slats or solid, profiled concrete elements have been tested in the Netherlands. These designs combine emission reduction from the floor (increased run off of urine) and from the pit (reduction of air exchange by rubber flaps in the floor slots). The emission abatement efficiency depends on the specific technical characteristics of the system. The measure is therefore considered as category 2 and is not included in table 6.

54. *Bedding material* in animal housing can affect NH_3 emission. The physical characteristics (urine absorbance capacity, bulk density) of bedding materials are of more importance than their chemical characteristics (pH, cation exchange capacity, carbon to nitrogen ratio) in determining ammonia emissions from dairy barn floors (Misselbrook and Powell, 2005; 2008a; Gillespy et al., 2009). However, further assessment is needed on the effect of bedding on emissions for specific systems while taking into account the whole manure management path.

55. *Chemical or acid air scrubbers, while* effective in decreasing NH_3 emissions from force-ventilated pig housing, cannot generally be implemented in cattle housing which are mostly naturally ventilated across the UNECE region. Also. there are few data for scrubbers on cattle housing so they are currently considered a category 2 technique (Ellen et al., 2008).

Category 3 techniques

56. *Scraping and flushing systems*. A number of systems have been tried involving the regular removal of the slurry from the floor to a covered store outside of the building. These involve flushing with water, acid, diluted or mechanically-separated slurry, or scraping with or without water sprinklers. In general, these systems have proven to be ineffective or too difficult to maintain. The use of smooth and/or sloping floors to assist in scraping or flushing contributes to slipping which is very detrimental to cow health. These systems are therefore considered as category 3 techniques.

57. Table 6 summarizes emissions and abatement from different cattle housing systems (reference system and category 1 and 2 techniques).

Table 6: Ammonia emissions of different cattle housing systems (reference systems and category 1 and 2 techniques)

Housing Type	Reduction %	[b/] NH3 Emission (kg/cow place/year)
Cubicle house (Reference system)	n.a.	12[c]
Tied system[a/] (Traditional reference system)	n.a.	4.8
Grooved floor (Cat. 1)	25-46	9
Optimal barn climatization with roof insulation (Cat. 1)	20	9.6
Chemical air scrubbers (forced ventillation systems only) (Cat. 2)	70-95	1.2
Grazing 12h/24h (Cat. 2), relative to ref 1	10	10.8[d]
Grazing 18h/24h (Cat. 1) relative to ref 1	30	8.4[d]
Grazing 22h/24h (Cat. 1) relative to ref 1	50	6.0[d]

a/ Tied systems are not favoured for animal welfare reasons. These systems are traditional reference systems for continuity in emission inventories.

b/ Emissions with full time housing of the animals.

c/ Based on a walking area of 4-4.5 m^2 per cow and permanent housing.

d/ These numbers hold for season-long grazing (assumed about 200 days). They show the relative reduction of annual emissions as compared to the reference system with no grazing. Grazing for part of the days requires that barn surfaces are always kept clean.

n.a. Not applicable.

B. Housing systems for pigs

58. *Reference system:* Emissions from fully slatted pig houses with a storage pit underneath are taken as the reference, although in some countries these systems are prohibited for animal welfare reasons.

59. Designs to reduce NH_3 emissions from pig housing systems have been described in detail in BREF (2003), and apply the following principles:

(a) Reducing manure surfaces such as soiled floors, slurry surfaces in channels with sloped walls. Partly slatted floors (~50% area), generally emit less NH_3, particularly if the slats are metal- or plastic-coated rather than concrete, allowing the manure to fall rapidly and completely into the pit below. Emissions from the non-slatted areas are reduced by inclined, smooth surfaces, by locating the feeding and watering facilities to minimize fouling these areas, and by good climate control in the building;

(b) Removing the slurry from the pit frequently to an external slurry store with vacuum or gravity removal systems or by flushing systems at least twice a week;

(c) Additional treatment, such as liquid/solid separation;

(d) Circulating groundwater in floating heat exchangers to cool the surface of the manure in the under-floor pit to at least 12°C. Constraints include costs and need to locate a source of groundwater away from the source of drinking water;

(e) Changing the chemical/physical properties of the manure such as decreasing pH;

(f) Using surfaces which are smooth and easy to clean (see ‘a’ above);

(g) Treatment of exhaust air by acid scrubbers or biotrickling filters;

(h) Lowering the indoor temperature and ventilation rate, taking into account animal welfare and production considerations especially in winter;

(i) Reducing air flow over the manure surface.

60. For a given slat width, manure drains from concrete slats less efficiently than from steel and plastic covered slats and this is associated with greater emissions of NH_3. Note that steel slats are not allowed in some countries for animal welfare reasons.

61. These cross-media effects have been taken into account in defining BAT on the various housing designs. For example, frequent flushing of slurry (normally once in the morning and once in the evening) causes nuisance odour events. Flushing slurry also consumes energy unless manually-operated passive systems are used.

62. Use of straw in pig housing is expected to increase due to concern for the welfare of the pigs. In conjunction with (automatically controlled) naturally-ventilated housing systems, straw allows the animals to self-regulate their temperature with less ventilation and heating, reducing energy consumption. In systems with litter, the pen is sometimes divided into solid areas with litter and slatted dunging areas. However, pigs do not always use these

areas in the desired way, using the littered area to dung and the slatted area to cool off in warm weather. Generally, pens should be designed to accommodate desired excreting behaviour of pigs to minimize fouling of solid floors. This is more difficult in regions with a warm climate. Note that integrated evaluation of straw use should consider the added cost of the straw and mucking out the pens; possible increased emissions from storage and application of manure with straw; and the benefit of adding organic matter to the soil.

63. *Reference technique for growers/finishers:* The reference system, used commonly in Europe, is a fully slatted floor with a deep manure pit underneath and mechanical ventilation; emission ranges from 2.4 to 3.2 kg NH_3 per pig place per year. Since growers/finishers are always housed in a group, most systems used for group housing of sows are applicable to growers.

64. *Reference technique for farrowing sows:* Farrowing sows in Europe are generally housed in crates with steel or plastic slatted floors and a deep manure pit underneath. In the majority of houses, sows are confined while piglets are free to walk around. All houses have controlled ventilation and often a heated area for the piglets during their first few days after birth. The difference between fully and partly slatted floors is not as distinct for farrowing sows as for growers because the sow is confined and excretion generally takes place in the slatted area. Reduction techniques therefore focus on alterations in the manure pit.

65. *Reference technique for mating and gestating sows* The reference system for housing of mating and gestating sows is the fully slatted floor (concrete slats) with a deep pit. Mating and gestating sows are currently housed individually or in groups. Throughout the EU, group housing is compulsory for newly built sow housing and starting in 2013 group housing will be required also for all mating and gestating sows for a four week period after insemination. Group-housing systems require special feeding systems (e.g. electronic sow feeders or open stalls) and a pen design that influences sows to use distinct areas for manuring and lying. Group-housing has similar emission levels as individual housing (Groenestein et al., 2001) and similar emission reduction techniques can be employed.

66. *Reference technique for weaners*: Weaners are group-housed either in conventional pens or flat decks (raised pens). Because manure removal method is similar, it is assumed that reduction measures applicable to conventional weaner pens can also be applied to flat decks. Straw-based systems with solid concrete floors are conditional BATs but no data on NH_3 emissions have been reported.

67. Table 7 summarizes the design and techniques for reducing emissions, including estimated efficiencies and costs, for all classes of pig houses. The estimated costs vary widely due to farm-specific conditions such as building size. Note that some techniques are very costly to apply in existing houses. Information about the economic costs of low-emission techniques and strategies can be found in Reis (2012).

68. A study conducted in 2007 showed that the overall cost of NH_3 emission reduction from pig housing systems in the Netherlands averaged 0.016 euro per kg of pig carcass produced (Baltussen et al., 2010). At the time of the study, only large (IPPC) farms already had technologies installed to reduce emissions by a target of 40-60% (from combined housing and storage). However, it is estimated that cost will rise to 0.04 euro per kg of pig carcass in 2013 when even small pig farms in the Netherlands will have to comply with both emission and welfare standards. Assuming 200 kg of pig meat is produced per pig place per year, the cost of the NH_3 emission reduction and welfare measures are 7.2 euro per pig place or 3 euros per kg NH3-N saved; both of these estimates are considered robust in the Netherlands. The estimates do not take into account that some of the conserved ammonia may be lost further down the manure chain.

69. The various systems for reducing emissions reported in paragraphs 74-79 and 83 are all based on the principles noted in paragraph 63, those being reducing emitting area and rapid manure removal.

Category 1 techniques

70. Ammonia emission can be reduced by 25% by reduction of emitting surface area through frequent and complete vacuum assisted drainage of slurry from the floor of the pit. Where this is possible to do, this is technique has no cost.

71. Partly slatted floors covering 50% of floor area generally emit 15-20% less NH_3, particularly if the slats are metal or plastic-coated which is less sticky for manure than concrete. Decreasing risk of emissions from the solid part of the floor can be achievedby using an inclined (or convex), smoothly finished surface; by appropriate siting of the feeding and watering facilities to minimize fouling of the solid areas; and by good climate control. (Aarnink et al., 1996; Guigand and Courboulay, 2007; Ye et al., 2008a, 2008b).

72. Further reduction of the emitting area can be achieved by making both the partly slatted area and the pit underneath smaller. With the smaller slatted area, the risk of greater fouling of the solid area can be mitigated by installing a small second slatted area with a water-canal underneath at the other side of the pen where the pigs tend to eat and drink. The canal is filled with about two cm of water to dilute any manure that might eventually drop into it. This slatted area will have low emissions because any manure dropped here will be diluted. This combined manure-canal and water-canal system can reduce ammonia emissions by 40-50% depending on the size of the water canal.

73. Reducing emitting surface area by having one or two slanted pit walls, in combination with partly slatted floors and frequent manure removal can reduce emission by up to 65%.

74. Reducing the emitting surface area with shallow V-shaped gutters (max. 60 cm wide, 20 cm deep) can reduce emission in pig houses by 40 to 65%, depending on pig category and the presence of partly slatted floors. The gutters should be flushed twice a day with the liquid (thin) fraction of the slurry rather than water; flushing with water dilutes the manure and increases the cost of transporting the manure.

75. For lactating sows, emission reduction of 65% can be achieved by reducing the emitting area by means of constructing a pan under the slatted floor of the pen. The pan is a sloped subfloor (at least 3°) with manure drainage at the lowest point. Although the pan can be retrofitted into existing housing, in practice it may be quite costly to alter the manure drainage system.

76. Reducing ammonia emission can be achieved by acidifying the slurry to shift the chemical balance from NH_3 to NH_4^+. The manure (especially the liquid fraction) is collected into a tank with acidified liquid (usually sulfuric acid, but organic acids can be used as well) maintaining a pH of less than 6. In piglet housing emission reduction of 60% has been observed.

77. Surface cooling of manure with fins using a closed heat exchange system is a category 1 technique with reduction efficiency of 45-75% depending on animal category and surface of cooling fins. This technique is most economical if the collected heat can be exchanged to warm other facilities such as weaner houses (Huynh et al., 2004). In slurry systems this technique can be retrofitted into existing buildings. This system is not applicable when straw bedding is used or when the feed contains a lot of roughage because a layer of floating residue may develop on top of the slurry.

78. Treatment of exhaust air by acid scrubbers (mainly sulphuric acid) or biotrickling filters has proven to be practical and effective for large-scale operations in Denmark, Germany, France and the Netherlands and hence is category 1 (e.g., Melse et al., 2005, Guinand, 2009). This is most economical when installed in new houses because retrofitting in existing housing requires costly modification of ventilation systems. Acid scrubbers have demonstrated ammonia removal efficiencies of 70 to 90%, depending on their pH-set values. Scrubbers and biotrickling filters also reduce odor and particulate matter by 75% and 70%, respectively (Guinand, 2009). Further information is needed on the suitability of these systems in South and Central Europe. Operational costs of both acid scrubbers and trickling filters are especially dependent on the extra energy use for water recirculation and to overcome increased back pressure on the fans. Optimisation methods are available to minimize costs (Melse et al., 2012) and costs will be lower for large operations.

Category 2 Techniques

79. Floating balls in manure pits may reduce emissions by 25% by partially covering the emitting surface. Manure dropping on the balls causes them to turn, and because of their non-stick surface, the clean side of the ball rotates upward. This technique can be used in existing houses. Because this technique has not been evaluated outside the Netherlands, it is considered category 2.

80. A V-shaped belt installed underneath the slatted floor can be used to remove manure frequently from the house. The shape of the belt allows the urine to continuously run off, segregating it from the urease enzyme contained in the faeces, thus minimizing the conversion (hydrolysis) of urea to ammonia. Due to both rapid removal and reduced ammonia production, ammonia emission is reduced by about 70% (Aarnink et al., 2007). Note that with this technique no pit is required thus offsetting some of the building construction costs. Also, by separating the manure, efficient application of P and N to the soil can be arranged. The V-belt system is considered a category 2 technique because it has only been evaluated in the Netherlands. It has potential for all pig categories but has been evaluated only with fatteners.

Table 7: Category 1 and 2 techniques: reduction and costs of low-emission housing systems for pigs; see text for suitability for retrofitting. For economic cost of the abatement techniques, see Reis (2012).

Category 1 technique (unless specified Cat 2)	**NH3 emission (kg NH3 / place per year)**	**Emission reduction, %**	**Extra Cost (€/place per year) (*)**	**Extra cost (€/kg NH3-N reduced)**
Gestating Sows	**4.2**			
Frequent manure removal with vacuum system		25	0**	0**
Flushing gutters		40	33	23
Cooling manure surface		45	19	12
(Group) housing with feeding stalls and manure pit with slanted walls		45	16	10
Floating balls on manure surface (Cat 2)		25	14	16
Air scrubbing techniques		70-90	22-30	8-10
Lactating Sows	**8.3**			
Water- and manure channel		50	2	0.5
Manure pan underneath		65	40-45	9
Cooling manure surface		45	45	15
Floating balls on manure surface (Cat 2)		25	14	8
Air scrubbing techniques		70-90	35-50	7-10
Piglets after weaning	**0.65**			
Partially slatted floor with reduced pit		25 – 35	0	0
Frequent manure removal with vacuum system		25	0**	0**
Partly slatted floors and flushing gutters		65	5	14
Partly slatted floor and collection in acidified liquid		60	5	15
Partly slatted floor and Cooling manure surface		75	3-4	7-10
Partly slatted floor and manure channel with slanted walls		65	2	5-6
Floating balls on manure surface (Cat 2)		25	1	6-7
Air scrubbing techniques		70-90	4-5	8-12
Growers – Finishers	**3.0**			
Partially slatted floor with reduced pit		15-20	0	0
Frequent manure removal with vacuum system		25	0**	0**
Partially slatted floor with water- and manure channel		40	2	2
Partially slatted floor with water-channel and manure-channel with slanted walls		60-65	3-5	2-3
Flushing gutters		40	10-15	10-15
Partially slatted floor and cooling manure surface		45	5-7	4-6
Floating balls on manure surface (Cat 2)		25	2	4
Partially slatted floors and separated removal of liquid and solid manure fraction by V-shaped belt (Cat 2)		70	0-5	0-3
Air scrubbing techniques		70-90	10-15	5-9

(*)Prices are calculated based on new buildings. Only cooling systems, floating balls and scrubbers can be installed in existing buildings.
(**) if vacuum manure removal system is already installed.

C. Housing systems for poultry

81. Designs to reduce NH_3 emissions from poultry housing systems apply the following principles:

(i) Reducing emitting manure surfaces;
(ii) Removing the manure frequently to an external slurry store (e.g. with belt removal systems);
(iii) Quickly drying the manure;
(iv) Using surfaces which are smooth and easy to clean;
(v) Treatment of exhaust air by acid scrubbers or biotrickling filters;
(vi) Lowering the indoor temperature and ventilation as animal welfare and/or production allow.

i. Housing systems for laying hens

87. The evaluation of housing systems for layers in the European Union (EU) Member States has to consider the requirements laid down by the European Directive 1999/74/EC on housing of laying hens (EC, 1999). This directive prohibits the use of conventional cage systems starting in 2012. Instead, only enriched cages (also called furniture cages), or non-cage systems, such as litter (or deep litter) housing system or aviary system, are allowed

88. *Reference system for conventional cage housing*. This system uses an open manure storage underneath the cages. Although banned in the EU from 2012, some UN-ECE states still house laying hens in conventional cages and most of the reports on NH_3 emission reduction refers to this type of housing as a reference. This reference is also maintained for continuity in emission inventory calculation.

89. *Reference system for 'enriched' cage houses*. This system can replace conventional cages without the need for significant alteration of existing building. Enriched cages provide the laying hens increased space including areas for nesting, scratching and perching. Birds are kept in groups of 40-60. A (ventilated) belt placed under cages is the most common method of manure removal. The enriched cage housing measures are presented in a separate table because the reference system, rather than conventional cages, is an enriched cage with a belt underneath to remove manure regularly without drying. For animal welfare reasons enriched cages are not allowed in the Netherlands and in Germany, instead they have colony housing or Kleingruppenhaltung. The difference with enriched cages is a larger surface area per animal, higher cages and more defined areas with litter and nests. Ellen and Ogink (2009) substantiated that the same ammonia emission factors can be applied as for enriched cages.

90. *Reference system for non-caged houses: Deep pit housing in combination with partly littered floor.* The building is characteristically equipped with 80- to 90-cm high dropping pits covered with wooden or plastic slats or wire mesh. The manure is collected in pits under the slats which occupy two-thirds of floor area. The remaining one third of the floor is covered with litter such as sand, wood shavings or straw and used for scratching and dust-bathing. The stocking density in these houses is up to 9 hens per m² of floor area.

91. *Aviary system (perchery).* The building is divided into different functional areas used for feeding and drinking, egg laying, scratching and resting, with litter is provided. The available surface area is increased by means of elevated slatted floors combined with stacks allowing a stocking density of up to 18 hens per m² of floor area. As in cage systems aviaries employ belts placed under the tiers to collect the manure; ventilated belts can be installed for collection, drying and removal of litter.

92. In some countries, the definition of "free range" includes deep-pit housing system with partly littered floor (or deep litter) or aviary system provided with outdoor access to the birds. In countries where "free-range " hens are housed on solid or partly slatted floors, the solid floor area is covered with litter and the hens have some access to the outdoors. Manure accumulates either on the solid floor or under the slatted area for the 14-month laying period.

Category 1 techniques

93. Ammonia emissions from battery deep-pit or channel systems can be lowered by reducing the moisture content of the manure by ventilating the manure pit.

94. The collection of manure on belts and the subsequent removal of manure to covered storage outside the building can also reduce NH_3 emissions, particularly if the manure has been dried on the belts through forced ventilation. The manure should be dried to 60–70% dry-matter to minimize the formation of NH_3. Manure collected from the belts into intensively ventilated drying tunnels, inside or outside the building, can reach 60 –80% dry matter content in less than 48 hours but in this case exposure to air and emissions are increased. Weekly removal from the manure belts to covered storages reduces emissions by 50% compared with bi-weekly removal. In general, emission from laying hen houses with manure belts will depend on (a) length of time that the manure is present on the belts; (b) drying systems; (c) poultry breed; (d) ventilation rate at the belt (low rate = high emissions) and (e) feed composition. Aviary systems with manure belts for frequent collection and removal of manure to closed storages reduce emission by more than 70% compared to the deep litter housing system.

95. Treatment of exhaust air by acid scrubber or biotrickling filters has been successfully employed in several countries (Melse etal., 2005; Ritz et al., 2006; Atterson and Adrizal, 2005; Melse et al., 2012). Acid scrubbers remove 70-90% of NH3 while biological scrubbers remove 70%; both also remove fine dust and odour. To deal with the high dust loads multistage air scrubbers with pre-filtering of coarse particles have been developed

(Ogink and Bosma, 2007; Melse et al., 2008). Yet some Parties consider this technique as only Cat. 2 because of the dust loading issue.

96. Emission reduction techniques are summarized for conventional cages housing (Table 8), for enriched caged housing (Table 9) and for non-caged housing (Table 10).

Category 2 Techniques

97. Regular addition of aluminum sulfate (alum) to the litter in non-caged housing systems decreases ammonia emissions from the buildings by up to 70%, and reducing also in–house concentrations of both ammonia and particulate matter ($PM_{2.5}$) thus improving production. The alum also lowers phosphorus leaching losses from land applied manure. Studies in the USA show that the benefits of alum treatment are twice the cost, but as there is no experience yet in other countries, this technique is considered Cat 2.

Table 8: Caged housing systems for laying hens (reference system): techniques and associated NH_3 emission reduction potential. For economic cost of the abatement techniques, see Reis (2012)

Category 1	**kg NH3 /year/ place**	**NH_3 reduction (%)**	**Extra cost (€/place/ year**	**Cost (€/Kg NH3-N abated/year)**
Conventional cages, non-aerated open manure storage under cages *(Reference Technique)*	0.1-0.2	0	0	0
Conventional cages, aerated open manure storage under cages to dry manure		30		0-3
Conventional cages, rapid manure removal with belt to closed manure storage		50–80		0-5
[a] Scrubbing of exhaust air[a]		70-90		1-4

a: with acid scrubbers 70-90% reduction can be achieved, with biological scrubbers 70%; some members consider this Category 2

Table 9: Enriched Cage housing systems for laying hens: techniques and associated NH_3 emission reduction potential. For economic cost of the abatement techniques, see Reis (2012)

Category 1	kg NH3 /year/ place	NH_3 reduction (%)	Extra cost (€/place/ year	Cost (€/Kg NH3-N abated/year)
Belts, two removals a week *(Reference Technique)*	0.05-0.1			
Ventilated belts, two removals a week [a]		30-40	0	0
Ventilated belts, removals more then two times a week		35-45		0-3
Scrubbing of exhaust air [b]		70-90		2-5

a: reduction percentage depending on ventilation rate of drying fan
b: with acid scrubbers 70-90% reduction can be achieved, with biological scrubbers 70%; some experts consider this Category 2.

Table 10: Non-caged housing systems for laying hens: techniques and associated NH_3 emission reduction potential. For economic cost of the abatement techniques, see Reis (2012)

Category 1 and 2 techniques	kg NH3 /year/ place	NH_3 reduction (%)	Extra cost (€/place/year	Cost (€/Kg NH3-N abated/year)
Deep litter or deep pit with partial litter, (Reference Technique)	0.3	0	0	0
Aviaries, perch design, non ventilated manure belts (Cat. 1)		70 - 85		1-5
Aviaries, ventilated manure belts (Cat.1)		80 - 95		1-7
Scrubbing of exhaust air [a]		70-90		6-9
Litter, partly slatted, manure belts (Cat 2)		75		3-5
Litter with forced manure drying (Cat.3)		40-60		1-5
Regular addition of aluminium sulphate to litter (Cat 2)		70		?

a: with acid scrubbers 70-90% reduction can be achieved, with biological scrubbers 70%; some experts consider this Category 2.

ii. Housing systems for broilers (Table 11)

98. *Reference system for broilers*: The reference system for broilers is the traditional building used in Europe with a solid, fully littered floor.

99. To minimize NH_3 emission in broiler housing, it is important to keep the litter dry. Litter moisture and emissions are influenced by:

(a) Drinking-water design and function (leakage and spills);
(b) Animal weight and density, and duration of the growing? period;
(c) Ventilation rate, use of in-house air purification, and ambient weather;
(d) Use of floor insulation;
(e) Type and amount of litter;
(f) Feed.

Category 1 techniques

100. *Reducing spillage of water from the drinking system*: A simple way to reduce spillage of water from the drinking system is using a nipple instead of bell drinkers.

101. *Air scrubber technology* to remove NH_3 from ventilation air is highly effective, but not widely implemented because of costs. Packed-bed filters and acid scrubbers currently available in the Netherlands, Germany remove 70-90% of NH3 from exhaust air. Questions about long-term reliability due to high dust loads lead some Parties to consider this as Cat. 2 only. Various multi-pollutant scrubbers have been developed to also remove odor and particulate matter (PM_{10} and $PM_{2.5}$) from the exhaust air (Zhao et al., 2011; Ritz et al., 2005; Patterson and Adrizal, 2005.

Category 2 techniques

102. *Forced drying*: Effective emission reduction can be achieved through forced drying but current systems are energy-intensive and may increase dust emissions. However, there may be some saving in heating costs due to improved heat distribution.

103. The *Combideck System*: This system consists of heat exchangers in the concrete floor: in the beginning of the fattening period the floor is heated to dry the litter and later in the fattening period the floor is cooled to reduce microbial activity which reduces breakdown of uric acid. Because the effectiveness of this technique depends on local conditions it is considered as category 2.

104. Use of additives (aluminium sulphate, micro-organisms) may reduce ammonia emissions, lead to a higher dry matter content of the manure, and reduce mortalities (Aubert et al., 2011), but results are either inconsistent (e.g., McCrory and Hobbs, 2001), or tested in one country only (in case of alum).

Table 11: Housing systems for broilers: techniques and associated NH_3 emission reduction potential. Data on economic costs of low-emission housing systems are scarce, also because there are often only few of these systems in practice yet. For economic cost of the abatement techniques, see Reis (2012)

Category 1 and 2 techniques	kg NH3 /year/ place	NH_3 reduction (%)	Extra cost (€/place/ year	Cost (€/Kg NH3-N abated/year)
Deep litter; fan ventilated house (*Reference Technique*)	0.080	0		
Naturally-ventilated house or insulated fan-ventilated house with a fully littered floor and equipped with non-leaking drinking system (Cat.1)		20-30	0	0
Litter with forced manure drying using internal air (Cat.1)		40-60		2-4
Scrubbing of exhaust air (Cat 1)[a]		70-90		10-15
Tiered floor and forced air drying (Cat. 2)		90		?
Tiered removable sides; forced air drying (Cat.2)		90		?
Combideck System (Cat. 2)		40		6

a: with acid scrubbers 70-90% reduction can be achieved, with biological scrubbers 70%; some Parties consider this Category 2

*) 1. BREF, 2003; 2. Draft revised BREF 2011

iii. Housing systems for turkeys and ducks

105. *Reference system for turkeys:* Reference system for turkeys for fattening is the traditional building used in Europe with solid, fully littered floor in closed, thermally insulated buildings with forced ventilation (as broilers) or in naturally ventilated houses with open sidewalls. Manure is removed at the end of each growing period. Ammonia emission with a fully littered floor is 0.680 kg NH_3-N per turkey place per year. Turkeys are a minor source of NH_3 in most UNECE parties.

106. *Reference system for ducks:* The reference system for duck is a traditional building similar to housing of broilers. Ducks for roasting generates slurry and ducks for ‘foie gras’ generates solid manure. Partly slatted/partly littered floor and fully slatted floor are other housing systems for fattening of ducks. Like turkeys, ducks are a minor source of NH_3 in the UNECE region.

107. Ammonia emission reducing techniques used for broiler production can be applied to turkeys and duck housing. However, except for scrubbers, the efficacy of the techniques will be less than with broilers because of the larger amount of manure and a higher dry matter content of the litter. In the Netherlands, the effectiveness is considered half of that in broiler housing. For ducks provided with water bowls (in consideration of the welfare of water birds) efficacy may be even lower. Therefore, these techniques are considered category 2.

VI. MANURE STORAGE TECHNIQUES

108. *Reference technique.* The baseline for estimating the efficiency of an abatement measure is the emission from the same type of store, without any cover on the surface. Baseline emissions are assumed to be 1.4 and 2.7 kg NH_3-N per m^2 per year based on data from western European countries; lower values might be observed where stored manure is frozen for several months and higher values in warm countries. Since baseline data are limited, Parties are encouraged to determine appropriate baseline values for their conditions. Table 12 summarizes the different emission abatement measures for slurry stores and their efficiency in reducing NH_3 emissions.

109. After removal from animal houses, slurry is commonly stored in concrete or steel tanks or silos, or in lined earth-banked lagoons. Lagoons tend to have larger surface area per unit volume than tanks and there is recent evidence of intense natural chemical denitrification in large lagoons due in part to wind action. Emissions from slurry stores can be reduced by decreasing the airflow across the surface by installing solid or floating covers, by allowing the formation of a surface crust, or by increasing depth of stores to reduce the ratio of surface area to volume of the store. Reducing the surface area is only a consideration for new structures. Co-benefits: solid covers (and open roofs) prevent rain from filling the storage so there is more predictable capacity and, with less water, hauling costs are lower; covers reduce odour and most also reduce greenhouse gas emissions although under some conditions straw cover may increase emission of N_2O; reducing the surface to volume ration tends to have the same co-benefits as covers.

110. For long term storage of dry poultry manure (e.g. from broiler housing), a barn or building with an impermeable floor and with sufficient ventilation should be used to keep the manure dry and minimize further NH_3 losses.

111. It is important to minimize also the possible NH_3 losses during land spreading of the slurries and manure from covered storages, otherwise the benefits of the covered storage will evaporate like the NH_3.

Category 1 techniques

112. *'Tight' lid, roof or tent structure*: The best proven and most practicable method to reduce emissions from slurry stored in tanks or silos is to cover with a 'tight' lid, roof or tent structure. While it is important that such covers are well sealed or "tight" to minimize air exchange, some venting must be provided to prevent the accumulation of flammable gases, especially methane. The ability to retrofit these structures on <u>existing</u> stores depends on the structural integrity of the stores or whether they can be modified to accept the extra load.

113. *Floating cover:* floating cover sheeting may be a type of plastic, canvas, geotextile or other suitable material. It is considered to be a category 1 technique only for *small* earth-banked lagoons. Floating covers are difficult to implement on tanks, especially those with high sides, because of the substantial vertical movement needed during filling and emptying.

114. *Storage bags* are suitable for reducing emissions from slurry on small farms (e.g. < 150 fattening pigs); note that the cost of this measure includes the both storage structure and cover.

115. *Formation of natural crust*: Minimizing stirring of stored cattle slurry and some pig slurries (depending on diet of the pits and the dry matter content of the slurry) and introducing new slurry below the surface will allow the build-up of a natural crust. Crusts can significantly reduce NH_3 emissions at little or no cost for the time that the crust is sufficiently thick and fully covers the slurry surface. The emission abatement efficiency will depend on the nature and duration of the crust (Misselbrook, et al., 2005; Smith et al., 2007). Abatement with natural crust is an option only for farms that do not have to frequently mix the manure for frequent spreading, and do have slurries that produce crusts.

116. LECA (light expanded clay aggregates) balls, Hexa-covers can be easily applied to non-crusting pig manure or digestate from anaerobic digestors. A recent review of abatement methods (van der Zaag et al., 2012) proposes that these are category 1 since they are not subject to many of the issues associated with sheets, such as water collection and tearing. In addition, they are easy to apply.

117. *Replacement of lagoons by tanks/silos:* If shallow earth-banked lagoons are replaced by deeper tanks or silos, emissions will be proportionately reduced due to the reduced surface area per unit volume. This could be an effective (though expensive) NH_3 reduction option, particularly if the tanks are covered by a lid, roof or tent structure (category 1 techniques). The cost effectiveness of this option is difficult to quantify, as it depends strongly on the characteristics of the lagoon and the tank. Mixing manure in tall structures is difficult.

Table 12: Ammonia emission abatement measures for cattle and pig slurry storage. For economic cost of the abatement techniques, see Reis (2012)

Abatement Measure	NH_3 emission reduction %	Applicability	Costs (OPEX) (€ per m^3/yr)-[c]	Extra costs (€/kg NH3-N reduced)**
Store with no cover or crust (Reference)	0			
'Tight' Lid, roof or tent structure (Cat. 1)	80	Concrete or steel tanks and silos. May not be suitable on existing stores.	2-4	1.0-2,5
*Plastic sheeting (floating cover) (Cat. 1)	60	Small earth-banked lagoons.	1.5-3	0.6-1.3
Allowing formation of natural crust by reducing mixing and manure input below the surface (floating cover) (Cat. 1)	40	Only for slurries with higher content of fibrous material. Not suitable on farms where it is necessary to mix and disturb the crust in order to spread slurry frequently. Crust may not form on pig manure in cool climates.	0.00	0
Replacement of lagoon, etc. with covered tank or tall open tanks (depth > 3 m) (Cat.1)	30– 60	Only new build, and subject to any planning restrictions concerning taller structures.	15 (ca 50% cost of tank)	
Storage bag (Cat. 1)	100	Available bag sizes may limit use on larger livestock farms.	2.50 (includes cost of storage)	
Floating LECA balls, 'Hexa-covers' (Cat.1)	60	Not suitable for crusting manures	3-4	2-5
*Plastic sheeting (floating cover) (Cat. 2)	60	Large earth-banked lagoons and concrete or steel tanks. Management and other factors may limit use of this technique.	1.50-3	0.5-1.3
"Low technology" floating covers (e.g. chopped straw, peat, bark, etc.) (Cat. 2)	40	Concrete or steel tanks and silos. Probably not practicable on large earth-banked lagoons. Not suitable if materials likely to cause slurry management problems.	1.50–2.50	0.3-0.9

* Sheeting may be a type of plastic, canvas or other suitable material.
c/ Based on a depreciation period of 10 years, and an interest rate of 6 per cent, and an additional cost of €12,000. (The cost €2.5 maybe adjusted)
** calculated for storage of pig slurry in stores ranging from 500 to 5000m³ capacity for temperate regions of central Europe. The reference is slurry with no crust.

Category 2 techniques

118. *Floating covers (for stores other than small earth-banked lagoons):* There is a range of floating cover types made from permeable and impermeable materials that can reduce NH_3 emissions from stored slurries by restricting contact between the slurry and the air. However, the effectiveness and practicality of these covers is still uncertain except for

well tested plastic sheeting on small earth-banked lagoons, and are likely to vary according to management and other factors. Examples include plastic sheeting, chopped straw, peat, Impermeable floating covers need venting and a method to remove rain water that gathers on top. Permeable floating covers must be carefully retrained against the wind and both types must allow for vertical movement during filling and emptying, The durability of floating covers is not well tested. Floating covers might hinder homogenization of the slurry prior to spreading or hinder the spreading process itself. This aspect needs technical attention and optimization

119. *Covering farmyard manure*: There are few options for reducing NH_3 emissions from stored farmyard (solid) manures for cattle and pigs. Experiments have shown that covering farmyard manure piles with plastic sheeting can substantially reduce NH_3 emissions and with no significant increase in methane or nitrous oxide emissions (Chadwick, 2005; Hansen et al., 2006). At present, this is considered as a category 2 technique, due to the need for more general testing of abatement efficiency and practicability.

VII. MANURE APPLICATION TECHNIQUES

120. *Reference technique*. The reference manure application technique is defined as untreated slurry or solid manure spread over the whole soil surface ("broadcast") and not followed by incorporation, and not targeting application timing conditions that minimize ammonia loss. For slurry, for example, this would typically consist of a tanker equipped with a discharge nozzle and splash-plate. For solid manures, the reference case would be to leave the manure on the soil surface without incorporation.

121. Emissions of ammonia from the reference technique expressed as a percentage of the TAN (total ammoniacal nitrogen) applied are typically in the range of 40-60% (although emissions outside this range are also common). Emissions will vary with the composition of the slurry or solid manure and with prevailing weather and soil conditions. Emissions of ammonia as a percentage of TAN applied are normally decreased with decreasing: evapotranspiration (air temperature, wind speed, solar radiation); and slurry DM concentration. Emissions of ammonia as a percentage of TAN applied are normally decreased with increasing: TAN concentration; and application rate. Emissions from different manure types will also vary. Emissions are also dependant on soil conditions that affect infiltration rates. For example, well-draining, coarse textured, dry soils, which allow faster infiltration, will give rise to lower emissions than wet and compact soils with reduced infiltration rate (Søgaard et al., 2002). However, when very dry, some soils may become hydrophobic which can also reduce infiltration and therefore increase emissions.

122. *Specification of abatement efficiency.* Emissions will vary with the composition of the slurry and solid manure and with prevailing weather and soil conditions. Abatement efficiencies will also vary relative to reference emissions depending on these factors. For this reason, the figures quoted in Table 14 represent averages from many studies in different countries over a wide range of conditions. The absolute magnitude of ammonia emission levels of the reference techniques varies temporally and at a regional scale in response to variation in environmental conditions. While these factors also affect the absolute magnitude of ammonia emissions from low-emission approaches, the relative emission levels are comparable; for this reason the benefits of using low-emission approaches are expressed as percentage reduction compared with the reference.

123. Category 1 techniques include machinery for substantially decreasing the exposed surface area of slurries applied to surface of soil or burying slurry or solid manures through injection or incorporation into the soil. Economic costs of these techniques are in the range 0.1 to 5 Euro per kg NH_3-N saved, with the smallest costs for immediate incorporation of slurries and solid manure, where this is feasible (i.e. on bare arable land). The estimates are very sensitive to assumed farm size, with substantially improved economies of scale on larger farms, where low emission equipment is shared between several farms, or where specialist contractors are used. The techniques included in category 1 are:

(a) Band-spreading slurry at the soil surface using trailing hose or trailing shoe methods
(b) Injecting slurry – open slot;
(c) Injecting slurry – closed slot;
(d) Incorporation of surface-applied solid manure and slurry into soil;

(e) Dilution of slurry by at least 50%, when applied in low pressure water irrigation systems.

The average NH_3 abatement efficiencies of category 1 techniques, relative to the reference, and an indication of the cost of each technique relative to the reference are given in Table 14 for slurries and Table 15 for solid manures.

Table 14: Category 1 abatement techniques for slurry* application to land. The abatement measures refer to the category 1 techniques listed in provision 123.

Abatement measure	Land use	Emission reduction (%)†	Factors affecting emission reduction	Applicability compared with the reference	Cost (€/Kg NH_3 abated/year)
(a) Band-spreading slurry with a trailing hose	Grassland Arable	30-35%	More crop canopy will increase reduction, depending on placement precision and the extent of herbage contamination.	Less suitable where: Slope >15% Can be used on solid seeded crops and wide units may be compatible with tramlines	-0.5 – 1.5 (note that the costs may be reduced if the equipment is locally designed and built)
Band spreading with trailing shoe	Grassland Arable (pre-seeding) and row crops	30-60%	More crop canopy will increase reduction, depending on placement precision and the extent of herbage contamination.	Not suitable for use in growing solid seeded crops but may be possible to use in the rosette stage and in row crops.	-0.5 – 1.5
(b) Injecting slurry (open slot)	Grassland	70%	Injection depth ≤ 5 cm	Unsuitable where: Slope >15%; High stone content; Shallow soils; High clay soils (>35%) in very dry conditions, Peat soils (>25% organic matter content). Tile drained soils susceptible to leaching	-0.5 – 1.5
(c) Injecting slurry (closed slot)	Grassland Arable	80% (shallow slot 5-10 cm) 90% (deep injection >15cm)	Effective slit closure		-0.5 – 1.2
(d) Incorporation of surface applied slurry	Arable	Immediately by ploughing = 90%			-0.5 – 1.0
		Immediately by non-inversion cultivation (such as discing) = 70%			-0.5 – 1.0
		Incorporation within 4 hrs = 45-65%	Efficiency depends on application method and weather conditions between application and incorporation		-0.5 – 1.0
		Incorporation within 24 hours = 30%			0 – 2.0
(e) Active dilution of slurry of >4% DM to <2% DM for use in water irrigation systems	Arable Grassland	30%	Emission reduction is proportional to the extent of dilution. A 50% reduction in dry matter (DM) content is necessary to give a 30% reduction in emission	Limited to low pressure water irrigation systems (not 'big guns'). Not appropriate where irrigation is not required.	-0.5 – 1.0

* slurry is defined as flowable manure usually less that 12% dry matter. Material with a higher dry matter content or containing high amounts of fibrous crop residue may require pretreatment (e.g. chopping or water addition) to be applied as a slurry, and should otherwise be handled as for solid manures (Table 18b). Costs assume medium or high usage of equipment. Where a low use is made of the relevant equipment costs per unit N saved may be higher.
† Average emission reductions agreed to be achievable across the UNECE region. The wide ranges reflect differences in techniques, management, weather conditions, etc.

Table 15: Category 1 abatement techniques for solid manure*) application to land.

Abatement measure	Land use	Emission reduction (%) †	Factors affecting emission reduction	Limitations to applicability compared with the reference	Cost (€/Kg NH_3 abated/year)
(d) Incorporation of surface applied manure	Arable	Immediately by ploughing = 90%	Degree of burying the manure		-0.5 – 1.0
		Immediately by non-inversion cultivation = 60%	Degree of burying the manure		0 – 1.5
		Incorporation after 4 hrs = 45-65%	Degree of burying the manure Efficiency depends on time of day of spreading and weather conditions between application and incorporation;		0 – 1.5
		Incorporation within 12 hours = 50%			0.5 – 2.0
		Incorporation within 24 hours = 30%			0.5 – 2.0

* solid manure is defined as non-flowable manure usually with more than 12% dry matter
† Emissions reductions are agreed as likely to be achievable across the UNECE region.

124. Each efficiency for techniques (a)–(c) is valid for soil types and conditions that allow infiltration of liquid and satisfactory travelling conditions for the machinery.

125. Tables 14 and 15 also summarize the limitations that must be taken into account when considering the applicability of a specific technique. These factors include: soil type and condition (soil depth, stone content, wetness, travelling conditions), topography (slope, size of field, evenness of ground), manure type and composition (slurry or solid manure). Some techniques are more widely applicable than others. Additional costs are negligible, if the ploughing or soil cultivation has to be done anyway, but for emission mitigation this has to be done directly after application, which may require additional resources.

126. Techniques (a) - (c) operate on the basis that the surface area of slurry exposed to the prevailing weather conditions is reduced by at least 75% through confining the slurry to lines / bands which are approximately 250 (+/- 100) mm apart. The slurry is distributed through a number of relatively narrow pipes (usually 40-50 mm diameter). These machines usually incorporate systems for filtering, chopping and homogenising slurry, which minimise the occurrence of blockages in narrow pipes caused by slurries that are very viscous or that contain large amounts of fibrous material or foreign objects such as stones. Band-spreading and injection systems are normally fitted to the rear of slurry tankers, which are either towed by a tractor or form parts of a self-propelled machines. An alternative is for the application system to be attached directly to the rear of a tractor and slurry transported to it by an 'umbilical' hose from a stationary tanker or store. Such umbilical systems can reduce soil compaction damage caused by heavy slurry tankers.

127. ***Band-spreading slurry at or above the soil surface.*** Band-spreading at or above the soil surface can be carried out using implements commonly referred to as 'trailing hose' (also known as 'drag hose' and 'drop hose')' and 'trailing shoe' (also known as 'drag shoe' and 'sleighfoot'). Trailing shoe and trailing hose systems are distinguishable from

each other through the presence (trailing shoe) or absence (trailing hose) of a ‘shoe’ or ‘foot’ device at the outlet of each slurry distribution-application pipe which slides (or floats) on the surface of the ground with little or no penetration. The hose or shoe is intended to part of the herbage or any crop residue present to allow slurry placement directly on the soil surface. Greater efficiency generally reported with the sliding shoe (Webb et al. 2010) is attributed to manure being in narrower bands, having more contact with the soil and having less contact with live or dead vegetative material because it is better pushed aside by the shoe than the hose, even if the hose is very close to the ground. The benefit of the shoe compared with the hose is greatest for taller canopies because of the reduced degree of canopy contamination. Both systems are usable in a range of cropping situations although of the two the hoses are less restrictive because they can be wider, used in standing crops without damage and are amenable to tramline systems. Both systems apply manure more uniformly, and are less susceptible to wind, compared to the reference system. They increase the time available for spreading and allow spreading closer to field margins with low risk of contaminating adjacent areas.

128. ***Trailing hose:*** This technique discharges slurry at or just above ground level through a series of hanging or trailing pipes or flexible hoses, which either hang a short distance (<150 mm) above the soil or are dragged along the soil surface. The working width is typically between 6 and 12 m, although larger units of up to 24 m width are commercially available. The possible working width (requiring manual or powered swing arms for transport) is much larger than for the ‘splash plate’ reference system (6-9 m), representing a clear advantage of the trailing hose method. The spacing between bands (centre to centre) is typically 250-350 mm. The technique is applicable to grass and arable crops, and can be used with tramlines. The pipes may become clogged if the DM content of the slurry is high (>7-10%) or if the slurry contains large solid particles. However, the clogging of pipes is usually avoided by including a chopping and distribution system. This system improves spreading uniformity which improves nutrient use, but contributes significantly to the cost and maintenance of the system. The chopper/ distributor device can often be designed and built locally so that the costs may be quite low.

129. ***Trailing shoe:*** This technique is mainly applicable to grassland and arable crops at early stages or with widely spaced rows. The machine working width is typically limited to 6 – 8 m, which, as with the reference system, is insufficient for practical operation in growing combinable crops, which are normally established in 12 m or 24 m tramline systems. The method is not recommended for growing solid seeded arable crops where the action of the shoe can result in excessive plant disturbance. Grass leaves and stems are parted by trailing a narrow shoe or foot over the soil surface and slurry is placed in narrow bands on the soil surface. The spacing between bands is typically between 200 and 300 mm. Ammonia emission reductions are optimised when the slurry bands are partially sheltered by a crop canopy. Applicability is limited where there are significant stones on the soil surface. Large amounts of crop residue such as on untilled land will gather on the trailing shoes and interfere with their performance.

130. The ammonia emission abatement potential of trailing shoe or trailing hose machines is more effective when slurry is applied below well-developed crop canopies rather than on bare soil because the crop canopy increases the resistance to air turbulence from wind and shades the slurry from solar radiation. In general, ammonia emission reductions have typically been found to be larger from trailing shoe than from trailing hose, which is most likely due to the higher degree of canopy contamination resulting from certain types and implementation of the trailing hose methods. This emphasizes the need to avoid canopy contamination with slurry when using either method, which also has benefits for herbage quality.

131. ***Injection – open slot:*** This technique is mainly for use on grassland or minimum till cropland prior to planting. Different shaped knives or disc coulters are used to cut vertical slots in the soil up to 50 mm deep into which slurry is placed. Spacing between slots is typically 200–400 mm and machine working width is typically ≤6 m. To be effective in both reducing ammonia emissions and increasing the availability of nitrogen to the crop, while also reducing crop injury, injection should be to a depth of approximately 50 mm and the space between injector tines should be ≤ 300 mm. Also, the application rate must be adjusted so that excessive amounts of slurry do not spill out of the open slots onto the surface. The technique is not applicable on very stony soils, or on very shallow or compacted soils, where it is impossible to achieve uniform penetration to the required working depth. The method may not be applicable on very steeply sloping fields due to the risk of runoff down the injection furrows. Slurry injection systems will have a higher tractor power requirement than broadcast or band-spreading equipment.

132. ***Injection – closed slot.*** This technique can be relatively shallow (50–100 mm depth) or deep (150–200 mm). Slurry is <u>fully covered</u> after injection by closing the slots with press wheels or rollers fitted behind the injection tines. Deeper injection is required when greater volumes of manure are injected to avoid the manure oozing to the surface. Shallow closed-slot injection is more efficient than open-slot in decreasing NH_3 emission. To obtain this added benefit, soil type and conditions must allow effective closure of the slot. The technique is, therefore, less widely applicable than open-slot injection. Some deep injectors comprise a series of tines fitted with lateral wings or “goose feet” to aid soil penetration and lateral dispersion of slurry in the soil so that relatively large application rates can be achieved. Tine spacing is typically 250–500 mm and working width ≤4 m. Although NH_3 abatement efficiency is high, the applicability of the technique is mainly restricted mainly to pre-sowing application to arable land and widely spaced row crops (e.g. maize), while mechanical damage may decrease herbage yields on grassland or growing solid-seeded arable crops. Other limitations include soil depth, clay and stone content, slope and a high tractor power requirement and increased risk of leaching particularly on tile drained soils.

133. ***Incorporation of surface-applied solid manure and slurry into soil***: Incorporating surface applied manure or slurry by either ploughing or shallow cultivation is an efficient means of decreasing NH_3 emissions. Highest reduction efficiencies are achieved when the manure is completely buried within the soil (Table 15). Ploughing results in higher emission reductions than other types of machinery for shallow cultivation. The applicability

of this technique is confined to arable land. Incorporation is not applicable on permanent grassland, although it may be possible to use in grassland systems either when changing to arable land (e.g. in a rotation) or when reseeding pasture although nutrient requirements may be low at both of these times. It is also less applicable to arable crops grown using minimum cultivation techniques compared to crops grown using deeper cultivation methods. Incorporation is only possible before crops are sown. The technique is the main technique applicable to achieve emission reductions from application of solid manures on arable soils although new applicators for injecting poultry litter into sod are being tested in North America. The technique is also effective for slurries where closed-slot injection techniques are not possible or available or present a risk of leaching. Cultivation also reduces macropores which can facilitate leaching. The success of this approach has been shown in many studies, including in the Russian Federation (Eskov et al., 2001).

134. Ammonia loss takes place quickly (over several hours and days) after manures are spread on the surface, so greater reductions in emissions are achieved when incorporation takes place immediately after spreading. Immediate incorporation often requires a second tractor to be used for the incorporation machinery, which must follow closely behind the manure spreader. Where labour or machinery requirements limit this option, such as for small farms, manures should be incorporated within 4 hours of spreading the manure, but this is less efficient in reducing emissions (Table 15). Incorporation within 24 hours of spreading will also reduce emissions to an even smaller extent, but increases agronomic flexibility, which may be especially important for small farms. It is most important to incorporate rapidly when manure is applied near midday in hot conditions. It may be possible to spread and incorporate with a single implement. This can work well, provided that less than 25% of the manure is left exposed to the atmosphere.

135. ***Slurry dilution for use in irrigation systems.*** Ammonia emissions from dilute slurries with low dry matter (DM) content are generally lower than for whole (undiluted) slurries because of faster infiltration into the soil (e.g. Stevens and Laughlin, 1998; Misselbrook et al., 2004). Doses of slurry, calculated to match the nutrient requirement of crops, can therefore be added to irrigation water to be applied onto grassland or growing crops on arable land. Slurry is pumped from the stores, injected into the irrigation water pipeline and brought to a low pressure sprinkler or travelling irrigator (not big gun with high pressure), which sprays the mix onto land. Dilution rates may be up to 50:1 water: slurry. This approach is included as a Category 1 method so far as this is an active dilution for use in water irrigation systems with a dilution of at least 50% (1:1 water:slurry) sufficient to reduce emissions by at least 30%, where there is a need for water irrigation. In the case of slurry with a DM content of 4%, this would need to be diluted to ≤ 2% DM content (see Figure 1). In order to be considered a category 1 method, the following conditions should apply:

i. The slurry is actively diluted for use in irrigation systems by at least the required amount of 1:1 dilution with water. By contrast, the slurry should not simply be dilute through poor management practice, such as because of slurry storage in shallow uncovered lagoons that collect a lot of rainwater. These storages are discouraged because they are in themselves potentially significant sources of emissions that are difficult to control with covers.

ii. Conditions are suitable for irrigation to meet crop water needs. Dilution of slurry without a water need adds to hauling costs and may exacerbate nitrate leaching.

iii. The amounts of slurry applied are calculated to match nutrient needs. The method should not be seen as an easy option for slurry disposal, with the possible risk of over fertilization and nitrate leaching or manure runoff, especially on sloped fields.

iv. Soil conditions allow for rapid soaking of dilute slurries because there are no physical impediments to infiltration, such as high soil water content, poor soil structure, fine texture or other soil attributes that reduce infiltration rates of liquids in to soil, and that there is no decrease in infiltration rate due to high application volumes.

136. In addition to the specific dilution of slurry in irrigation systems, other methods of reducing slurry DM content can provide a useful means to reduce ammonia emissions. These include reducing DM levels through anaerobic digestion and by solid-liquid separation. Because such methods can tend to increase the pH of the low DM fraction and also produce a sludge with higher DM content, they are not included as Category 1 methods. Such methods can, nevertheless, provide a useful approach as part of Category 2 methods, where verification of the emission reductions should be provided.

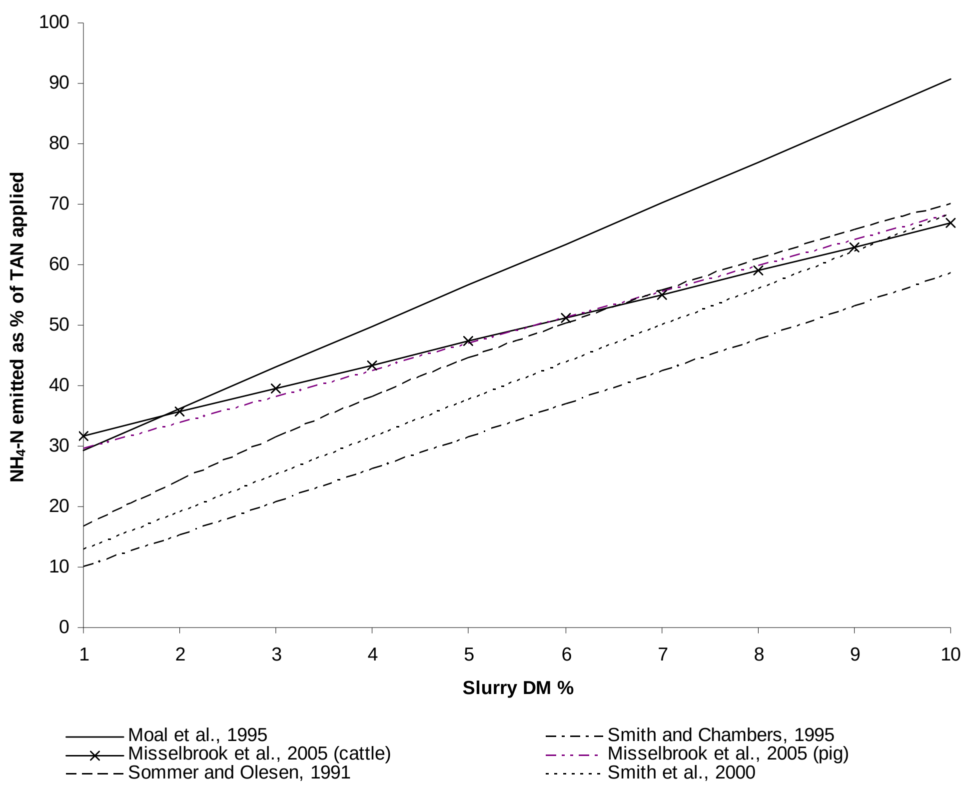

Figure 1: Relationship between the percentage of total ammoniacal nitrogen (TAN) emitted as ammonia during the land application of slurry and the dry matter content (DM % weight) of the slurry, according to six estimates. Even though ammonia emissions are still significant at 1% DM

content (10-30% of TAN lost through volatilisation), a 50% reduction in DM content will achieve roughly a 30% reduction in average ammonia emissions.

137. ***Additional benefits of techniques to reduce ammonia emissions from the land application of slurry and solid manure.*** The experimental quantification of increased manure N efficiency associated with reduced ammonia emissions has given variable results (Webb et al. 2010). This may be partly explained by the difficulty implicit in any attempt to detect a significant crop response to low N fertilizer additions against relatively large background soil N mineralisation rates. In practice, the reduction in ammonia emission translates into a reduction of application rate of additional N. Although the uptake of the ammonia-N by the crop will vary, the TAN that is not volatilised can be considered as potentially equivalent to chemical N fertilizer. Therefore, reduced ammonia losses can be considered to replace chemical fertilizer applications on a 1:1 ratio.

138. Band-spreading and injection techniques, as well as the rapid incorporation of solid manures, considerably reduce the odour associated with manure application. The reduction in odour emissions achieved by these techniques can allow application on areas or at times that may otherwise be unavailable due to complaints.

139. Band-spreading and injection techniques can allow more accurate slurry application rates than the reference technique, as the slurry should be distributed in equal proportions to pipes that are equally spaced apart along a fixed bout width. By comparison, the spatial distribution following application using the splashplate applicator (the reference system) is often more variable, depending on the design and condition of the splashplate unit. Also, the bout width using splashplates can be more variable (e.g. affected by wind), resulting in imperfect alignment of adjacent bout strips and less accurate application along field boundaries. This potential improvement in accuracy of application increases efficiency of slurry as a nutrient source. The improvement in application accuracy also reduces the risk of nitrate, phosphorus and microbial pollution by avoiding spreading slurry onto adjacent areas such as near water courses.

140. The window of opportunity for slurry application using the reference technique (broadcast spreading) is restricted by the risk of crop quality deterioration or damage caused by slurry contamination. Band-spreading and injection reduce the occurrence of herbage contamination and therefore increase the crop canopy height onto which slurry can be applied without threatening crop quality. This is particular relevant to grassland, where slurry contamination can reduce grazing palatability or silage quality and may transfer pathogens (eg Johne’s disease) between farms if manure or equipment is shared. These methods also allow slurry application on growing arable crops (particularly cereals) which are generally not considered suitable to receive slurry applied using splashplate. The use of low-emission techniques can therefore help to increase the flexibility of slurry application management by allowing more land area to be available on days when weather conditions are more suitable for reduced ammonia volatilisation and optimal slurry-N utilisation, and when soil moisture conditions are suitable to allow machinery traffic with minimal soil compaction.

141. ***Potential cost implications of abatement techniques.*** Cost increases associated with purchasing and maintaining, or hiring contractors with, new application machinery can be a disincentive to adoption. Injection techniques also require higher tractor power, further adding to the cost of adoption for those systems. These additional costs can be partially or totally outweighed by the financial benefit of improving yield and yield consistency, reducing nitrogen losses (by reducing mineral fertilizer requirements), by more precise delivery of manure nitrogen to the crop, by the increased agronomic flexibility and by other co-benefits such as reduction of odour and crop contamination and improved visual aesthetics during and fter manure application (Webb et al. 2010). The overall benefit-cost ratio depends especially on equipment costs and abatement efficiency.

142. ***Impact of reduced ammonia losses on N cycle.*** If no crops are present, or growing, following manure application to take up the readily available N, the risk of N loss via leaching or gaseous N_2O increases. Hence incorporation and especially injection of manures involves a risk of exchanging air pollution for water pollution, but reduces the risk of surface run-off from subsequent rainfall events. For this reason, the timing of slurry and solid manure application needs to balance the potential for low ammonia emissions against the other loss pathways, while considering the timing of crop needs. To avoid overall losses of N, manure should not be applied when there is no or very limited crop uptake. Ammonia mitigation makes an important contribution to the overall reduction of nitrogen losses from agriculture, thereby maximizing the agronomic benefits of applied mineral fertilisers. The financial benefit to the farmer of reducing the need for mineral nitrogen fertilizers is complemented by a regional-scale greenhouse gas benefit due to reduced mineral fertilizer needs, given the fertilizer related N_2O emissions from soils and the high energy costs of nitrogen fertilizer manufacture.

143. Results suggest that injection of slurry may either increase or have no impact on emissions of N_2O. The addition of readily-degradable C in slurry has been proposed as a mechanism responsible for increasing emissions of N_2O by more than would be expected due to the additional N entering the soil as a result of ammonia abatement. This addition of readily-degradable slurry-C, without significantly aerating the soil, may increase denitrification activity. There are a number of reasons why reduced ammonia emission application techniques would not always lead to greater emissions of N_2O such as: (1) deeper injection (> 5 cm) or incorporation, by increasing the length of the diffusion path from the site of denitrification to the soil surface, may lead to a greater proportion of denitrified N being emitted as N_2; (2) the subsequent soil moisture status and hence aeration may not be suitable for increased N_2O production; (3) in soils already well-supplied with both readily-degradable C and mineral N any increase in N_2O emission may be too small to have a significant effect; and (4) the impact of subsequent weather on soil moisture content and water-filled soil pore space will also effect subsequent emissions of N_2O. The reflection of these interactions is that mitigation of ammonia emissions reduces the N_2O emissions associated with atmospheric nitrogen deposition to semi-natural ecosystems and allows a saving of fertilizer inputs, leading to overall reduction in N_2O emissions.

144. Incorporation of farmyard manure (FYM) appears to reduce or have no impact on N_2O emissions. In contrast to slurry, there is evidence that readily-degradable-C is lost as part of the effluent arising during storage of solid manures. Hence the C added to soil by incorporation of solid manures will have less effect than slurry on microbial metabolism.

Category 2 techniques

145. ***Verification of Category 2 techniques.*** Category 2 techniques may form a useful part of a package of measures to reduce ammonia emissions, but may be more uncertain or the emission reductions inherently harder to generalize. For this reason, Annex IX specifies that, where Category 2 methods are used to achieve the specified emission reductions, details should be provided by parties to verify the reported emission reductions from the methods. Such verification should also be provided for Category 3 methods where these are used. For techniques based on a) increasing the rate of infiltration into the soil and b) pressurized injection of slurry, documentation should describe the practice used and give evidence from field or farmscale measurements demonstrating and justifying the emission reduction. Specific requirements apply to the verification of Application Timing Management Systems (ATMS) as described in the paragraph below.

146. ***Increasing rate of infiltration into the soil.*** When soil type and conditions allow rapid infiltration of liquid, NH_3 emission decreases with decreasing slurry dry matter content. Dilution of slurry with water not only decreases the ammonium-N concentration, but also increases the rate of infiltration into the soil following spreading on land. For undiluted slurry (i.e. 8–10% dry matter), dilution must be at least 1:1 (one part slurry to one part water) to achieve reduced emissions by at least 30%. A major disadvantage of the technique is that extra storage capacity may be needed and a larger volume of slurry must be applied to land. In some slurry management systems, slurry may be already diluted (e.g. where milking parlour or floor washings, rainfall, etc. are mixed with the slurry) and there may be only a small advantage in actively diluting further. Extra cost for storage capacity and, mainly, for transport in land application, should discourage use of this technique. Also, there may be more risk of aquifer pollution, more water wastage and greater carbon footprint because of the additional transport. Experience from the Russian Federation shows that pre-cultivation to increase infiltration (e.g. discing or slotting) provides a useful means to increase infiltration rate prior to slurry application (Eskov et al., 2001).

147. When applying diluted slurries to land there may be a greater risk of surface run-off and leaching and this must be guarded against by paying attention to application rate, soil conditions, slope of the land, etc. For these reasons, apart from the active dilution of slurry for irrigation (Category 1), this method is included as Category 2.

148. Another means of decreasing slurry dry matter content, and hence increasing the rate of infiltration into the soil, is to remove a proportion of the solids by mechanical separation or anaerobic digestion. Using a mechanical separator with a mesh size of 1–3

mm reduces NH_3 loss from the separated liquid by a maximum of 50 per cent. Another advantage lies in reduced soiling of grass swards. Disadvantages of the technique include the capital and operating costs of the separator and ancillary equipment, the need to handle both a liquid and a solid fraction, and emissions from the solids. Information to verify such systems should include demonstration of the overall ammonia emission reduction, taking account of the emissions from both the low DM and high DM fractions.

149. A third option for increasing infiltration rate is to wash slurry off grass and into the soil by applying water after spreading. A plentiful supply of water is needed, the application of which is an additional operation, but Canadian results have shown that 6 mm of water can under some circumstances reduce NH_3 losses by 50 per cent compared to surface application alone. Information to verify such systems should specify the time delay between slurry application and washing the grass with water, the amounts of water used, and the percentage emission reduction achieved. When applying water after spreading, there may be a greater risk of surface run-off and leaching, depending on soil conditions, slope of the land, etc. For these reasons, apart from the active dilution of slurry for irrigation (Category 1), this method is included as Category 2.

150. ***Pressurized injection of slurry.*** In this technique, slurry is forced into the soil under pressure of 5–8 bars. Because the soil surface is not broken by tines or discs the technique is applicable on sloping land and stony soils where other types of injector cannot be used. Emission reductions of typically 60 per cent, similar to that for open slot injection, have been achieved in field trials, but further evaluation of the technique is needed.

151. ***Application timing management systems (ATMS)***. Ammonia emissions are highest under warm, dry, windy conditions (i.e. when evapotranspiration rates are high). Emissions can be reduced by optimising the timing of application, i.e. cool humid conditions, in the evenings, before or during light rain and by avoiding spreading during warm weather conditions, particularly during periods when solar elevation, and hence solar radiation input, is most intense (June/July) (Reidy and Menzi 2007). This is potentially a cost-effective approach as it can be done using broadcast application equipment. The ATMS approach might also lead an additional benefit when used in combination with a low-emission application technique, like the trailing hose. Potential emission reductions achievable through these measures will vary depending on regional and local soil and climatic conditions, and therefore the suite of measures that may be included will be specific to regional conditions.

152. While the benefits of using such timing management practices has been long known, the main constraints are:

(a) the need to demonstrate that the approach can deliver a specified ammonia emission reduction target in practice,
(b) the need to carefully define what is meant by reference conditions (in order to ensure correct reporting of the outcomes),

(c) the need to implement a system to manage this approach that verifies its efficacy and implementation and
(d) reduced flexibility when spreading manure with respect to soil trafficability, labour and equipment availability and consideration of other regulations.

153. This approach can be considered as rather different to the technical methods listed as Category 1, such as band spreading and manure incorporation, where the efficiencies reported in Tables 13 and 14 are based on the average outcomes from many studies. In the case of ATMS the assessment uses the responses of models (based on many studies and accounting for meteorological conditions) to the actual timing practice.

154. In order to allow the benefits of timing practices to be included as an abatement measure, the above listed constraints must be addressed. This can be achieved through the use of an Application Timing Management System (ATMS), which is here defined as: *a verifiable management system for the direction and recording of solid and liquid manure application at different times, the adoption of which is demonstrated to show quantified farm scale reductions in ammonia emissions.* The use of any ATMS must demonstrate achievement of a specified ammonia emission reduction target, by comparison to the reference, in order for its benefit to be considered as part of international emission control strategies.

155. Application Timing Management Systems may be designed to exploit several principles in the variation of ammonia emissions, the benefits of which will vary with local climate, so that ATMS implementations will vary regionally. The following principles may be exploited in an ATMS:

(a) *Weather-determined variation in ammonia emissions.* Ammonia emissions tend to be smaller in cool and wet conditions and after light rain (though water-logging of soils can make spreading conditions unfavourable). Ammonia emissions can therefore be forecasted by coupling ammonia emissions models with weather forecasting, as is already available in some countries, with land application timing restricted to forecasted periods of low ammonia emissions.
(b) *Seasonal variation in ammonia emissions.* Ammonia emissions can be estimated on a seasonal basis by generalising weather conditions for particular seasons. For example, seasonal variations lead to largest ammonia emissions in warm summer conditions and smaller emissions in cool moist winter conditions. Subject to other constraints, such as the objective to match manure application to the timing of crop needs, and the need to avoid water pollution, a targeted seasonal management of solid and liquid manure application has the potential to reduce overall annual ammonia emissions.
(c) *Diurnal variation in ammonia emissions.* Ammonia emissions tend to be smaller at night due to reduced windspeed, cooler temperatures and higher humidity.
(d) *The effect of timing of animal housing versus grazing on ammonia emissions.* Ammonia emissions from livestock allowed to range outdoors with sufficient foraging area (e.g. cattle grazing) tend to be much smaller than for housed livestock, since this practice avoids ammonia emissions associated with housing, manure

storage and landspreading of slurries and solid manures. Therefore, subject to other constraints, such as water and soil quality issues arising from grazing during the winter, increasing the period in which animals are in the field (especially when 24 hours a day) can reduce ammonia emissions. Changes in timing practice may be included in an ATMS since these affect the total amounts of manure to be spread.

156. *Verification procedures for ATMS.* One of the main challenges for any ATMS is to demonstrate an appropriate verification of the approach, particularly given the requirement to demonstrate the achievement of a specified emission reduction. The ATMS approach is considered most relevant at a farm scale, as it results from the overall outcome of a package of timing practices. The emission reduction target should be applied on an annual scale as the emission reduction potential of this method is time dependent.

157. Verification of an ATMS should include each of the following steps:

(a) *Verification of the core biophysical modelling tool used.* A transparent description of the numerical model used should be provided, underpinned by appropriate independent verification from field measurements.
(b) *Verification of the effect of a specific timing management on ammonia emissions.* The degree to which the timing management leads to the target emission reduction required as compared with the reference conditions for that region should be demonstrated for any ATMS being used.
(c) *Verification that actual practices conform to those reported.* Any ATMS should be implemented in conjunction with an appropriate recording system, to ensure and demonstrate that the timing management recorded in the ATMS is being fully implemented.

158. *Definition of the reference conditions for an ATMS.* In the case of most low emission techniques for land application, the percentage reduction achieved can be generalized over a wide climatic area. By contrast, where an ATMS is used, a more detailed definition of the reference conditions is needed. Overall, the same *reference technique* applies (free broadcast surface application of slurries and solid manures), but where an ATMS is used, the reference must also be defined on a farm level according to existing practices. In order to account for regional variability in climate and inter-year variability in meteorological conditions, the reference condition for ATMS is extended to include: "*the combination of manure application management practices, and their timing, at a farm scale during a specified reference period, when using the reference application method (broadcast spreading), accounting for three-year variability in meteorological conditions"*.

159. The emission reduction potential of an ATMS should be verified for the region within which it is adopted. Numerical ammonia emission simulation models will, in general, need to be used as part of the verification of ATMS.

160. An ATMS may be used in combination with other measures for reducing ammonia emissions following land application of manures, such as slurry application technologies or

incorporation of manures into soil. However, the additional absolute ammonia emission reduction of an ATMS will vary depending on the emission reduction potential of the accompanying application method. The joint contribution of both low emission application methods and an ATMS should be assessed to ensure that the overall farm-scale ammonia reduction target is met.

161. Depending on the type of ATMS to be implemented, the main additional costs will be associated with reduced flexibility in timing of manure application, and the associated administrative costs necessary for the verification. Potential cost savings may be found by combining ATMS approaches with advice on managing farm nitrogen stocks more effectively such as through a proven expert system.

162. Application prior to or during weather conditions that increase the risk of nutrient loss to waters should be avoided. Aspects of safety associated with machinery operation at certain times, particularly during hours of darkness, should also be considered when designing an ATMS. Conditions that favour reduced ammonia emissions (e.g. humid, no wind) may give rise to problems with offensive odours by preventing their rapid dispersion.

163. *Acidified slurry:* The equilibrium between ammonium-N and NH_3 in solutions depends on the pH (acidity). High pH favours loss of NH_3; low pH favours retention of ammonium-N. Lowering the pH of slurries to a stable level of 6 and less is commonly sufficient to reduce NH_3 emission by 50 per cent or more. The technique of adding sulphuric acid to slurry is now practiced in Denmark, with considerable success. When adding acids to slurry, the buffering capacity needs to be taken into account, usually requiring regular pH monitoring and acid addition to compensate for CO_2 produced and emitted during the preparation of the acidified slurry. Acidification preferably has to be carried out during storage of slurry and also during spreading using specially designed tankers. Although efficient, the technique has the major disadvantage that handling strong acids on farms is very hazardous.

164. Options to achieve acidified slurry are by adding organic acids (e.g. lactic acid) or inorganic (e.g. nitric acid, sulphuric acid, phosphoric acid) or by the modifying or supplementation of animal feed (e.g. benzoic acid) (see section on Livestock Feeding Strategies) or slurry of components (e.g. lactic acid forming bacteria) that enhance pH reduction. Organic acids have the disadvantage of being rapidly degraded (forming and releasing CO_2); moreover, large quantities are required to achieve the desired pH level, since they are usually weak acids. Nitric acid has the advantage of increasing the slurry N content so giving a more balanced NPK (nitrogen-phosphorus-potassium) fertilizer, but has the potential large disadvantage of nitrification – denitrification mediated N_2O production and associated pH rise. A pH value of ~4 is required when using nitric acid to avoid nitrification and denitrification, causing loss of nitrate and production of unacceptable quantities of N_2O. Using sulphuric acid and phosphoric acid adds nutrients to the slurry that may cause over fertilization with S and P. Moreover, adding too much acid could produce hydrogen sulphide and worsen odour problems and health and safety issues. Acidification

of slurry to reduce ammonia emissions is now used operationally in Denmark at 125 farms, where the pH of slurry is reduced from c. 7.5 to c. 6.5. This approach is used both in the stable (giving and estimated 70% reduction in emissions) and in field application (giving an estimated 60% reduction). Adjacent to nature areas, shallow injection of manure is required. However, a new law in Denmark specifies that Trailing Hose/Trailing Shoe combined with slurry acidification in this manner is also compliant with the requirements.

164. bis *Addition of superphosphate and phosphogypsum.* According to many years of practice in the Russian Federation, an effective way to achieve a substantial reduction in losses of ammonia nitrogen from the storage and spreading of liquid manure and dung is the addition of superphosphate and phosphogypsum. Manure and phosphogypsum are used in a ratio of 20 to 1 depending on the retention periods, which reduces the emission of ammonia by 60%. The presence of phosphogypsum in composts based on manure and dung can increase the effectiveness of their use by half, especially when used for cruciferae crops (Novikov et al. 1989; Eskov et al., 2001). The main regulatory factor of using composts with phosphogypsum in an intensive mode is a dangerous excess accumulation of associated fluoride and strontium contaminants in soil. In the Russian Federation this practice represents the agricultural utilization of industrial phosphogypsum wastes arising from sulphuric acid manufacture. Care should be taken in nutrient management planning to match crop recommendations for both N and P, avoiding over supply of P.

Category 3 techniques

165. *Other additives*. Salts of calcium (Ca) and magnesium (Mg), acidic compounds (e.g. $FeCl_3$, $Ca(NO_3)_2$) and super-phosphate have been shown to lower NH_3 emission, but (with the exception outlined in paragraph 164) the quantities required are generally too large to be practically feasible. Absorbent materials such as peat or zeolites have also been used. There is also a range of commercially available additives, but in general these have not been independently tested.

VIII. FERTILIZER APPLICATION

(a) Urea-based fertilizers

166. Ammonia emission from fertilizer applications are dependant on fertilizer type, weather and soil conditions. Emissions from urea-based fertilizers are much greater than other fertilizer types because rapid hydrolysis of urea will cause localised rise in pH. Rapid hydrolysis often occurs in soils with a lot of urease enzyme due to an abundance of crop residue. Emissions from anhydrous ammonia may be significant when the injection in the soil is poor and the soil is not well covered following injection; success depends on having the right soil and soil moisture to allow the furrow to cloe well. Emissions from ammonium sulphate and diammonium phosphate are greater following application of these fertilizer types to calcareous (high pH) soils. Emission reduction techniques are therefore focused on applications of urea-based fertilizers to all soil types and of ammonium sulphate and diammonium phosphate applications to calcareous soils. Emission reduction techniques rely on either slowing the hydrolysis of urea to ammonium carbonate, or encouraging rapid transfer of the fertilizer into the soil (Sommer et al., 2004).

167. The use of methods to reduce ammonia emissions from urea-based compounds makes an important contribution to overall ammonia emission reductions in agriculture. In particular it should be noted that ammonia emissions from urea-based fertilizers (typically 5-40% nitrogen loss as ammonia) are much larger than those based on ammonium nitrate (typically 0.5-5% nitrogen loss as ammonia). Although ammonium nitrate is the main form of nitrogen fertilizer used in Europe, there remains an ongoing risk that its use might be restricted or prohibited in certain countries for security and/or safety consideration in the future. Already. due to security reasons and higher costs costs, ammonium nitrate has been largely replaced by urea forms throughout North America. Since the measures to reduce ammonia emissions from urea-based fertilizers remain limited in certain crops, especially on perennial crops, such a change would be expected to significantly increase regional ammonia emissions.

168. If applied at agronomically sensible rates and times, improved crop nitrogen uptake will be the main benefit of mitigating ammonia emissions, with minimal increases via the other loss pathways (e.g. nitrate leaching, denitrification). In addition, by reducing ammonia emissions, a similar reduction in indirect nitrogen losses is expected (e.g. by reduced leaching and denitrification from forest soils). Considering the whole system (agricultural land, non agricultural land and transfers by atmospheric dispersion), these measures are not generally expected to increase overall nitrate leaching or nitrous oxide loss. The measures focus on retaining nitrogen in the farming system, thereby maximizing productivity (see also the section on ‘Nitrogen management taking account of the whole nitrogen cycle).

169. *Reference technique.* The reference application technique is surface broadcast application of the nitrogen fertilizer. The effectiveness, limitations and cost of the low-emission application techniques are summarized in Table 16.

Category 1 techniques

170. Category 1 techniques for urea-based fertilizers include: urease inhibitors, slow-release coatings, soil injection, rapid soil incorporation, and irrigation immediately following application. Of these, soil injection, rapid soil incorporation, and irrigation immediately following application would also apply to ammonium sulphate (and diammonium phosphate) applications to calcareous soils.

171. *Urease inhibitors* delay the conversion of urea to ammonium carbonate by directly inhibiting the action of the enzyme urease. This delayed/slower hydrolysis is associated with a much smaller increase in pH around the urea prill and, consequently, a significantly lower ammonia emission (Chadwick et al., 2005; Watson et al., 1994). The delay to the onset of hydrolysis also increases the opportunity for the urea to be washed into the soil matrix, further reducing the potential for ammonia emissions. Approved urease inhibitors have been listed by the European Union (EC 1107/2008) (http://www.clrtap-tfrn.org/webfm_send/239).

172. *Polymer coated urea granules* provide a slow release fertilizer that may reduce ammonia emissions (e.g. Rochette et al., 2009), the extent to which will depend on the nature of the polymer coating and whether used with surface fertilizer application or combined with urea injection.

173. *Incorporation of fertilizer into the soil* either by direct closed-slot injection or by cultivation can be an effective reduction technique (Sommer et al., 2004). For urea prills, combining injection or incorporation with slow-release coatings may allow for a single fertilizer application prior to crop establishment negating the need for surface application at a later date. Depth of injection and soil texture will influence reduction efficiency. Mixing of the fertilizer with the soil through cultivation may be a less efficient reduction measure than injection to the same depth because a part of the mixed-in fertilizer will be close to the surface. For short season crops, the seasonal supply of N can be provided by injection of urea in the seeding operation saving time and money for the farmer. This has been widely adopted by farmers in Western Canada.

174. *Irrigation with at least 5 mm water* immediately following fertilizer application has been shown to reduce ammonia emissions by up to 70% (Oenema and Velthof, 1993; Sanz-Cobeña, 2010). Water should not be applied to wet soils beyond field capacity. This is only considered a category 1 technique where there is a water need for irrigation, as the method may otherwise increase the risk of nitrate leaching.

175. *Switching from urea to ammonium nitrate* fertilizer is a rather easy way to reduce ammonia emissions, with an effectiveness of around 90%. A possible negative side effect is the potential increase in nitrous oxide (N_2O), especially when the ammonium-nitrate based fertilizers are applied to moist or wet soils. The cost of this measure is simply the price differential between the two fertilizer types and the amounts of fertilizer N needed for optimum N fertilization. The gross cost of the ammonia nitrate fertilizer is higher that urea-based fertilizers, depending on market conditions (range 10-30%). However, the net cost may negligible or there may be a net gain, because of the lower N losses.

176. ***Potential cost implications.*** The increased cost of implementing these techniques will be offset to some extent (or provide a net benefit) by savings on fertilizer use to achieve the same yield as for the reference method, or an increased yield from the same rate of fertilizer application.

177. ***Impact on N cycle.*** If applied at agronomically sensible rates and times and placement, improved crop nitrogen uptake will be the main benefit of mitigating ammonia emissions, with minimal increases via the other loss pathways (e.g. nitrate leaching, denitrification). In addition, by reducing NH_3 emissions, a similar reduction in indirect nitrogen losses is expected (e.g. by reduced leaching and denitrification from forest soils). Considering the whole system (agricultural land, non agricultural land and transfers by atmospheric dispersion), these measures are not generally expected to increase overall nitrate leaching or nitrous oxide loss. The measures focus on retaining nitrogen in the farming system, thereby maximizing productivity.

Category 2 techniques

178. *Application timing management system (ATMS).* This represents a verified system to exploit the variation in ammonia emission potential based on environmental conditions, so as to use management of application timing to reduce overall emissions. Fertilizer applications under cooler conditions and prior to rainfall (although bearing in mind the need to avoid the associated risk of run-off to water bodies) are associated with lower ammonia emissions. If it is to be used, this strategy has to be associated with verification of the reference conditions and of the achieved reductions in emission.

179. *Mixing urea with ammonium sulphate.* Co-granulation of urea and ammonium sulphate may reduce ammonia emissions compared with urea alone on certain soil types (Oenema and Velthof, 1993). Further studies are required across more soil types before recommendations can be made.

Table 16: Mitigation options (Category 1) for reducing ammonia emissions from urea-based fertilisers.

Abatement measure	Fertilizer type	Emission reduction (%)	Factors affecting emission reduction	Applicability	Cost (€/kg NH3 abated /year)
Surface broadcast	Urea-based	Reference			
Urease inhibitor	Urea-based	70% for solid urea 40% for liquid urea ammonium nitrate		All	-0.5 – 2.0
Slow release fertilizer (polymer coatings)	Urea-based	c. 30%	Polymer coating type and integrity; fertilizer application technique (surface or injected)	All	-0.5 – 2.0
Closed-slot injection	Urea-based and anhydrous ammonia fertilizers	80-90%	Depth of placement; soil texture; closure of slot (improperly closed slots may lead to high emissions due to high concentration of urea in the slot increasing pH)	Tilled or reduced-till land prior to seeding or during the seeding operation or during the mechanical weed control operation after emergence	-0.5 – 1.0
Incorporation	Urea-based fertilizers	50-80%	Delay after fertilizer application; depth of mixing; soil texture	Tilled land prior to crop establishment	-0.5 – 2.0
Irrigation	All	40-70%	Irrigation timing and volume (immediate with c. 10mm is most effective); soil humidity; soil texture	Where crop irrigation is commonly practiced	-0.5 – 1.0
Substitution with ammonium nitrate	Urea-based and anhydrous ammonia fertilizers	Up to 90%	Under conditions where urea based fertilizers would have emissions of at least 40%.	All, especially where only surface application of fertilizer and no irrigation is possible	-0.5 – 1.0

Notes: 1. Local costs/benefits will vary, though trials have shown that the financial benefit of increased crop productivity can more than outweigh the costs of the technique for some abatement measures.

Category 3 techniques

180. *Band incorporation of urea.* This technique is not recommended on soils with high urease activity (e.g. with crop residue) and poor ability to adsorb urea as it can be associated with increased ammonia emissions in comparison with the reference technique (e.g. Rochette et al., 2009).

(b) Ammonium sulphate, phosphate and nitratebased fertilizers

181. *Reference technique.* The reference application technique is the surface application of ammonium sulfate and ammonium phosphate fertilizers.

Category 1 techniques

182. Several of the techniques described above for urea can also be used to reduce ammonia emissions from ammonium sulfate and ammonium phosphate based fertilizers. The highest risks occur when these fertilizers are applied on calcareous or other high pH soils. Category 1 techniques for ammonium sulphate and ammonium phosphate based fertilizers include: incorporation, injection, immediate irrigation and slow release fertilizers with polymer coatings on high-pH soils (subject to the result of trials).

Category 2 techniques

183. Emissions from non-urea fertilizers such as ammonium nitrate and calcium ammonium nitrate are small, but may occur partly as a result of direct fertilizer emission and partly from indirect emission resulting from plants as a consequence of fertilization. Grass cutting also contributes to the NH_3 emissions, with emissions arising from the re-growing sward as a consequence of cutting-induced N mobilization in the vegetation. Fertilizing grassland within the first few days after cutting provides surplus N resulting in a larger emission from the combined effects of cutting and fertilization. Delaying N fertilizer application following cutting allows the grass to recover thereby reducing NH_3 emissions. Model analysis found that a two-week delay in N fertilization reduced total (net annual) NH_3 emissions from cut and fertilized grassland by 15 per cent. Similar effects may be achieved with different timing depending on regional conditions. However, this practice is will cost herbage yield. Given the interactions with weather and the need for further work to identify the optimum delay in relation to different management systems, this is classed as a category 2 technique. The approach may be integrated into Application Timing Management Systems.

IX. OTHER MEASURES RELATED TO AGRICULTURAL NITROGEN

(a) Grazing

184. Urine excreted by grazing animals often infiltrates into the soil before substantial NH_3 emissions can occur. Therefore, NH_3 emissions per animal are less for grazing animals than for those housed where the excreta is collected, stored and applied to land. The emission reduction achieved by increasing the proportion of the year spent grazing will depend, inter alia, on the baseline (emission of ungrazed animals), the time the animals are grazed, and the N fertilizer level of the pasture. The potential for increasing grazing is somtimes limited by land availability, soil type, topography, farm size and structure (distances), climatic conditions, economic considerations, etc. It should be noted that additional grazing of animals may increase other forms of N emission (e.g. N_2O, NO_3). However, given the clear and well quantified effect on NH_3 emissions, this can be classed as a category 1 technique (in relation to modification of the periods when animals are housed or grazed for 24 hours a day). The abatement efficiency may be considered as the relative total NH_3 emissions from grazing versus housed systems (see also provisions 40 and 52).

185. The effect of changing the period of partial housing (e.g. grazed during daytime only) is less certain and is rated as a category 2 technique. Changing from a fully housed period to grazing for part of the day is less effective in reducing NH_3 emissions than switching to complete (24 hour) grazing, since buildings and stores remain dirty and continue to emit NH_3 (see also provisions 40 and 52).

(b) Manure treatment

186. Research on various options of reducing NH_3 emissions by manure treatment have been investigated. Some potentially promising options are:

(a) Composting of solid manure or slurry with added solids: experimental results are very variable and often show increased NH_3 emissions; for this reason, systems for composting of manure should consider the inclusion of additional methods to reduce NH_3 emissions from this source, such as covers and air scrubbing systems.
(b) Controlled denitrification processes in the slurry: pilot plants show that it might be possible to reduce NH_3 emissions by transforming ammonium to N_2 gas by controlled denitrification (alternating aerobic and anaerobic conditions). To achieve this, a special reactor is necessary. The efficiency and the reliability of the system and its impact on other emissions need further investigation.
(c) Manure separation to remove P or to provide bedding. Emissions from these systems need to be investigated.

187. The efficiency of manure treatment options should generally be investigated under country- or farm-specific conditions. Apart from NH_3 emissions, other emissions, nutrient fluxes and the applicability of the system under farm conditions should be assessed. Due to the mentioned uncertainties, these measures generally have to be grouped in categories 2 or 3. An exception is the use of air scrubbing systems for manure composting facilities (Category 1), which are well-tested but have significant costs.

(c) Non-agricultural manure use

188. If manure is used outside of agriculture, agricultural emissions may be reduced. Examples of such uses already common in some countries are the incineration of poultry manure and the use of horse and poultry manure in the mushroom industry. The emission reduction achieved depends on how fast the manure is taken away from the farm and how it is treated. An overall reduction of the emissions will only be achieved if the use of the manure itself does not generate large emissions (including other emissions than NH_3). For example, the use of manure in horticulture or the export of manure to other countries will not reduce overall emissions. There are also other environmental aspects to be considered, for example, poultry litter incineration is a renewable source of energy, but not all the nutrients in the litter will be recycled within agriculture.

X. NON-AGRICULTURAL STATIONARY AND MOBILE SOURCES

189. There are many non-agricultural sources of NH_3, including motor vehicles, waste disposal, residential solid-fuel combustion, and various industries, of which fertilizer production is likely to be the most significant across Europe. There is also a small, but collectively significant group of natural sources, including, for example, human breath and sweat and emissions from wild animals (Sutton et al. 2000). The UNECE Protocols for reporting emissions do not currently distinguish between natural and anthropogenic sources in the same way that they do for volatile organic compounds (VOCs).

190. A common factor across many of these sectors is that NH_3 emissions have previously been ignored. This is most notable with respect to transport, as shown below. A first recommendation for reducing NH_3 emissions from non-agricultural sources is therefore to ensure that NH_3 is considered when assessing the performance of industry and other sources. Where NH_3 emissions are found to arise, or are likely to increase through some technical development, it will be appropriate for operators and designers to consider ways in which systems may be optimized to avoid or minimize emissions.

(a) General techniques

191. *Venturi scrubbers* are suitable for large gas flows bearing large concentrations of NH_3. Abatement costs are in the region of €3,500 /ton, excluding effluent treatment costs. As in all cases discussed in this section, the precise cost-effectiveness will vary according to the size of plant, NH_3 concentrations and other factors.

192. *Dilute acid scrubbers*, consisting of a tower randomly packed with tiles through which slightly acidic water is circulated, are suitable for dealing with flows of between 50 and 500 tons per year. Barriers to the technology include its limited suitability for large volume gas flows, potentially high treatment costs for effluents, and safety hazards linked to storage of sulphuric acid. Reported costs show much variability, from €180 to €26,000 /ton NH_3. Variation is again largely a function of plant size and NH_3 flow rate.

193. Regenerative thermal oxidation uses a supplementary fuel (typically natural gas) to burn NH_3 present in a gas stream, with costs reported in the range of €1,900 to €9,100 /ton of NH_3.

194. Biofiltration is suitable for low-volume gas flows with low concentrations of NH_3, abating emissions of around 1 ton per year. It is the least cost system for small sources. Abatement costs of €1,400 to €4,300 /ton have been reported, depending on sector.

195. Abatement efficiencies of the techniques described in this section are typically around 90 per cent.

(b) Techniques suited to selected sectors

196. *Emissions of NH_3 from road transport* increased greatly in the 1990s as a result of the introduction of catalyst-equipped vehicles (an estimate for the United Kingdom shows a factor of 14 increase over this period). The problem is largely being resolved through the introduction of better fuel management systems, moving from carburetor control to computerized systems that exercise much tighter control over the ratio of air to fuel. Moves to reduce the sulphur content of fuels, some methods for NOx control from diesel-engine vehicles, and the use of some alternative fuels may start to increase emissions. Despite the consequences for NH_3 of all of these actions, it has not been considered as a priority pollutant by either vehicle manufacturers or by regulators. It is therefore important that for this and other sectors, account be taken of the impact of technological changes on NH_3 emissions. By doing so, actions can be undertaken to avoid or minimize emissions during the design phase, where potential problems are identified.

197. *Ammonia slippage in stationary catalytic reduction plant.* For a number of sectors, the most significant source of NH_3 release may be linked to the slippage of NH_3 from NOx abatement plant. Two types of technique are available, scrubbing NH_3-slip from the flue gases, which can reduce emissions from about 40 mg/m^3 by around 90 per cent, and more effective control of NO_x control equipment. The potential for NH_3 emissions from this source will need to be considered carefully as NO_x controls increase through wider adoption of BAT.

198. *Non-evaporative cooling systems* are applicable to the sugar beet industry. These systems are more than 95 per cent effective in reducing emissions. Costs are estimated at €3,500/ton NH_3 abated.

199. *Emissions from domestic combustion* can be reduced using a wide variety of techniques, ranging from the adoption of energy efficiency measures, to the use of better quality fuels, to optimization of burning equipment. There are significant barriers to the introduction of some of these options, ranging from the technical (e.g. lack of natural gas infrastructure) to the aesthetic (e.g. people liking the appearance of an open wood burning fire).

200. *Capping landfill sites.* Waste disposal by landfilling or composting has the potential to generate significant amounts of NH_3. Actions to control methane emissions from landfill, such as capping sites and flaring or utilizing landfill gas are also effective in controlling NH_3.

201. *Biofiltration* (see above) is effectively used at a number of centralized composting facilities, often primarily for control of odours, rather than NH_3 specifically. A more general technique, applicable to home composting as well as larger facilities, is to control the ratio of carbon to nitrogen, aiming for an optimum of 30:1 by weight.

202. *Horses.* Assessment needs to be undertaken of the extent to which emissions from horses are included in the agricultural and non-agricultural inventories. Many horses are kept outside of farms and so may be excluded from agricultural inventories. The most effective approach for reducing emissions from these sources is good housekeeping in stables, with provision of sufficient straw to soak up urine, and daily mucking out. More sophisticated measures for controlling emissions, such as the use of slurry tanks are unlikely to be implemented at small stables, but are described elsewhere in this document.

(c) Production of inorganic N fertilizers, urea and ammonia

203. The most important industrial sources of NH_3 emissions are mixed fertilizer plants producing ammonium phosphate, nitrophosphates, potash and compound fertilizers, and nitrogenous fertilizer plants manufacturing, inter alia, urea and NH_3. Ammonia phosphate production generates the most NH_3 emissions from the sector. Ammonia in uncontrolled atmospheric emissions from this source has been reported to range from 0.1 to 7.8 kg N/ton of product.

204. Nitrogenous fertilizer manufacture covers plants producing NH_3, urea, ammonium sulphate, ammonium nitrate and/or ammonium sulphate nitrate. The nitric acid used in the process is usually produced on site as well. Ammonia emissions are particularly likely to occur when nitric acid is neutralized with anhydrous NH_3. They can be controlled by wet scrubbing to concentrations of 35 mg NH_3/m^3 or lower. Emission factors for properly operated plants are reported to be in the range 0.25 to 0.5 kg NH_3/ton of product.

205. Additional pollution control techniques beyond scrubbers, cyclones and baghouses that are an integral part of the plant design and operations are generally not required for mixed fertilizer plants. In general, an NH_3 emission limit value of 50 mg $NH_3\text{-}N/m^3$ may be achieved through maximizing product recovery and minimizing atmospheric emissions by appropriate maintenance and operation of control equipment.

206. In a well-operated plant, the manufacture of NPK fertilizers by the nitrophosphate route or mixed acid routes will result in the emission of 0.3 kg/ton NPK produced and 0.01 kg/ton NPK produced (as N). However, the emission factors can vary widely depending on the grade of fertilizer produced.

207. Ammonia emissions from urea production are reported as recovery absorption vent (0.1-0.5 kg NH_3/ton of product), concentration absorption vent (0.1-0.2 kg NH_3/ton of product), urea prilling (0.5-2.2 kg NH_3/ton of product) and granulation (0.2-0.7 kg NH_3/ton

of product). The prill tower is a source of urea dust (0.5-2.2 kg NH_3/ton of product), as is the granulator (0.1-0.5 kg/ton of product as urea dust).

208. In urea plants, wet scrubbers or fabric filters are used to control fugitive emissions from prilling towers and bagging operations. This control equipment is similar to that in mixed fertilizer plants, and is an integral part of the operations to retain product. If properly operated, new urea plants can achieve emission limit values of particular matter below 0.5 kg/ton of product for both urea and NH_3.

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Appendix 1. Supplementary Information

Guidance Document for Preventing and Abating Ammonia Emissions from Agricultural Sources of the Gothenburg Protocol:

B. Nitrogen management, taking account of the whole nitrogen cycle

1. Management is commonly defined as 'a coherent set of activities to achieve objectives'. This definition applies to all sectors of the economy, including agriculture. Nitrogen management can be defined as 'a coherent set of activities related to nitrogen use in agriculture to achieve agronomic and environmental/ecological objectives' (e.g., Oenema and Pietrzak, 2002). The agronomic objectives relate to crop yield and quality, and animal performance in the context of animal welfare. The environmental/ecological objectives relate to nitrogen losses from agriculture. 'Taking account of the whole nitrogen cycle' emphasizes the need to consider all aspects of nitrogen cycling, also in 'NH_3 emissions abatement', to circumvent 'pollution swapping'.

2. Nitrogen is a constituent of all plant and animal proteins (and enzymes) and it is involved in photosynthesis, eutrophication, acidification, and various oxidation-reduction processes. Through these processes, nitrogen changes in form (compounds), reactivity and mobility. Main mobile forms are the gaseous forms di-nitrogen (N_2), ammonia (NH_3), nitrogen oxides (NO and NO_2), and nitrous oxide (N_2O), and the water soluble forms nitrate (NO_3^-), ammonium (NH_4^+) and dissolved organically bound nitrogen (DON). In organic matter, most nitrogen is in the form of amides, linked to organic carbon ($R\text{-}NH_2$). Because of the mobility in both air and water, reactive nitrogen is also called 'double mobile'.

3. The nitrogen cycle is strongly linked with the carbon cycle and with other nutrient cycles. Hence, managing nitrogen may affect the cycling of carbon and the net release of carbon dioxide (CO_2) into the atmosphere and the sequestration of carbon in soils. Generally, a leaky system for nitrogen is also a leaky system for carbon, and vice versa. This re-iterates the importance of considering N management from a whole-farm perspective.

4. Depending on the type of farming systems, N management at farm level involves a series of management activities in an integrated way, including:

- Fertilization of crops;
- Crop growth, harvest and residue management;
- Growth of catch or cover crops;
- Grassland management;
- Soil cultivation, drainage and irrigation;
- Animal feeding;
- Herd management (including welfare considerations), including animal housing
- Manure management, including manure storage and application;
- Ammonia emission abatement measures;
- Nitrate leaching and runoff abatement measures;

- Nitrous oxide emission abatement measures;
- Denitrification abatement measures;

To be able to achieve high crop and animal production with minimal N losses and other unintended environmental consequences, all activities have to be considered in an integrated and balanced way.

5. Nitrogen is essential for plant growth. In crop production, it is often the most limiting nutrient, and therefore must be available in sufficient amount and in a plant-available form in soil to achieve optimum crop yields. Excess and/or untimely N applications are the main source of N losses in the environment, including ammonia emissions to air. To avoid excess or untimely N applications is one of the best ways to minimize N losses (and other environmental impacts), while not affecting crop and animal production. Guidelines for site-specific best nutrient management practices should be adhered to, including:

- Nutrient management planning and record keeping, for all essential nutrients;
- Calculation of the total N requirement by the crop on the basis of realistic estimates of yield goals, N content in the crop and N uptake efficiency by the crop;
- Estimation of the total N supply from indigenous sources, using accredited methods:
    - mineral N in the upper soil layers at planting and in-crop stages (by soil and or plant tests);
    - mineralization of residues of the previous crops;
    - net mineralization of soil organic matter, including the residual effects of livestock manures applied over several years and, on pastures, droppings from grazing animals;
    - deposition of reactive N from the atmosphere;
    - biological N_2 fixation by leguminous plants;
- Computation of the needed N application, taking account of the N requirement of the crop and the supply by indigenous N sources;
- Calculation of the amount of nutrients in livestock manure applications that will become available for crop uptake. The application rate of manure will depend on:
    - the demands for nitrogen, phosphorus and potassium by the crops;
    - the supply of nitrogen, phosphorus and potassium by the soil, based on soil tests;
    - the availability of livestock manure;
    - the immediately-available nitrogen, phosphorus and potassium contents in the manure; and
    - the rate of release of slowly-available nutrients from the manure, including the residual effects.
- Estimation of the needed fertilizer N and other nutrients, taking account of the N requirement of the crop and the supply of N by indigenous sources and livestock manure;
- Application of livestock manure and/or N fertilizer shortly before the onset of rapid crop growth, using methods and techniques that prevent ammonia emissions;
- Where appropriate, application of N fertilizer in multiple portions (split dressings) with in-crop testing, where appropriate.

6. Preferred measures for reducing overall NH_3 emissions are those that decrease other unwanted N emissions simultaneously, while maintaining or enhancing agricultural productivity (measures with synergistic effects). Conversely, measures aimed at reducing NH_3 emissions, which increase other unwanted emissions (antagonistic effects) should be modified to such extent that the antagonistic effects are minimized. Such antagonistic effect may include increased methane (CH_4) emissions from ruminants. Similarly, abatement measures should avoid increasing other types of farm pollution (e.g., P losses, pathogens, soil erosion) or resource use (e.g., fuel), reducing the quality of food (e.g., increased antibiotics, hormones or pesticides) or detrimentally impacting the health and welfare of farm animals (e.g., by limiting barn size or animal densities) (Jarvis et al., 2011).

7. The effectiveness of nitrogen management can be evaluated in terms of (i) decreases of nitrogen surplus, and (ii) increases of N use efficiency. Nitrogen use efficiency (NUE) indicators provide a measure for the amount of N that is retained in crop or animal products, relative to the amount of nitrogen applied or supplied. N surplus is an indicator for the N pressure of the farm on the wider environment, also depending on the pathway through which surplus N is lost either as ammonia volatilization, N leaching and/or nitrification/ denitrification. Management has a large effect on both the nitrogen use efficiency (Tamminga 1996; Mosier et al., 2004) and N surplus.

8. While the ratio of total N output (via products exported from the farm) and total N input (imported into the farm, including via biological N_2 fixation) (mass/mass ratios) is an indicator for the N use efficiency at farm level, the total N input minus the total N output (mass per unit surface area) is an indicator of the N surplus (or deficit) at farm level.

9. Commonly, a distinction is made between N input-output balances and N input-output budgets. Balances and budgets apply similar input items; the main difference is that balances record the N output in harvested/marketable products only, while budgets records the N output via harvested/marketable products and losses from the system. Hence, budgets provide a full record and account of all N flows.

10. There are various procedures for making nitrogen input-output balances, including the gross nitrogen balance, the soil-surface balance, the farm-gate balance, and the farm balance (e.g., Watson et al., 1999; Schroder et al., 2003; Oenema et al., 2003; OECD, 2008;). Basically, the gross nitrogen balance and the soil-surface balance record all N inputs to agricultural land and all N outputs in harvested crop products from agricultural land. However, the balances differ in the way they account for the N in animal manure; the gross nitrogen balance includes the total amount of N excreted as N input item, while the soil-surface balance corrects the amount of N excreted for NH_3 losses from manure in housing systems and manure storage systems. The farm-gate balance and the farm balance records all N inputs and all N outputs of the farm; the farm balance includes N inputs via atmospheric deposition (both reduced and oxidized N compounds) and biological N_2 fixation. Various methods can be applied at field, farm, regional and country levels; it is important to use standardized formats for making balances and to report on the methodology, so to improve comparability.

11. A farm nitrogen budget of a mixed crop-animal production farm is the most complex budget (Figure S1). The main inputs are mineral/inorganic fertiliser, imported animal manure, fixation of atmospheric nitrogen (N_2) by some (mainly leguminous) crops, deposition from the atmosphere, inputs from irrigation water and livestock feed. Inputs in seed and bedding used for animals are generally minor inputs, although the latter can be significant for some traditional animal husbandry systems. The main outputs are in crop and animal products, and in exported manure. Gaseous losses occur from manure in animal housing, in manure storage and after field application. Other gaseous losses occur from fields; from applied fertiliser, crops, soil and crop residues. Losses to ground and surface water occur via leaching or run off of nitrates, ammonium and dissolved organic nitrogen (DON). Run-off of undissolved organic N may also occur.

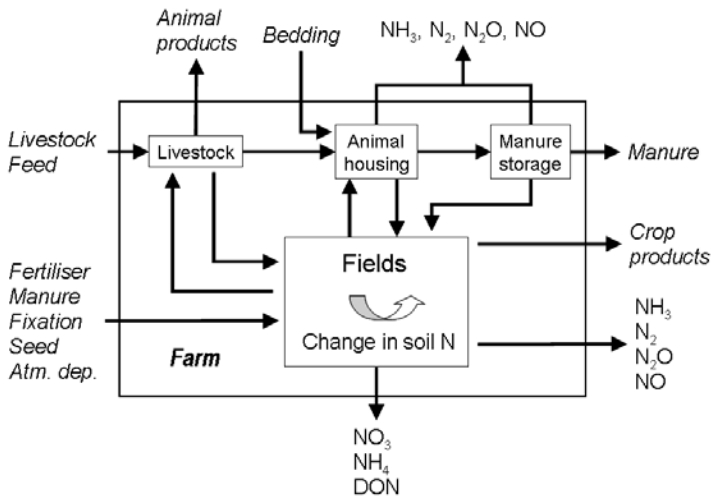

Figure S1. A farm N budget of a mixed crop-animal production farm (from Jarvis et al., 2011).

12. The corresponding components of a farm nitrogen balance of a mixed crop-animal production farm are shown in Figure S2. Evidently, a farm N balance is much simpler than a farm N budget, as N losses to air, groundwater and surface waters are not included in the N balance. A farm N balance of a specialized crop production farm or a specialized animal production farm are much simpler than a farm gate-balance of a mixed crop-animal production farm, because of less types of N inputs and outputs.

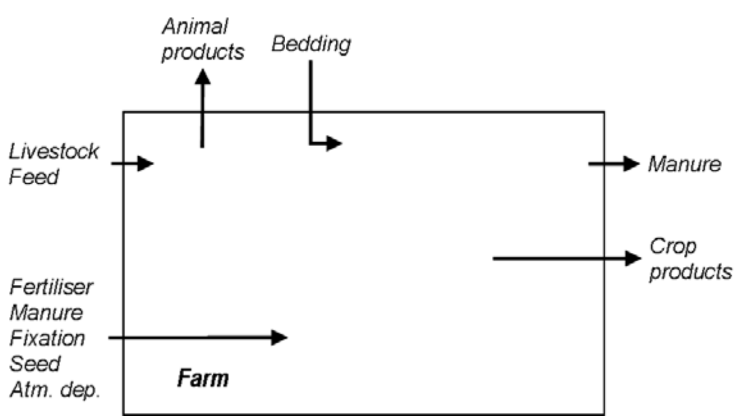

Figure S2: Components of a farm N balance of a mixed crop-animal production farm.

13. A soil surface nitrogen balance of agricultural land is shown in figure S3. The main N inputs are mineral/inorganic fertiliser, animal manure, fixation of atmospheric nitrogen by some (mainly leguminous) crops and deposition from the atmosphere. Other N inputs may include bio-solids, and organic amendments like compost and mulches. Inputs in seed and composts are generally minor inputs. The main outputs are in harvested crop products, which may be the grain or the whole crop. Note that animal products other than animal manure do not show up in the soil surface balance, as they are not placed onto the soil surface.

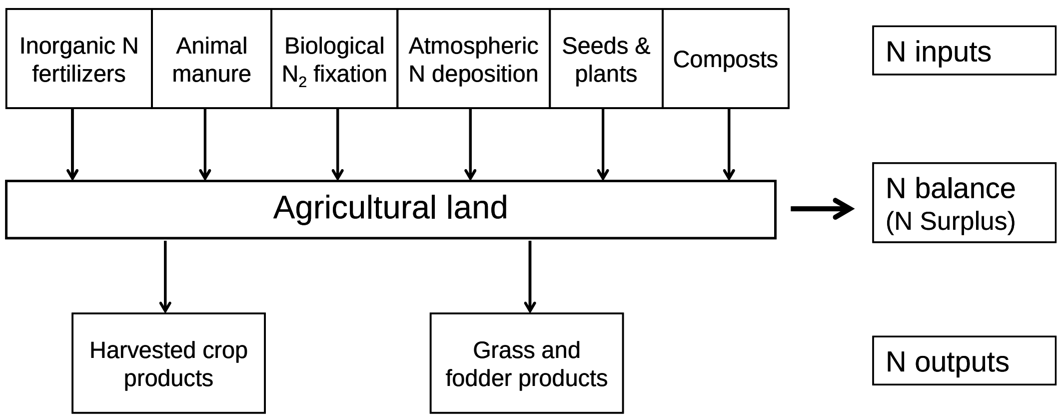

Figure S3: Components of a soil surface nitrogen balance of agricultural land (see OECD, 2008).

14. For using N balances and N use efficiency (NUE) as indicators at farm level, a distinction has to be made between:

(a) specialized crop production farms,
(b) mixed crop (feed) – animal production farms and
(c) specialized animal production farms.

Specialized crop production farms have relatively few NH_3 emission sources (possibly imported animal manure, urea and ammonium-based fertilizers, crops and residues). These farms can be subdivided according to crop rotation (e.g., percentage of cereals, pulses, vegetables and root crops). Specialized animal production farms produce only animal products (milk, meat, egg, animal by-products and animal manure) and all these products are exported from the farm. Energy may also be produced through digestion of organic carbon. These farms can be subdivided according to animal categories (e.g., pig, poultry, and cattle). Mixed systems have both crops and animals; the crops produced are usually fed to the animals, while the manure produced by the animals is applied to the crop land. These farms can be subdivided according animal categories (e.g., dairy cattle, beef cattle, pigs, and) and livestock density (or feed self-sufficiency).

15. The variation between farms in NUE (output/input ratios) and N surpluses (input minus output) is large in practice, due to the differences in management and farming systems (especially as regards the types of crops and animals, the livestock density and the farming

system). Indicative ranges can be given for broad categories of farming systems (see Table S2).

16. Nitrogen balances and N output-input ratios can be made also for compartments within a farm, especially within a mixed farming system. For estimating NUE, three useful compartments or levels can be considered:

(a) feed N conversion into animal products (feed-NUE or animal-NUE),
(b) manure and fertilizer N conversion into crops (manure/fertilizer-NUE), and
(c) whole-farm NUE.

These NUEs are calculated as the percentage mass of N output per mass of N input:
- feed-NUE = [(N in milk, animals and eggs) / (N in feed and fodder)] x 100%
- manure/fertilizer-NUE = [N uptake by crops / N applied as manure/fertilizer] x 100%
- whole-farm NUE = [Σ(N exported off-farm) / Σ(N imported on to the farm)] x 100%

Indicative ranges of NUEs for dairy farms are shown below in Table S1(Powel et al., 2010).

Table S1. Indicative values for N input and NUE of dairy farms (from Powell et al., 2010)

Input to output parameters	N input range	NUE range (%)	Source
Feed to milk (feed-NUE)	512–666 g cow^{-1} day^{-1}	26–33	Powell et al. (2006a)
	289–628 g cow^{-1} day^{-1}	22–29	Kebreab et al. (2001)
	200–750 g cow^{-1} day^{-1}	21–32	Castillo et al. (2000)
	496–897 g cow^{-1} day^{-1}	21–36	Chase (2004)
	838–1360 g cow^{-1} day^{-1}	16–24	Aarts et al. (2000)
Manure and fertilizer to crops and pasture (manure/fertilizer-NUE)	359–749 kg ha^{-1}	53–77	Aarts et al. (2000)
	Not available	16–57	Beegle et al. (2008)
Farm inputs to farm outputs (whole-farm NUE)	215–568 kg ha^{-1}	14–55	Rotz et al. (2006)
	150–370 kg ha^{-1}	39–47	Rotz et al. (2006)
	260–380 kg ha^{-1}	23–36	Rotz et al. (2005)
	240–423 kg ha^{-1}	34–46	Rotz et al. (1999)
	63–840 kg ha^{-1}	8–55	Ovens et al. (2008)
	Not available	25–64	Histov et al. (2006)

17. For assessing the feed-NUE or animal-NUE, the amounts of feed + fodder consumed and the N contents of the feeds + fodders have to be known. Also the amounts of N in animal products (protein in milk, meat and eggs) have to be known. Default values can be used for N in milk-protein, eggs and live-weight, carcass-weight and meat for cattle, pigs, and poultry.

Table S2: Nitrogen surplus and nitrogen use efficiency indicators of farming systems, with typical values for specialized crop production farms, specialized animal production farms and mixed farms (see text).

Index	Calculation	Interpretation	Typical levels
N surplus = sum of all nitrogen inputs minus the nitrogen outputs that pass the farm gate, expressed in kg/ha/yr	N surplus = Σ (Inputs$_N$) – Σ (outputs$_N$)	•N surplus depends on types of farming system, crops and animals, and indigenous N supply, external inputs (via fertilizers and animal feed) management and environment •N surplus is a measure of the total N loss to the environment •N deficit [Σ (Inputs$_N$) < Σ (outputs$_N$] is a measure of soil N depletion •For specialized animal farming systems (landless), the N surplus can be very large, depending also on the possible N output via manure processing and export	Depends on types of farming systems, crops and animals: Crop: 0-50 kg/ha Mixed: 0-200 kg/ha Animal: 0-1000 kg/ha
NUE = nitrogen use efficiency, i.e., the N output in useful products divided by the total N input	NUE = Σ (outputs$_N$) / Σ (Inputs$_N$)	•N use efficiency depends on types of farming system, crops and animals, and indigenous N supply, external inputs (via fertilizers and animal feed) management and environment •For specialized animal farming systems (landless), there may be N output via manure processing and export	Depends on types of farming systems, crops and animals: Crop 0.6-1.0 Mixed: 0.5-0.6 Animal 0.2-0.6* Animal 0.8-0.95** *) no manure export **) landless farms; all manure exported off-farm

18. For assessing the manure/fertilizer-NUE, it is useful to make a distinction between different N input sources. The ‘fertilizer N equivalence value’ indicates how well N from animal manures, composts and crop residues are used relative to the reference fertilizer (commonly NH_4NO_3 based fertilizers), which is set 1 (100%). A high value is indicative for a high N use efficiency. The fertilizer N equivalence value depends on the type (solid, slurry or liquid), origin (cattle, pigs, poultry) of manure and the time frame (year of application versus long-term effects). It also depends on crop type and environmental conditions (soil type, temperature, rainfall). A most decisive factor for a high fertilizer N equivalence value is management, i.e. the time and method of application. Table 3 gives ranges of N fertilizer equivalence values for cattle, pig and poultry manure, slurries and liquid manures, as found in literature. Organic N sources usually contain a significant fraction organically-bound N, which becomes available to growing crops only after mineralization. Therefore, a distinction is made between short-term (i.e. during the growing season immediately after application of the organic N source) and long-term fertilizer N equivalence values; the latter being higher than the former. Some organic N sources have only mineral N and easily mineralizable organic N, and as a consequence there is essentially no difference between short-term and long-term values.

Table S3: Ranges of short-term and long-term fertilizer nitrogen equivalence values (FNEV) of applied animal manures and crop residues, expressed in percentage of the reference fertilizer ammonium-nitrate. The manures are applied with common low-emission application techniques. The short-term fertilizer nitrogen equivalence values relate to the fertilizer nitrogen equivalence value of timely applications during the year of application. The long-term fertilizer nitrogen equivalence values include residual effects and assume repeated annual applications.

Nitrogen sources	**Fertilizer nitrogen equivalence values, %**	
	Short-term	**Long-term**
Separated cattle and pig liquid manures	70-100	70-100
Digested cattle and pig slurries	40-60	50-80
Cattle slurries	30-50	50-80
Pig slurries	30-65	50-80
Poultry slurries	30-65	50-80
Solid cattle, pig and poultry manures	20-40	40-60
Composts of cattle, pig and poultry manures	20-40	40-60
Urine and dung from grazing animals	10-20	20-40
Crop residues with more than 2.5% N	10-40	30-50
Crop residues with 1.5 – 2.5% N	0-30	20-40
Crop residues with less than 1.5% N	0	0-20

References: Berntsen et al., 2007; Bittman et al., 2007; Burton and Turner, 2003; Chadwick et al., 2000; Gutser et al., 2005; Hadas et al., 2002; Hart et al., 1993; Hatch et al., 2004; Janssen, 1984; Jenkinson and Smith, 1988; Kolenbrander and De La Lande Cremer, 1967; Langmeier et al., 2002; MacDonald et al., 1997; Mosier et al., 2004; Nevens and Reheul, 2005; Rufino et al., 2006; Rufino et al., 2007; Schils and Kok, 2003; Schroder et al., 2000; Schroder and Stevens, 2004; Schroder 2005; Schroder et al., 2005; Schroder et al., 2007; Sommerfeldt et al., 1988; Sorensen, 2004; Sorensen and Amato, 2002; Sorensen et al., 2003; Sorensen and Thomsen, 2005; Van der Meer et al., 1987; Velthof et al., 1998;

19. For whole-farms, the N surplus and NUE of specialized crop production farms are estimated as follows:

SurplusN = [FertN + ManureN + CompostN + BNF + Atm.N + SeedN] – [CropN] [1]

NUEcrop = [CropN] / [FertN + ManureN + CompostN + BNF + Atm.N + SeedN] [2]

Where,

SurplusN =	N Surplus at farm level, kg/ha
NUEcrop =	N use efficiency at farm level, mass/mass ratio (dimensionless)
FertN =	Amount of fertilizer N fertilizer imported to the farm, kg/ha
ManureN =	Amount of manure N imported to the farm, kg/ha
CompostN =	Amount of compost N imported to the farm, kg/ha
BNF=	Amount of biologically fixed N_2 by leguminous crops, kg/ha
Atm.N =	Amount of N from atmospheric deposition, kg/ha.
SeedN =	Amount of N imported via seed and plants, kg/ha.
CropN =	Net amount of N in harvested crop exported from the farm, including residues, kg/ha

There may be additional N inputs at the farm via for example autotrophic N_2 fixation, crop protection means, irrigation water, biosolids, mulches. These inputs are usually small relative to the former and are also difficult to manage. Therefore, these additional N inputs are often disregarded. However, when these inputs are a significant percentage of the total input (>10%), they should be included in the balance calculations. This may hold for farms on organic soils where the net mineralization of organically bound N may release 20-200 kg of N per ha per year, depending on the trophic status of the peat and drainage conditions.

20. A more accurate expression of the N use efficiency and N surplus of specialized crop production farms takes into account the differences in fertilizer N equivalence values of manure, composts and BNF, and is estimated as follows:

NUEcrop = [CropN] / [FertN+(ManureN x FnevM)+(CompostN x FnevC)+(BNF)+Atm.N+ SeedN] [7]

Where,
FnevM = fertilizer N equivalence value for manure, kg/kg
FnevC = fertilizer N equivalence value for compost, kg/kg

21. For specialized landless animal production farms, the N surplus and NUE are estimated as follows:

SurplusN = [FeedN] – [AnimalN + ManureN] [3]

NUEanimal = [AnimalN + ManureN] / [FeedN] [4]

Where,
SurplusN = N Surplus at farm level, kg
NUEanimal = N use efficiency at farm level, mass/mass ratio (dimensionless)
FeedN = Net amount of N in animal feed imported to the farm, kg
AnimalN = Net amount of N in animals exported from the farm (i.e., including dead animals and corrected for imported animals), kg
ManureN = Net amount of manure N exported from the farm (including feed residues), kg

There will be small additional N inputs at the farm via for example drinking and cleaning water, litter (bedding material) and medicines but these inputs are usually small (<5%) relative to the former and may be disregarded in this case.

22. For mixed crop – animal production farms, the N surplus and NUE are estimated as follows:

SurplusN = [FertN+ FeedN + $ManureN_i$ +CompostN+BNF+Atm.N+SeedN]–[AnimalN + CropN + $ManureN_e$] [5]

NUEmixed=[AnimalN+CropN+$ManureN_e$]/[FertN+ FeedN + $ManureN_i$+CompostN+BNF+Atm.N+SeedN] [6]

Where,
SurplusN = N Surplus at farm level, kg/ha
FertN = Amount of fertilizer N fertilizer imported to the farm, kg/ha
FeedN = Amount of N in animal feed imported to the farm, kg/ha
$ManureN_i$ = Amount of manure N imported to the farm, kg/ha
CompostN = Amount of compost N imported to the farm, kg/ha
BNF= Amount of biologically fixed N_2 by leguminous crops, kg/ha
Atm.N = Amount of N from atmospheric deposition, kg/ha.
SeedN = Amount of N imported via seed and plants, kg/ha.
CropN = Amount of N in harvested crop exported from the farm, including residues, kg/ha
AnimalN = Amount of N in animals exported from the farm (i.e., including dead animals and corrected for imported animals), kg
$ManureN_e$ = Amount of manure N exported from the farm, kg/ha

23. Improvements in N management (and hence decreases in N losses) over time follow from decreases in N surpluses and increases in N use efficiencies over time. Progress in N management can thus be assessed through the monitoring of the annual N surplus and N use efficiency at farm level. To account for annual variations in weather conditions and incidental occasions, it is recommended to calculate five-year averages of N surplus and NUE.

24. The relative performance of the N management of farms can be assessed on the basis of comparisons with other farms, model farms or experimental farms. Target values for N surpluses and NUE of specialized crop production systems can be based on the performance of best managed (experimental/model) crop production systems in practice taking soil factors into account.

25. Crops differ in their ability to take up N from soil, due to differences in root length distribution and length of the growing season. Graminae (cereals and grassland) have a high uptake capacity; leafy vegetable (lettuce, spinach) a small uptake capacity. Indicative target values for N surplus and NUE should be specified according to the areal fraction of cereals and grassland on the farm (e.g. in case of five classes: <25%; 25-50, 50 – 75, 75 - 90 and >90%) (Table S4).

26. For specialized crop production farms growing cereals on > 90% of the area, and using the input items of equation [7] and Fertilizer N equivalence values (FNEV) of Table 3, the harvested N roughly equals the total effective N input and NUEcrop may be up to 100%. However, NUEcrop decreases with increasing N input, impact of pests, or limitation of other nutrients; the challenge is to find the optimum N fertilization level where both crop yield, crop quality and NUE are high and N surplus is low. With decreasing relative area of cereals in the crop rotation, target NUE will decrease and N surpluses will increase, depending also on the effective N input (Table S4). The N surplus and NUE also depend on the fate of the crop residue; harvesting and withdrawal of the crop residues increases NUE and decreases N surplus, especially at short term. However, removing crop residues may contribute ultimately to decreasing stocks of soil organic matter and nitrogen. Note that NUE and N surplus are inversely related (Table S4). However, this is not always the case; there are possible situations where increasing NUE is associated with slightly increasing N surplus.

Table S4: Indicative values for N use efficiency (NUE) and N surpluses of specialized crop production farms at moderate and high N inputs, and as function of the percentage of cereals in the crop rotation (see text).

Cereals, %	Moderate N inputs			High N inputs		
		N surpluses, in kg/ha/yr			N surpluses, in kg/ha/yr	
	NUE, %	50 kg/ha/yr	100 kg/ha/yr	NUE, %	150 kg/ha/yr	200 kg/ha/yr
90 – 100	100	0	0	80	30	40
75 – 90	95	2.5	5	75	37.5	50
50 – 75	90	5	10	70	45	60
25 – 50	80	10	20	60	60	80
<25	70	15	30	50	75	100

27. The NUE of specialized animal farms and mixed farms depend in part on the 'unavoidable' gaseous N losses from animal manures in housing systems and manure storages due to NH_3 volatilization and nitrification-denitrification processes. Unavoidable N losses are N losses that occur when using best available techniques (BAT). Target values for NUEanimal should be based on the following equation:

$$\text{TargetNUEanimal} = [\text{AnimalN} + (\text{ExcretedN} - \text{ManureNloss})] / [\text{FeedN}] \qquad [8]$$

Where,

TargetNUEanimal =	N use efficiency at farm level, mass/mass ratio (dimensionless)
AnimalN =	Net amount of N in animals exported from the farm (i.e., including dead animals and corrected for imported animals), kg
FeedN =	Net amount of N in animal feed imported to the farm, kg
ExcretedN=	Amount of N excreted by animals during confinement, kg
ManureNloss=	Unavoidable N losses from animal manure in animals housings and manure storages due to NH_3 volatilization and nitrification-denitrification processes, kg.

ExcretedN – ManureNloss = amount of manure N exported from the farm

28. ManureNloss values depend on the animal housing system, manure management systems and farm practices. For cattle and pigs housed whole-year in slurry-based systems with covered manure storages, ManureNloss will be in the range of 5-20% of manure N excreted during confinement, with the lower value for low-emission housing systems (and tie stalls) and the higher value for houses with partially slatted floors, but depending also on climatic conditions (Amon et al., 2001; Monteny and Erisman, 1998; Oenema et al., 2008). When animals are confined only during the winter season, less N will be excreted during confinement and ManureNloss per animal head will be lower. ManureNloss from housing systems with solid manure tend to be higher (20-40% when housed all-year), due to larger nitrification-denitrification losses during manure storage.

29. For poultry, ManureNloss is in the range of 10 to 50% of ExcretedN with the lower value for low-emission housing systems and the higher value for deep pits and ground-

based litter systems without scrubbing and retaining NH_3 from exhaust air (Groot Koerkamp and Groenestein, 2008).

30. NUE of specialized animal production farms increases with increasing feed N retention and decreasing ‘unavoidable gaseous N losses’ (Table S5; Figure S4). Feed N retention depends on animal type, animal productivity and animal feeding. The ‘unavoidable gaseous N losses’ depend on housing system and animal manure management, including low-emission management systems. Hence, NUE of specialized animal production farms is very responsive to gaseous N losses, including NH_3 volatilization losses; it is an integrated N management indicator.

Table S5: Calculated N use efficiency of specialized animal production farms as function of the feed N retention percentage and the percentage ‘unavoidable N losses’ during housing and storage of animal manure (according to equation [8]). It is assumed that all animal products, including animal manure, are exported from the farm (see text).

Feed N retention, %	N use efficiency, in % ‘unavoidable N losses’ as % of N excreted				
	5	10	20	40	60
5	95	91	81	62	43
10	96	91	82	64	46
20	96	92	84	68	52
30	97	93	86	72	58
40	97	94	88	76	64

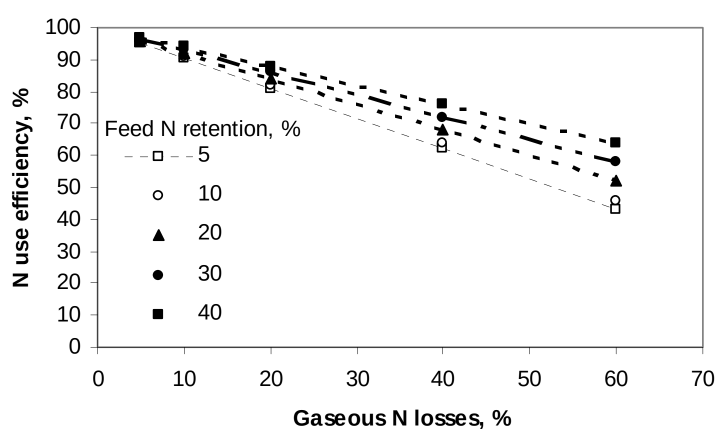

Figure S4: Calculated N use efficiency of specialized animal production farms as function of the feed N retention percentage and the percentage ‘unavoidable N losses’ during storage of animal manure; according to equation [8]. It is assumed that all animal products, including animal manure, are exported from the farm (see text)

31. Whole farm N balance and N use efficiency are indicators for estimating the pressure of N on the environment and the N resource use efficiency, respectively. Some countries (e.g., Denmark and The Netherlands) use and have used N balances and N surplus as an integrative regulatory instruments for decreasing N losses to the environment. However,

there is as yet no experience with using Nsurplus and NUE as specific indicators for abating NH_3 emissions. However, there is solid theoretical and also empirical evidence that increases in NUE are associated with decreases in N losses per unit of produce. Similarly, increases in NUE of animal production systems and mixed production systems are typically associated with decreases in NH_3 losses per unit of produce, as shown for example in Denmark (Mikkelsen et al., 2010; Nørregaard Hansen et al., 2008; Anonymous, 2008).

32. Experiences in Denmark and the Netherlands show that most farmers are able to understand the N balance and NUE indicators easily and are also able to establish N balances and NUE indicators on the basis of bookkeeping records and default values for N contents in various products. However, training and participation in farmers-discussion groups is helpful. Alternatively, N balances and NUE can be made by accountants, again on the basis of bookkeeping records and default values for N contents in various products. The annual costs for establishing N balances and NUE indicators is in the range of 200 - 500 euro per farm.

33. Roughly, three strategies / technologies can be distinguished to increase NUE and decrease N surplus: (i) increase N outputs through increasing crop and animal yields, while keeping N inputs more or less constant, (ii) decrease inputs via N fertilizers and purchased animal feed, while keeping crop and animal yields and N outputs more or less constant, and (iii) decrease N losses through N saving technologies (low emissions techniques, cover crops, better timing of N application, etc.) and thereby save on N inputs, while maintaining N outputs more or less constant. The last mentioned strategy relates in part to the other measures of Annex IX of the Gothenburg Protocol; the emphasis is here on cashing in the N saved through re-utilizing this N and through reducing N input concomitantly. The best results will occur when decreased losses will be associated with decreased inputs which, will reduce operating costs and increased outputs necessary for profitability. Hence, the approach to decrease N surplus and increase NUE is farm-specific; there is no uniform approach applicable to all farming systems.

34. There is an abundant amount of information available for increasing NUE and decreasing N surplus in crop production systems. Various institutions and fertilizer production companies provide clear guidelines. The International Plant Nutrition Institute IPNI provides easy-to-understand and easy accessible guidelines and videos on the website (http://www.ipni.net/4r) for using mineral fertilizers effectively and efficiently. The best management practices (BMPs) for fertilizer is known as the '4R nutrient stewardship concept', i.e., the Right Source, Right Rate, Right Time, and the Right Place. It can be applied to managing either crop nutrients in general (including organic sources) or fertilizers in specific. This concept can help farmers and the public understand how the right management practices for fertilizer contributes to sustainability goals for agriculture. In a nutshell, the 4R nutrient stewardship concept involves crop producers and their advisers selecting the right source-rate-time-place combination from practices validated by research conducted by agronomic scientists. Goals for economic, environmental and social progress are set by—and are reflected in performance indicators chosen by—the

stakeholders to crop production systems. These are all considered category 1 techniques. Inability to predict weather remains the main impediment to improving crop NUE; other factors include crop pests, poor soils, etc.

35. Increasing NUE and decreasing N surplus in mixed crop – animal production systems requires the measures and activities needed for the crop production component (e.g. the 4R concept indicated above in 53), as well as the measures and activities needed in the animal production component (animal feeding, housing and management), and the measures and activities related to manure storage and management. The measures and activities in the animal production components and manure storage and management are discussed further in the following chapters.

36. There is not much empirical information about the economic cost of increasing NUE and decreasing N surplus direct economic costs. Estimating the direct economic cost is also not easy; it requires proper definitions about the activities that are included in 'nitrogen management, taking account of the whole nitrogen cycle'. Also, a distinction should be made between direct costs and indirect cost. Direct costs relate to the activities needed to increase NUE and decrease N surplus, e.g., selection of high-yielding crop and animal varieties, improved tuning of N supply to N demand. These costs are estimated to range between -1 to +1 euro per kg N saved. Indirect cost relate to better education of farmers, increased data and information availability through sampling and analysis, and through keeping records. The indirect cost are higher than the direct costs, though part of these costs will be returned in terms of higher yields and quality.

Appendix 2. Supplementary Information

Guidance Document for Preventing and Abating Ammonia Emissions from Agricultural Sources of the Gothenburg Protocol:

C. Livestock feeding strategies

General considerations

1. Gaseous nitrogen losses from livestock production originate from the feces (dung) and urine excreted by the livestock. The animal feed composition and the feed management has a strong influence on animal performance and on the composition of the dung and urine, and thereby also on the emissions of ammonia (NH_3). This section focuses on feeding strategies to reduce NH_3 emissions.

2. *Reference techniques*. The abatement strategies described in this chapter are not defined and assessed against a uniform "reference" (or unabated or baseline) feeding strategy, because these "reference" feeding strategies are different for different UNECE Countries.

3. Animals require energy, protein, water, various nutrients including trace elements, and vitamins for their nutrition. The value of animal feed is usually defined by the quantity of energy and protein that can be metabolized by the animal after digestion of the feed in the gastrointestinal tract. The protein value of a diet is estimated by the fraction of protein that is absorbed from the gastrointestinal tract. For pig and poultry diets, the protein value is also defined by the quantity of individual amino acids absorbed in order to identify those amino acids that are most limiting protein deposition in animal products.

4. In practice, protein levels in animal feed are often higher than actually required. Safety margins in the protein content of the diet are used to account for: 1) suboptimal amino acid ratios; 2) variations in requirement between animals with different genotypes; 3) variations in requirement caused by differences in age or production stadiums; and 4) variations in the actual content and digestibility of essential amino acids in the diet. Protein content of the diet and the resulting N excretion can be reduced by matching the protein / amino acids content of the diet as close as possible to the animal's requirement.

5. The fraction of feed intake not digested, absorbed and retained by the animal is excreted via dung and urine. The excess N in the feed is excreted in the form of protein (organically bound nitrogen), urea, uric acid and ammonium. The partitioning of N over these compounds together with the pH of the dung and urine affects the potential for NH_3 loss.

6. There is large variation in the composition of dung and urine from dairy cattle, finishing pigs and chicken, due to variations in animal feeding. Table S6 provides ranges of values

observed in literature (Canh et al., 1998a; 1998b; Bussink and Oenema, 1998; Whitehead, 2000).

Table S6: Ranges of N components in dung and urine of some animal species.

Animal Category	Dry matter g per kg	Total N g per kg dung/urine	Urea-N % of total N	Uric acid – N, % of total N	Protein-N, % of total N	Ammonium-N, % of total N
Dairy cattle						
- Dung	100-175	10-17	0	0	90-95	1-4
- Urine	30-40	4-10	60-95	0-2	0	1
Finishing pigs						
- Dung	200-340	8-10	0		86-92	8-14
- Urine	30-36	4-7	70-90		10-20	2-10
Chicken	200-300	10-20	5-8	35-50	30-50	6-8

7. Since the losses of NH_3 are linked to the ammonium, urea and uric acid contents of the urine and dung, the main options to influence the NH_3 emissions potential by livestock feeding are by (Figure S5; Aarnink and Verstegen, 2007):

(a) Lowering the ammonium, urea and uric acid contents of the urine and dung, through:
   (i) Lowering the crude protein intake;
   (ii) Increasing the non-starch polysaccharides intake (which shifts the nitrogen excretion from urea/uric acid in urine to protein in dung);

(b) Lowering pH of manure by:
   (i) lowering the pH of dung;
   (ii) lowering the pH of urine.

(c) Lowering the urease activity, and hence the ammonium concentrations in manure.

8. The ammonium content of manure (dung + urine), following the hydrolysis of urea and the anaerobic digestion of protein in manure, can be calculated as follows (Aarnink et al., 1992):

$$[NH_4^+] = (dc*P_f - P_r + adc*(1-dc)*P_f) / (M_m)$$

Where: dc = apparent digestibility coefficient of protein
P_f = protein in feed
P_r = protein retention
adc = anaerobic digestion coefficient for protein in manure
M_m = mass of manure

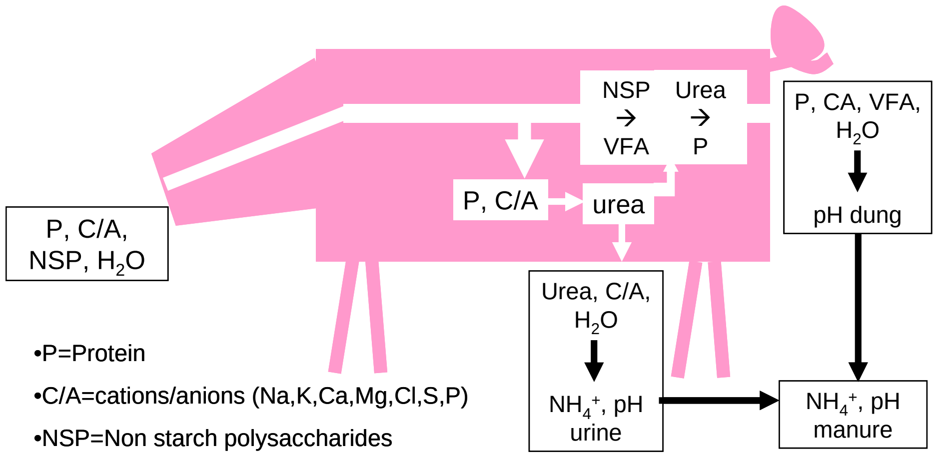

Figure S5: Schematic view of the main factors of the animal ration (protein content, cation-to-anion ratio and the content of non-starch polysaccharides) influencing the urea and ammonium contents and pH of the urine and dung excreted by animals.

9. The pH of urine and manure can be estimated by making a complete cation-to-anion balance. In this estimation also the concentration of ammonium and carbonate has to be included.

10. Livestock feeding strategies can influence the pH of dung and urine. The pH of dung can be lowered by increasing the fermentation in the large intestine. This increases the volatile fatty acids (VFA) content of the dung and causes a lower pH. The pH of urine can be lowered by lowering the electrolyte balance (Na + K – Cl) of the diet (Patience et al., 1987). Furthermore, the pH of urine can be lowered by adding acidifying components to the diet, e.g. $CaSO_4$, Ca-benzoate, benzoic acid. A low pH of the dung and urine excreted results also in a low pH of the slurry / manure during storage, also after a certain storage period. This pH effect can significantly reduce ammonia emissions from slurries during storage and also following application. These effects have been proven especially for pigs (Aarnink and Verstegen, 2007; Canh et al., 1998a; Canh et al., 1998c; Canh et al., 1998d; Canh et al., 1998e).

11. Depending on enzyme activity, urea and uric acid are hydrolyzed into ammonium usually within a few hours to days. The mineralization of organic nitrogen (apparent undigested protein) in dung is a slow process. At a temperature of 18 ^{o}C it takes 70 days before 43% of the organic nitrogen in pig manure is mineralized to ammonia (Spoelstra, 1979). Therefore, by shifting N excretion in cattle and pigs from urine to dung, the N excretion via protein (organically bound nitrogen) is increased and the N excretion via urea, uric acid and ammonium is decreased. As a result, NH_3 emissions from the urine are reduced (while NH_3 emissions from dung are not increased).

12. Two indicators are key to indicate the efficiency of conversion of feed into animal product. They are defined as follows:

(a) The requirement of crude protein (CP; often estimated as the N content multiplied by 6.25) as proportion of the dietary dry matter (DM). It depends on animal species, type of production, digestibility of the diet DM and the quality (amino acid ratio) in the CP. Information on this indicator for concentrate feeds is usually available from the feed company. For forages, notably grazed forages, this may be more difficult, but the sward surface height (SSH) may be a helpful tool; the higher SSH, the lower the protein content. However, with an increase of SSH, the digestibility of the herbage may decrease.

(b) Efficiency of N utilisation ($NUE = AY_N / F_N$), where AY_N is the mass of N in animal products (in kg), F_N is the mass of N in the feed used (kg). This indicator requires information on the N content of animal products and animal feeds. Such figures have been extensively tabulated in recent years.

13. Production of animal products (milk, meat, eggs) is not possible without first meeting the nutrient requirements to maintain the animals. Dietary protein levels required for maintenance are much lower than those needed for the synthesis of animal products. Hence, optimal levels of CP/DM vary with the proportion of ingested nutrients that is required for maintenance. This proportion is highest in slow growing animals, like replacement animals in cattle and lowest in rapidly growing animals like broilers.

Feeding strategies for ruminants (especially dairy and beef cattle)

14. Ultimately, the nitrogen use efficiency (NUE) in whole dairy production systems is limited by the biological potential of cows to transform feed N into milk and of crops and pasture to convert applied manure N and fertilizer N into grain, forage and other agronomic products. However, the disparity between actual NUE achieved by producers and the theoretical NUE indicates that substantial improvements in NUE can be made on many commercial dairy farms (e.g., Van Vuuren and Meijs, 1987). Although dairy producers can do little about the biological limitations of N use, practices such as appropriate stocking rates, manure N crediting and following recommendations to avoid wastage can substantially enhance NUE, farm profits and the environmental outcomes of dairy production. (Powell et al., 2009)

15. Lowering crude protein of ruminant diets is an effective and category 1 strategy for decreasing NH_3 loss. The following guidelines hold (Table S7):

- The average CP content of diets for dairy cattle should not exceed 150 – 160 g/kg DM (Broderick, 2003; Svenson, 2003). For beef cattle older than 6 months this could be further reduced to 120 g/kg DM.
- Phase feeding can be applied in such a way that the CP content of dairy diets is gradually decreased from 160 g/kg DM just before parturition and in early lactation to below 140 g/kg DM in late lactation and the main part of the dry period.
- Phase feeding can also be applied in beef cattle in such a way that the CP content of the diets is gradually decreased from 160 g/kg DM to 120 g/kg DM over time.

Table S7: Indicative target levels for crude protein (CP) content, in gram per kg of the dry mass of the ration, and resulting efficiency of N utilisation (NUE), in mass fractions (kg/kg) **for cattle (see text)**

Cattle species	CP, g/kg	NUE, kg/kg
Milk + maintenance, early lactation	150-160	0.30
Milk + maintenance, late lactation	120-140	0.25
Replacement	130-150	0.10
Veal	170-190	0.45
Cattle <3 months	150-160	0.30
Cattle 3-18 months	130-150	0.15
Cattle >18 months	120	0.05

16. In many parts of the world, cattle production is land-based or partly land-based. In such systems protein rich grass and grass products form a significant proportion of the diet, and the target values for crude protein noted in Table S7 may be difficult to achieve, given the high CP content of grass from managed grasslands. The CP content of fresh grass in the grazing stage (2000-2500 kg DM per ha) is often in the range of 180 to 200 g/kg, the CP content of grass silage often between 160 and 180 g/kg and the CP content of hay between 120 and 150 kg/kg (e.g., Whitehead, 2000). In contrast, the CP content of silage maize is only about 70 to 80 g/kg. Hence, grass-based diets often contain a surplus of protein and the magnitude of the resulting high N excretion strongly depends on the proportions of grass, grass silage and hay in the ration and the protein content of these feeds. The protein surplus and the resulting N excretion and NH_3 losses will be highest for grass-only summer rations with grazing young, intensively fertilized grass or grass legume mixtures. However, urine excreted by grazing animals typically infiltrates into the soil before substantial NH_3 emissions can occur and overall NH_3 emissions per animal are therefore less for grazing animals than for those housed where the excreta is collected, stored and applied to land.

17. The NH_3 emission reduction achieved by increasing the proportion of the year the cattle spent grazing outdoors will depend on the baseline (emission of ungrazed animals), the time the animals are grazed, and the N fertilizer level of the pasture. The potential to increase grazing is often limited by soil type, topography, farm size and structure (distances), climatic conditions, etc. It should be noted that grazing of animals may increase other forms of N emissions (e.g. N_2O, NO_3). However, given the clear and well quantified effect on NH_3 emissions, increasing the period that animals are **grazing can be considered as a category 1 strategy** to reduce emissions. The actual abatement potential will depend on the base situation of each animal sector in each country. The effect of changing the period of partial housing (e.g. grazed during daytime only) is less certain and is rated as a category 2 strategy. Changing from a fully housed period to grazing for part of the day is less effective in reducing NH_3 emissions than switching to complete (24 hour) grazing, since buildings and stores remain dirty and continue to emit NH_3. Grazing management (strip grazing, rotational grazing, continuous grazing) is expected to have little additional effect on NH_3 losses and is considered a category 3 strategy.

18. In general, increasing the energy/protein ratio in the diet by using 'older' grass (higher sward surface height, SSH) and/or supplementing grass by high energy feeds (e.g., silage

maize) is category 1 strategy. However, for grassland-based ruminant production systems, the feasibility of these strategies may be limited, as older grass may reduce feeding quality, especially when conditions for growing high energy feeds are poor, and therefore have to be purchased. Hence, full use of the grass production would no longer be guaranteed (under conditions of limited production, e.g. milk quotas or restrictions to the animal density). Hence, improving the energy/protein equilibrium on grassland-based farms with no possibilities of growing high energy feeds is therefore considered a category 2 strategy.

19. The use of modern protein evaluation systems (e.g., PDI in France, MP in the UK, DVE/OEB in The Netherlands, AAT/PBV in Scandinavian countries) is recommended (e.g. Van Duinkerken et al., 2011). In dairy cattle, the use of rumen protected limiting amino acids, like lysine and methionine may be helpful to better balance the amino acid composition of protein digested from the small intestine. Because for a successful introduction of this method detailed additional information on the behaviour of the feed in the digestive tract is required, this is considered a category 2 strategy.

20. Shifting N excretion from urea in urine to protein in dung is also an effective measure for decreasing ammonia loss. Dietary composition should be such that a certain degree of hindgut fermentation is stimulated, without disturbing rumen fermentation. This will shift the excretion of N from urine to dung. Hind-gut fermentation can be stimulated by the inclusion of rumen resistant starch or fermentable fibre that escapes fermentation in the rumen (Van Vuuren et al., 1993). Because in the hindgut acetogenic rather than methanogenic bacteria are present, there is little risk of elevated CH_4 losses. Knowledge on factors responsible for shifting N excretion from urea in urine to protein in dung are still insufficient and this approach is considered a category 3 strategy.

21. The pH of freshly excreted urine ranges from 5.5-8.5 and mainly depends on the electrolyte content of the diet. Although the pH will eventually rise towards alkaline values due to the hydrolysis of urea irrespective of initial pH, the initial pH and the pH buffering capacity of urine determine the rate of NH_3 volatilization from urine immediately following urination. Lowering the pH of urine of ruminants is theoretical possible. However, there are interactions with urine volume, ruminant performance, and animal welfare and it is therefore considered a category 3 technique. Similarly, lowering the pH of dung is theoretically possible, but this might easily coincide with disturbed rumen fermentation and is therefore not recommended. Because of the possible side effects involved this is considered a category 3 technique. Dung consistency could be used to monitor the adequacy of rumen fermentation.

22. Monitoring the protein status is possible with the (calculated) rumen degradable protein balance (e.g. PBV in Scandinavian countries, OEB in The Netherlands) and/or milk urea nitrogen (MUN) can be used too (e.g. Van Duinkerken et al., 2011b). MUN should preferably not exceed 10 mg/dl (milk urea below 22 mg/dl). Knowledge on factors responsible for variation in MUN is still insufficient and this approach is considered a category 2 strategy.

23. There are also herd management options to reduce NH_3 emissions. Firstly, by increasing the genetic potential of the cows (more milk per cow). This will lead to a higher NUE at herd level because of the lower share of maintenance energy. By equal total annual milk output per country the number of dairy cows and replacement cattle will consequently decrease. Secondly, by increasing the number of lactations per cow. This will reduce the number of replacement cattle. Finally, the actual number of replacement cattle per dairy cow should be optimized. All three options are a long term approach, but nevertheless represent category 1 techniques where to reduce overall ammonia emissions. Also, these strategies may have positive animal welfare implications, and likely contribute to a decrease in methane (CH_4) emissions from enteric fermentation as well, especially when expressed in terms of emissions per unit of milk produced (Tamminga, 1996; Kreab et al., 2001; Powel et al., 2009).

24. Rotational corralling of ruminants on crop land may reduce NH_3 emissions and increase N recovery from animal manure compared to the conventional practice of barn manure collection and land application of manure (Powell and Russelle, 2009). Overall results demonstrated that corralling dairy cattle on cropland improves urine N capture, reduces ammonia loss and enhances manure N recycling through crops. This is considered as a category 2 strategy.

25. Various feed strategies are able to reduce urinary N excretion from housed dairy cattle. A close matching of diets to animal nutritional requirements, feeding only enough protein to meet cows' metabolizable protein requirements, reducing particle size to increase ruminal digestion of grain starch and increase microbial protein formation (so long as ruminal pH is not depressed) optimizes microbial protein synthesis, maximizes feed N conversion into milk and minimizes urinary N excretion. These are considered as category 2 strategies.

Feeding strategies for pigs

26. Feeding measures in pig production include phase feeding, formulating diets based on digestible/available nutrients, using low-protein amino acid-supplemented diets, and feed additives/supplements. These are all considered category 1 techniques. Further techniques are currently being investigated (e.g. different feeds for males (boars and castrated males) and females) and might be additionally available in the future.

27. Phase feeding (different feed composition for different age or production groups) offers a cost-effective means of reducing N excretion from pigs and could be implemented in the short term. Multi-phase feeding depends on computer-aided automated equipment.

28. The crude protein content of the pig ration can be reduced if the amino acid supply is optimised through the addition of synthetic amino acids (e.g. lysine, methionine, threonine,

tryptophan) or special feed components, using the best available information on “ ideal protein’ combined with dietary supplementation.

29. A crude protein reduction of 2 to 3 per cent (20 to 30 g/kg of feed) can be achieved depending on pig production category and the current starting point. The resulting range of dietary crude protein contents is reported in Table S8. The values in the table are indicative target levels and may need to be adapted to local conditions.

Table S8: Indicative target crude protein levels in feed for pig rations (Adopted from IPPC-BREF-2003 document)

Species	Phases	Crude protein content, % *)
Weaner	< 10 kg	19–21
Piglet	< 25 kg	17–19
Fattening pig	25–50 kg	15–17
	50–110 kg	14–15
	>110 kg	12-13
Sows	Gestation	13–15
	Lactation	15–17

*) With adequately balanced and optimal amino acid supply

30. For every 10 g/kg reduction in crude protein content of the diet a 10% lower TAN (total ammonia nitrogen) content of the pig slurry and 10% lower NH_3 emissions can be achieved in growing finishing pigs (Canh et al., (1998b). Currently, the most common crude protein content of the diet of growing-finishing pigs is approximately 170 g/kg. In experiments, it has been demonstrated that decreases to 120 g protein per kg diet can be achieved without any effect on growth rate or feed efficiency when limiting amino acids are added (= 50% NH_3 emission reduction). In practice, 140 g protein per kg diet is economically feasible (= 30% NH_3 emission reduction, relative to the baseline value with a protein content of 170 g/kg). This can be achieved by phase feeding and adding the most limiting amino acids (Canh et al., 1998b; Dourmad et al., 1993; Lenis and Schutte, 1990). Economically feasible means that the cost of lowering the protein content till 140 g/kg (plus the supplementation with synthetic amino acids) more or less balance the benefits of improved animal performance. Although still some work needs to be done for the practical implementation, this is considered a category 1 technique for growing-finishing pigs. For sows and weaned piglets additional studies are needed, so for these categories it is considered a category 2 technique.

31. The addition of special components with high non-starch polysaccharide (NSP) content (e.g. sugar beet pulp, soybean hulls) can reduce the pH of pig excreta and thus NH_3 emissions. Increasing the amount of non-starch polysaccharides (NSP) in the diet increases the bacterial fermentation in the large intestine, which results in the immobilization of urea-N from the blood into bacterial protein. Ammonia emissions decrease by approximately 16 and 25% when NSP content of the diet increases from 200 to 300 and further to 400 g/kg diet, respectively. However, the effect on NH_3 emissions depends to a certain extent also on the kind of NSP in the diet. Increasing the level of NSP in the diet may also have negative impacts. At high NSP levels, nutrient digestibility decreases and this increases waste production, which is undesirable in animal dense areas. Furthermore, at increasing NSP

levels in the diet volatile fatty acids (VFA) concentrations in the manure increases. Although VFA's are not the most important odorous compounds, increased VFA levels may increase odour release from the manure. At increasing NSP levels in the diet methane production from animal and manure may also increase (Kirchgessner et al., 1991; Jarret et al., 2011). Because of all these reasons increasing the amount of NSP in the diet as means to decrease NH_3 emissions is considered a category 3 strategy in animal dense areas and a category 2 strategy in other areas. Including too much NSP in pig diets can have a negative effect on pig performance and reduce feed conversion efficiency.

32. Replacing $CaCO_3$ in the animal feed by $CaSO_4$, $CaCl_2$, or Ca-benzoate reduces the pH of urine and slurry and the NH_3 emission from the urine and slurry. By replacing calcium (6 g/kg) in the diet in the form of $CaCO_3$ by Ca-benzoate, urinary and slurry pH can be lowered by more than 2 units. In that case NH_3 emission can be reduced up to 60%. Benzoic acid is degraded in the pig to hippuric acid, that lowers the urine pH and consequently the pH of the slurry stored in the pig house. Benzoic acid is officially allowed in the EU as acidity controlling agent (E210), and is also admitted as feeding additive for fattening pigs (1% dosage) and piglets (0.5% dosage) (registered trade mark: Vevovitall). Addition of 1% benzoic acid to the diet of growing-finishing pigs lowers NH_3 emissions by approximately 20% (Aarnink et al., 2008; Guingand et al., 2005). A similar replacement of $CaCO_3$ by Ca-sulphate or Ca-chloride reduces the pH of slurry by 1.2 units and NH_3 emission by approximately 35% (Canh et al., 1998a; Mroz et al., 1996). Addition of benzoic acid is considered a category 1 technique for growing-finishing pigs and a category 2 technique for other pig categories. Replacement of $CaCO_3$ by $CaSO_4$, $CaCl_2$, or Ca-benzoate is considered a category 2 technique for all pig categories.

33. The effects of the various feeding measures have independent effects on NH_3 emission. This means that these effects are additive (Bakker and Smits (2002). Combined feeding measures are considered category 2 techniques for all categories of pigs.

Feeding strategies for poultry

34. For poultry, the potential for reducing N excretion through feeding measures is more limited than for pigs because the conversion efficiency currently achieved on average is already high and the variability within a flock of birds is greater. A crude protein reduction of 1 to 2 per cent (10 to 20 g/kg of feed) can usually be achieved depending on the species and the current starting point. The resulting range of dietary crude protein contents is reported in Table S9. The values in the table are indicative target levels, which may need to be adapted to local conditions. Further applied nutrition research is currently being carried out in EU Member States and North America and this may support further possible reductions in the future. A reduction of the crud protein content by 1-2% is a category 1 measure for growers and finishers.

Table S9: Indicative target crude protein levels in feed for poultry

Species	Phases	Crude protein content, % *)
Chicken, broilers	Starter	20–22
	Grower	19–21
	Finisher	18–20
Chicken, layers	18–40 weeks	15.5– 16.5
	40+ weeks	14.5– 15.5
Turkeys	< 4 weeks	24–27
	5–8 weeks	22–24
	9–12 weeks	19 –21
	13+ weeks	16-19
	16+ weeks	14 –17

*) With adequately balanced and optimal amino acid supply

Summary and synthesis and of feeding strategies

35. Low-protein animal feeding is one of the most cost-effective and strategic ways of reducing NH_3 emissions. For each percent (absolute value) decrease in protein content of the animal feed, NH_3 emissions from animal housing, manure storage and the application of animal manure to land are decreased by 5 to 15%, depending also on the pH of the urine and dung. Low-protein animal feeding also decreases N_2O emissions, and increases the efficiency of nitrogen use in animal production. Moreover, there are no animal health and animal welfare implications as long as the requirements for all amino acids are met.

36. Low-protein animal feeding is most applicable to housed animals and less for grassland-based systems with grazing animals, because grass in an early physiological growth stage and grassland with leguminous species (e.g. clover and lucerne) have a relatively high protein content. However, there are strategies to lower the protein content in herbage (balanced N fertilization, grazing/harvesting the grassland at later physiological growth stage, etc.) as well as in the ration of grassland-based systems (supplemental feeding with low-protein feeds), but these strategies are not always fully applicable.

37. Table S10 presents ranges of target crude protein values for various animal categories and for three ‘ambition levels’ of ammonia emission mitigation. The ‘high ambition values’ relate to the lowest ranges of crude protein contents for best feed management practices and low-protein feeding management. These values have been tested manifold in research and proven to be solid in practice. The medium and low ambition target crude protein values have been derived from the high ambition targets by simply increasing the target crude-protein content by 1 percent point. The achievable ambition levels for housed animals depend on the management skill of the farmer and the availability of the animal feedstuffs with low protein content, including synthetic amino acids.

38. The high ambition values presented in Table S10 may be difficult to achieve when the feed quality is low (high fiber content and low digestibility of the feed). In these conditions, specific feed additives may help to increase the digestibility. Ruminants and also pigs

(especially sows) need minimum fiber content in the feed for proper functioning of the rumen and for welfare reasons.

39. For producing special meat (and milk) products, the recommended protein content of the animal feed for a specific animal category may be slightly above the upper value of the indicated ranges in Table S10.

Table S10: Possible crude protein levels (percent of dry feed with a standard dry matter content of 88%) for housed animals as function of animal category and for different ambition levels. These crude protein values can be used as annual mean targets in low-protein animal feeding strategies.

Animal type	**Mean crude protein content of the animal feed, %[2]**		
	Low ambition	**Medium ambition**	**High ambition**
Dairy cattle, early lactation (>30kg/day)	17-18	16-17	15-16
Dairy cattle, early lactation (<30kg/day)	16-17	15-16	14-15
Dairy cattle, late lactation	15-16	14-15	12-14
Replacement cattle (young cattle)	14-16	13-14	12-13
Veal	20-22	19-20	17-19
Beef <3 months	17-18	16-17	15-16
Beef >6 months	14-15	13-14	12-13
Sows, gestation	15-16	14-15	13-14
Sows, lactation	17-18	16-17	15-16
Weaner, <10 kg	21-22	20-21	19-20
Piglet, 10-25 kg	19-20	18-19	17-18
Fattening pig 25-50 kg	17-18	16-17	15-16
Fattening pig 50-110 kg	15-16	14-15	13-14
Fattening pigs >110	13-14	12-13	11-12
Chicken, broilers, starter	22-23	21-22	20-21
Chicken, broilers, growers	21-22	20-21	19-20
Chicken, broilers, finishers	20-21	19-20	18-19
Chicken, layers, 18-40 weeks	17-18	16-17	15-16
Chicken, layers, >40 weeks	16-17	15-16	14-15
Turkeys, <4 weeks	26-27	25-26	24-25
Turkeys, 5-8 weeks	24-25	23-24	22-23
Turkeys, 9-12 weeks	21-22	20-21	19-20
Turkeys, 13 -16 weeks	18-19	17-18	16-17
Turkeys, >16 weeks	16-17	15-16	14-15

[2] With adequately balanced and optimal digestible amino acid supply.

40. The economic cost of animal feeding strategies to lower the NH_3 volatilization potential of the animal excrements through adjusting the crude protein content, the cation-anion-balance and the non-starch polysaccharide (NSP) content (e.g. sugar beet pulp, soybean hulls) depends on the initial animal feed composition and on the prices of the feed ingredients on the market. In general, the economic costs range from -2 to +2 euro per kg N saved, i.e. there are potential net gains and potential net costs. Commonly, the economic costs increase when the target for lowering the NH_3 volatilization potential increases. The increasing marginal costs relate in part to the cost of synthetic amino acids supplementation relative to using soya beans. The economic costs depend on world market prices of these amino acids and soya bean, but the costs of amino acids supplementation tend to go down. The cost of supplementation of amino acids increases when the target protein content in the animal feed is lowered. This is show below for feed of fattening pits (personal communication Dr. Andre Aarnink, October, 2009). Additional information is provided in the report on the workshop "Economic Cost of Ammonia Emission Abatement", Paris 25-25 October 2011.

Target protein content, %.	Extra costs, euro per 100 kg feed
15	0.00
13.5	0.90
12.7	3.10