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**DRAFT GUIDANCE DOCUMENT FOR PREVENTING AND ABATING AMMONIA EMISSIONS FROM AGRICULTURAL SOURCES**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 first results of the workshop on "The Costs of Ammonia abatement and the climate co-benefits" (Paris, 25-27 October 2010, but a further up-date will be made and discussed during the TFRN-7 meeting in Italy in May 2011.

# 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, and focusing on livestock feeding strategies. This guidance will facilitate the implementation of the Basic Obligations of the Protocol mentioned in Article 3, as regards $NH_3$ Emission, 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 Table 3 (amended version of December 2005).

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 addresses the provisions in the proposal for revision of the Annex IX of the 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol). Following a brief introduction to 'livestock production and development', this Guidance Document follows the order of the provisions in the proposal for revision of Annex IX.

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 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 strategies***: These are promising, but research on them is at present inadequate, or it will always be difficult to 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 strategies***: These have been shown to be ineffective 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* part of the definition of these categories, and that category 1 techniques are not necessarily the cheapest or most convenient. If a particular technique is well researched and effective it may be classed as category 1. Information on costs is provided to support decisions on the use of the techniques.

6. Separate guidance has also been prepared under the Integrated Pollution Prevention and Control (IPPC) Directive 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. 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 may be lost. Likewise, controlling emissions from land application will have less benefit on the farm or national scale if large losses occur in barns and storages. Reduction in 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, such as GAINS, in order to optimise their abatement strategies. Therefore the whole farm context has also been added to this document.

8. Many measures may incur both capital and annual 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.

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

| Consideration | Notes |
|---|---|
| Capital for fixed equipment or machinery. | Fixed equipment includes buildings, conversions of buildings, feed storage bins, or manure storage. 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. |

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 though use of contractors with access to suitable equipment.

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.

## II. LIVESTOCK PRODUCTION AND DEVELOPMENTS

11. 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 briefly explain the livestock sector.
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12. 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 and fibre for growing urban populations, livelihoods for almost one billion poor producers as well as global public goods related to food security, environmental sustainability and public health (Geers and Madec, 2006; FAO, 2010; Steinfeld et al., 2010).

13. 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 for deforestation and biodiversity loss (Steinfeld et al., 2006; FAO, 2010; 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).

14. Livestock production systems can broadly be classified in (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. Less than 10% of the dry matter fed to animals is produced on the farm. Relevant indicators for livestock production systems are animal density in animals 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).

15. 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, which may coincide with the distinction between conventional and organic farming, but not necessarily. 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).

16. 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).

17. Increasingly, production chains are organized and regionally clustered in order to minimize production 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 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, specialized, and intensive (FAO, 2009; Steinfeld et al., 2010 and references therein).

18. Livestock production systems are dynamic systems because of continuous developments and changes in technology, markets, transport and logistics. Such developments lead to changes in livestock production systems and in its institutional organization and geographical locations. 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-cast 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. With high rates of consumption, rapid growth rates and a shift towards animal-derived foods, urban populations increasingly drive the sector. The retail, processing industry and suppliers of animal feed and technology greatly influence the sector, while the farmers, the livestock producers become increasingly integrates the organization of the whole food chain (FAO, 2009; Steinfeld et al., 2010).

19. 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 into the future.

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

20. 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'.

21. Nitrogen is a constituent of all plant and animal proteins (and enzymes) and 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 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'.

22. 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.

23. 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.

24. 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. To avoid excess or untimely N applications, 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 availability of livestock manure;
  - the demands for nitrogen, phosphorus and potassium by the crops,
  - the immediately-available nitrogen, phosphorus and potassium contents in the manure;
  - the rate of release of slowly-available nutrients from the manure;
  - the nutrient that will be sufficiently supplied at the lowest application rate (to ensure no nutrient is over supplied- requires soil testing for non-N nutrients);
- 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.

25. Nitrogen management which takes account of the whole nitrogen cycle aims at identifying measures for reducing all unwanted N emissions, including $NH_3$ emissions, in a cost-effective way, i.e., to a level where the value of marginal damages to human health and biodiversity is (approximately) equal to the marginal cost of achieving further reductions. Preferred measures for reducing $NH_3$ 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. Similarly, abatement measures must avoid increasing other types of farm pollution (e.g., P losses, pathogens, soil erosion) or resource use (e.g., fuel), reduce the quality of food (e.g., increased antibiotics, hormones or pesticides) or the health and welfare of farm (e.g., by limiting barn size or animal densities).

26. The effectiveness of nitrogen management can be evaluated in terms of (i) decreases of nitrogen losses, 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. Management has a large effect on the nitrogen use efficiency (Tamminga 1996; Mosier et al., 2004).

27. Output / input ratios (mass/mass ratios) and balances (input minus output, in mass per unit surface area) are the best indicators for expressing overall N use efficiency (NUE) at farm level (Table 2). 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) is an indicator for the N use efficiency at farm level, the N surplus (or deficit) is an indicator for the N pressure of the farm on the wider environment, assuming that ultimately all surplus N is lost via either ammonia volatilization, N leaching and/or nitrification/ denitrification.

28. 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., OECD, 2001; Oenema et al., 2003). 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; the difference between the gross nitrogen balance and the soil-surface balance is the way $NH_3$ losses from manure in housing systems and manure storage systems is treated. 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 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.

29. 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.

30. A farm-gate nitrogen budget of a mixed crop-animal production farm is the most complex budget (Figure 1). The main inputs are mineral/inorganic fertiliser, imported animal manure, fixation of atmospheric nitrogen 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

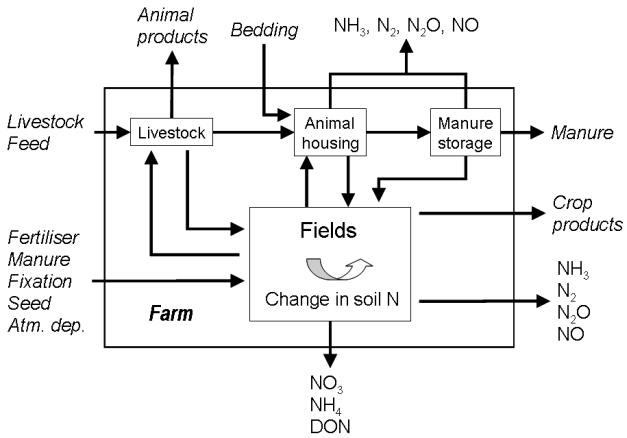


**Figure 1.** A farm nitrogen budget of a mixed crop-animal production farm.

31. The corresponding components of a farm nitrogen balance of a mixed crop-animal production farm are shown in Figure 2. Evidently, a farm N balance is much simpler than a farm-gate 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.

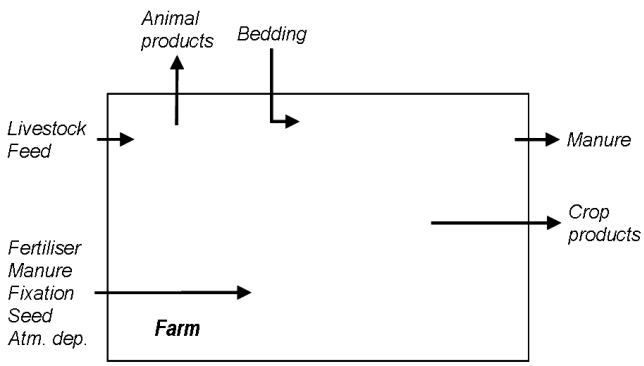


**Figure 2:** Components of a farm-gate nitrogen balance of a mixed crop-animal production farm.

32. A soil surface nitrogen balance of agricultural land is shown in figure 3. 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.

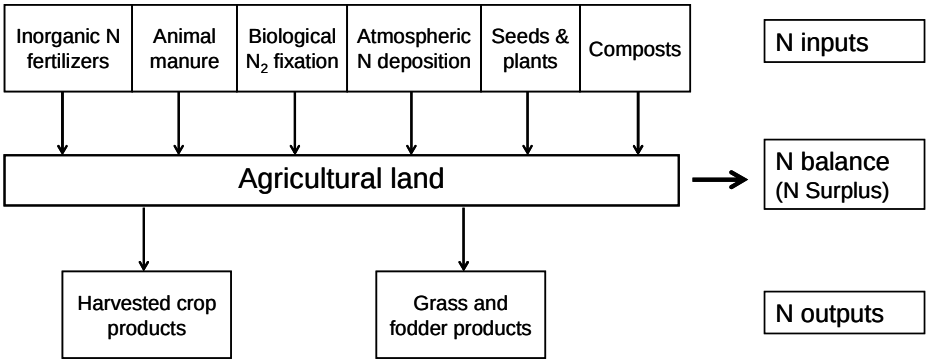


**Figure 3:** Components of a soil surface nitrogen balance of agricultural land (see OECD, 2001).

33. For using N balances and 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., areal percentage of cereals, pulses, vegetables and root crops). Specialized animal production farms produce only animal products (milk, meat, egg 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).

34. The variation between farms in NUE (output/input ratios) and N surpluses (input minus input) is large in practice, due to the differences in management and farming systems (especially as regards the types of crops and animals, and the livestock density). Indicative target values can be given for broad categories of farming systems (see Table 2).

35. Nitrogen balances and N input-put 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, meat 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 (Powel 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) |

36. 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 2:** 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 = $\Sigma$ ($Inputs_N$) – $\Sigma$ ($outputs_N$) | •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<br>•N surplus is a measure of the total N loss to the environment<br>•N deficit [$\Sigma$ ($Inputs_N$) < $\Sigma$ ($outputs_N$] is a measure of soil N depletion<br>•For specialized animal farming systems (land-loose), 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:<br><br>Crop: 0-50 kg/ha<br>Mixed: 0-200 kg/ha<br>Animal: 0-1000 kg/ha |
| **NUE** = nitrogen use efficiency, i.e., the N output in useful products divided by the total N input | NUE = $\Sigma$ ($outputs_N$) / $\Sigma$ ($Inputs_N$) | •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<br>•For specialized animal farming systems (land-loose), there may be N output via manure processing and export | Depends on types of farming systems, crops and animals:<br><br>Crop 0.6-1.0<br>Mixed: 0.5-0.6<br>Animal 0.4-0.6*<br>Animal 0.8-0.95**<br><br>*) no manure export<br>**) landless farms; all manure exported off-farm |

37. 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 target ranges of N fertilizer equivalence values for cattle, pig and poultry manure, slurries and liquids, 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 3:** 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 liquids | 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;

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

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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.

39. 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.

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

SurplusN = [FertN+ManureN+CompostN+BNF+Atm.N+SeedN]–[AnimalN + CropN + ManureN] [5]

NUEmixed=[AnimalN+CropN+ManureN]/[FertN+ManureN+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 = 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 = Amount of manure N exported from the farm, kg/ha

41. A more accurate expression of the N use efficiency 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

42. 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.

43. 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.

44. 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. Target values for N surplus 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%).

45. 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. 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 4). 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 4). However, this is not always the case; there are possible situations where increasing NUE is associated with slightly increasing N surplus.

**Table 4:** Possible target 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 | | |
|---|---|---|---|---|---|---|
| | Target NUE, % | N surpluses, in kg/ha/yr | | Target NUE, % | N surpluses, in kg/ha/yr | |
| | | 50 kg/ha/yr | 100 kg/ha/yr | | 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 |

46. 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 technology (BAT). Target values for NUEanimal should be based on considering 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

47. ManureNloss values depend on the animal housing system and manure management systems. 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 slattened floors, but depending also on climatic conditions. 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.

48. 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.

49. NUE of specialized animal production farms increases with increasing feed N retention and decreasing 'unavoidable gaseous N losses' (Table 5; Figure 4). 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 5:** 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 |

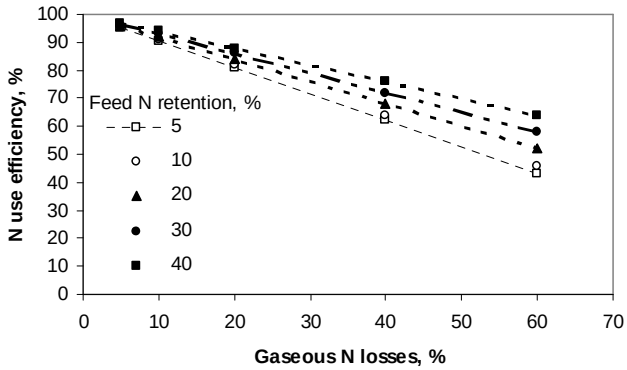


**Figure 4:** Calculated N use efficiency of specialized animal production farms as function of the feed N retention percentage and the percentage 'unavoidable N losses' during storage of animal manure; according to equation [8]. It is assumed that all animal products, including animal manure, are exported from the farm (see text)

50. 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 regulatory instruments for decreasing N losses to the environment. However, there is as yet no experience with using Nsurplus and NUE as 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).

51. 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.

52. 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.

53. 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 contribute 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.

54. 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 52), 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.

55. There is not much empirical information about the economic cost of increasing NUE and decreasing N surplus direct economic cost. 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 cost 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 cost, though part of these cost will pay back in terms of higher yields and quality.

56. A simple Microsoft Excel spreadsheet program (NUE Calculator) is available for examining the effects of management factors on N surplus and NUE. This Excel spreadsheet program contains defaults values for various farming systems, and can be easily adjusted to farm-specific conditions.

## IV. LIVESTOCK FEEDING STRATEGIES

### General considerations

57. 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.

58. 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.

59. 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 N excretion can be reduced by matching the protein / amino acids content of the diet as close as possible to the animal's requirement.

60. 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.

61. There is large variation in the composition of dung and urine from dairy cattle, fattening pigs and chicken, due to variations in animal feeding. Table 6 provides ranges of values observed in literature (Canh et al., 1997; Bussink and Oenema, 1998; Whitehead, 2000).

**Table 6:** 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 |

62. The main options to influence the $NH_3$ emissions potential by livestock feeding are by (Figure 5; 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 activty, and hence the ammonium concentrations in manure.

63. 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 (after 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

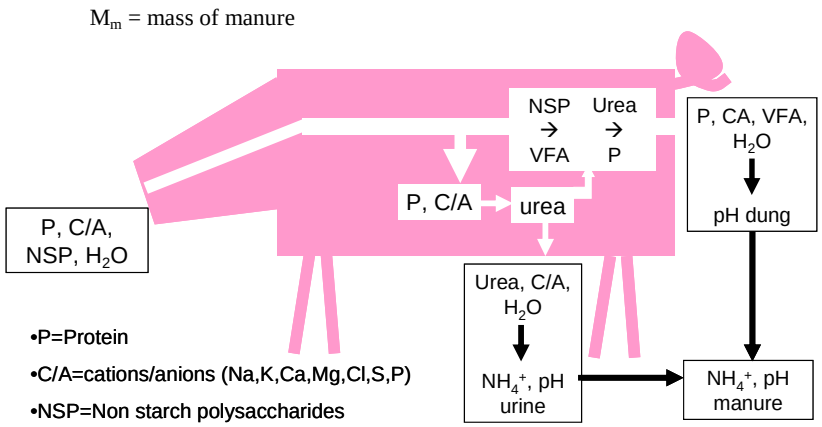


**Figure 5:** Schematic view of the main factors of the animal ration (protein content, cation-to-anion ratio and the content of non-starch polysaccharides) influencing the urea and ammonium contents and pH of the urine and dung excreted by animals.

64. 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.

65. 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).

66. 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 $^oC$ 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.

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

(a) Dietary crude protein (Nx6,25) content **(CP/DM)**. The requirement of crude protein (CP) as proportion of the dietary dry matter (DM) 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.

(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.

68. 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, target 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. Target levels for NUE show the opposite.

**Feeding strategies for ruminants (especially dairy and beef cattle)**

69. Nitrogen use efficiency (NUE) in dairy production 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 potential NUE indicates that substantial improvements in NUE can be made on many commercial dairy farms. 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)

70. Lowering crude protein of ruminant diets is an effective and category 1 strategy for decreasing $NH_3$ loss. The following guidelines hold (Table 7):

- 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 during the first 3 months to 120 g/kg DM thereafter.

**Table 7:** Target levels for crude protein (CP) content, in gram per kg of the dry mass of the ration, and 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 | 120-130 | 0.10 |
| Veal | 170-190 | 0.45 |
| Beef <3 months | 150-160 | 0.30 |
| Beef >6 months | 120 | 0.20 |

71. 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 7 may be difficult to achieve. Such 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 $NH_3$ emissions per animal are therefore less for grazing animals than for those housed where the excreta is collected, stored and applied to land.

72. 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.

73. 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 this strategy may be limited, especially when conditions for growing high energy feeds are poor and therefore have to be purchased, with as consequence that a 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 animal production constraints and no possibilities of growing high energy feeds is therefore considered a category 2 strategy.

74. 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. 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.

75. 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 as yet insufficient and this approach is considered a category 2 strategy.

76. 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, it are the initial pH and the pH buffering capacity of urine which 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 health risks involved this is considered a category 3 technique. Dung consistency could be used to monitor the adequacy of rumen fermentation.

77. 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. MUN should preferably not exceed 10 mg/dl (milk urea below 22 mg/dl). Knowledge on factors responsible for variation in MUN is as yet insufficient and this approach is considered a category 2 strategy.

78. 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.

79. 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.

80. 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 RUP 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.

**Feeding strategies for pigs**

81. 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 and females) and might be additionally available in the future.

82. 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.

83. 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.

84. 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 8. The values in the table are indicative target levels and may need to be adapted to local conditions.

**Table 8:** 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

85. For every 10 g/kg reduction in crude protein content of the diet a 10% lower TAN content of the pig slurry and 10% lower $NH_3$ emissions can be achieved in growing finishing pigs (Canh et al., (1998b). Currently, 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). 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.

86. 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). 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.

87. 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.

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

### Feeding strategies for poultry

89. For poultry, the potential for reducing N excretion through feeding measures is more limited than for pigs because the conversion efficiency 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 9. 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.

**Table 9:** 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**

90. 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.

91. 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.

92. Table 10 presents ranges of target crude protein values for various animal categories and for three 'ambition levels' of nitrogen mitigation. The 'high ambition values' relate to the lowest ranges of crude protein contents in the current guidelines 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.

93. The high ambition values presented in Table 10 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.

94. 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 10.

95. 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 there 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 depends 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 will be 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 |

**Table 10:** 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, %[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.

# V. LIVESTOCK HOUSING

96. Animal housing varies enormously across the UN/ECE region and $NH_3$ emissions will vary accordingly. In general, emissions from livestock housing will be reduced if the surface area of exposed manures is reduced and/or such manures are frequently removed and placed in covered storage outside the building. Emission reductions can also be achieved in poultry housing by drying manure and litter to a point where $NH_3$ is no longer formed by hydrolysis of uric acid. Many of the options for reducing emissions from housing can be implemented only for newly built houses. Others require significant structural changes or energy inputs. For these reasons they are often more expensive than improved techniques for livestock diets, manure storage and the application of manure to land.

97. *Reference techniques*. The level of $NH_3$ emission reduction achieved through new livestock housing designs will depend critically on the housing types currently in use. The reference techniques are described according to each livestock type.

## A. Housing systems for dairy and beef cattle

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

- Decreasing the surface area fouled by manure;
- Adsorption of urine (e.g. by straw);
- Rapid removal of urine; rapid separation of faeces and urine;
- Decreasing of the air velocity above the manure;
- Reducing the temperature of the manure and of surfaces it covers.

99. 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 these systems all or part of the excreta is collected in the form of slurry. If solid manure is produced, it may be removed from the house daily. Loose housing systems are most commonly slurry-based. 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 pits and channels beneath the slats/floor.

100. *Reference Systems:* Two references apply for cattle housing depending on national practices: the cubicle house and the tied animal house. In Table 11, cubicle housing is referred to as reference 1, while tied housing is reference 2. Buildings in which the cattle are held in tied stalls emit less $NH_3$ than loose housing, because a smaller floor area is fouled with dung and urine. However, tied systems are not recommended because of animal welfare considerations.

101. *Animal welfare considerations* tend to lead to an increase of the soiled walking area per animal and a corresponding increase of emissions. Changes in building design to meet new animal welfare legislation in some countries (e.g. changing from tied stall to cubicle housing) will therefore increase $NH_3$ emissions unless other measures are introduced at the same time to combat this increase. Conversely, changes in building design to meet animal welfare requirements represent an important opportunity to introduce $NH_3$ mitigation measures in at the same time, thereby reducing the costs of the mitigation measures.

**Category 1 techniques**

102. *In the "grooved floor" system* for dairy and beef cattle housing, the use of a "toothed" scraper 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, and therefore reduced-emission floor surface, while still providing enough grip for the cattle to prevent problems of slipping. This system is implemented on several farms in the Netherlands.

103. In houses with traditional slats (either non-sloping, 1% sloping or grooved), an optimal barn climatization with roof insulation (RI) and/or automatically controlled natural ventilation (ACNV) can achieve a moderate emission reduction due to the decreased temperature (especially in summer) and reduced air velocities.

**Category 2 techniques**

104. *Different improved floor types* based on slats or solid, profiled concrete elements are being 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. Quantification is not yet possible. However, measurement programs to establish emission factors are implemented in the Netherlands.

105. *Solid versus slurry manure systems.* Research to date has shown that straw-based systems 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. However, straw-based systems producing solid manure can give less $NH_3$ emission than slurry after spreading the manure on the field. Similarly, the physical separation of faeces (which contains urease) and urine in the housing system can reduce both emissions during housing and emissions at the time of manure spreading. 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).

106. *Bedding material* in animal housing can have impacts on $NH_3$ emissions. 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). Ammonia emissions were significantly lower from sand (23% of applied urine N), followed by pine shavings (42% of applied urine N), than from the other four (straw, newspaper, cornstalks and recycled manure solids) bedding types (mean 63% of applied urine N). Ammonia emissions (g/cow/d) from manure solids (20.0), newspaper (18.9) and straw (18.9) were similar and significantly greater than emissions using pine shavings (15.2).

107. *Chemical air scrubbers* are effective in decreasing $NH_3$ emissions from animal houses, but are less applicable to cattle housing. Although such scrubbers have been demonstrated to be very effective for pig housing systems, due to the need for more research with cattle housing they are considered here as a category 2/3 technique.

**Category 3 techniques**

108. *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 proved to be ineffective or too difficult to maintain. The use of smooth and/or sloping floors to assist in scraping or flushing has given rise to problems with animal slipping and potentially injuring themselves. None of these systems can therefore be considered as category 2 techniques at present.

109. Table 11 gives emissions from different cattle housing systems (reference systems and category 1 and 2 techniques).

**Table 11:** Ammonia emissions of different cattle housing systems (reference systems and category 1 and 2 techniques)

| Housing type | Reduction[b] (%) | [c/] Ammonia emission (kg/cow place/year) |
|---|---|---|
| Cubicle house (Reference 1) | 0 | 12[d/] |
| Tied system[a/] (Reference 2) | 60 | 4.8 |
| Grooved floor (Cat. 1) | 25 | 9 |
| Optimal barn climatization with roof insulation (Cat. 1 | 20 | 9.6 |
| Chemical air scrubbers (forced ventilation systems only) (Cat.2 | 70-95 | 1.2 |
| Bedding of sand (slurry manure system only) Cat 2 | 60 | 4.8 |
| Bedding of pine shavings (solid manure system only) | 30 | 8.4 |

a/ Tied systems are not favoured for animal welfare reasons. Any conversion from tied stall to cubicle houses (e.g. to meet welfare requirements) should address the opportunity to include $NH_3$ emission mitigation measures at the same time.
[b]/ relative to either of the reference systems

c/ Emissions with full time housing of the animals. With grazing, emissions have to be reduced proportionally to the absence of the animals from the house.
d/ Based on a walking area of 4-4.5 $m^2$ per cow and permanent housing.

## B. Housing systems for pigs

110. *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.

111. Designs to reduce $NH_3$ emissions from pig housing systems apply the following principles:

(a) Reducing emitting manure surfaces (soiled floor, slurry surface in channels);
(b) Removing the manure (slurry) from the pit frequently to an external slurry store;
(c) Additional treatment, such as aeration, to obtain flushing liquid;
(d) Cooling the manure surface;
(e) Changing the chemical/physical properties of the manure, such as decreasing pH, and/or;
(f) Using surfaces which are smooth and easy to clean;
(g) Treatment of exhaust air by acid scrubbers or biotrickling filters.
(h) Lowering the indoor temperature as animal welfare and production allow.
(i) Reducing ventilation rate taking into account the minimum levels required for animal welfare reasons.
(j) Reducing air flow over the manure surface

112. Designs to reduce all emissions from pig housing are also described in the BREF relating to intensive pig production (larger pig installations).

113. Concrete, steel and plastic are used in the construction of slatted floors. Generally speaking, and given the same slot width, manure dropped on concrete slats takes longer to fall into the pit and this is associated with greater emissions of $NH_3$ than when using steel or plastic slats. It is worth noting that steel slats are not allowed in some countries.

114. Frequent removal of manure by flushing with slurry may result in a peak in odour emissions with each flush. Flushing is normally done twice a day: once in the morning and once in the evening. These peaks in odour emissions can cause nuisance to neighbours. Additionally treatment of the slurry also requires energy, unless passive systems are used where the plug can be removed manually. These cross-media effects have been taken into account in defining BAT on the various housing designs.

115. With respect to litter, it is expected that the use of straw in pig housing will increase due to raised awareness of animal welfare. It may be applied in conjunction with (automatically) controlled naturally-ventilated housing systems, where straw would allow the animals to control the temperature themselves, thus requiring less energy for ventilation and heating. In systems where litter is used, the pen is divided into a dunging area (without litter) and a littered solid floor area. It is reported that pigs do not always use these areas in the correct way and dung in the littered area and use the slatted area to lie on. However, the pen design can influence the behaviour of the pigs, although it is reported that in regions with a warm climate this might not be sufficient. Integrated evaluation of straw use would include the extra costs for straw supply and mucking out as well as the possible consequences for the emissions from storage of farmyard manure and for the application onto land. The use of straw results in farmyard manure has the benefit of increasing the organic matter (carbon storage) of the soils.

116. Growers/finishers are always housed in a group and most of the systems for group housing of sows apply here as well. The reference system for growers/finishers is a fully slatted floor with a deep manure pit underneath and mechanical ventilation. The associated emission level range is between 2.39 and 3.16 kg $NH_3$ per pig place per year. The system has been applied commonly throughout Europe.

117. Farrowing sows in Europe are generally housed in crates with steel and/or plastic slatted floors and a deep manure pit underneath. In the majority of the houses, sows are confined in their movement, with piglets walking around freely. All houses have controlled ventilation and often a heated area for the piglets during the first few days. The difference between fully and partly slatted floors is not so distinct in the case of farrowing sows, where the sow is confined in its movement. In both cases, manuring takes place in the same slatted area. Reduction techniques therefore focus predominantly on alterations in the manure pit.

118. Mating and gestating sows are housed individually or in a group. Group-housing systems require other feeding systems (e.g. electronic sow feeders) and a pen design that influences sow behaviour (use of manure and lying areas). Group housing is compulsory in new sow housing throughout EU Member States and in 2013 all mating and gestating sows, four weeks after being served or inseminated, will have to be housed in groups. Group-housing systems have similar emission levels to those from individual housing, if identical emission reduction techniques are applied. The reference system for housing of mating and gestating sows is the fully slatted floor (concrete slats) with a deep pit.

119. Weaners are housed in a group in pens or flat decks. In principle, manure removal is the same for a pen and a flat deck (raised pen) design. It is assumed that in principle, reduction measures applicable to conventional weaner pens can also be applied to the flat deck. Straw-based systems with solid concrete floors are conditional BAT, but cannot be assigned to a category as no data on $NH_3$ emissions have been reported.

**Category 1 techniques**

120. A number of manure removal or treatment systems can be used to reduce $NH_3$ emissions from pig housing:

(a) *Reducing the emitting manure surface*. Partly slatted floors (some 50% area), generally emit less $NH_3$, particularly if the slats are metal- or plastic-coated, allowing the manure to fall more rapidly and more completely into the pit below. Emissions from the solid part of the floor can be reduced by using an inclined or convex, smoothly finished surface, by appropriate location of the feeding and watering facilities to prevent fouling the solid areas and by good climate control.

(b) *Flushing systems*. There are many different types of flushing systems. Low-emission flushing systems remove the manure from the pit rapidly.

(c) *Vacuum systems.* Rapid removal of manure from pits can be achieved by vacuum removal systems operated at least twice a week.

(d) *Manure cooling.* Cooling of the surface of the manure in the under-floor pit to $12^{\circ}$ C or less by pumping groundwater through a floating heat exchanger can substantially reduce $NH_3$ emissions. A readily-available source of groundwater is required and the system may not be allowed where drinking water is extracted. There may be significant costs to setting up such a system.

121. A housing system has been developed incorporating manure surface cooling fins using a closed system with heating pumps. It performs well (Category 1), but is a very costly system. In retrofit situations this technique can be economically viable, but this has to be decided on a case-by-case basis. It should be noted that energy efficiency can be less in situations where the heat that arises from the cooling is not used, e.g. because there are no weaners to be kept warm.

122. New designs for pig housing should, ideally, integrate the floor, manure pit and removal system with pen geometry to influence drinking and dunging areas in combination. Manure pit surface area can be reduced by using, for example, manure pans, manure gutters or small manure channels.

123. *Treatment of exhaust air* by acid scrubbers or biotrickling filters is another option that has proven to be practical and effective for large scale operations in Denmark, Germany and the Netherlands. A number of manufacturers provide scrubber and trickling filters that are subject to field test and certification procedures in these countries to be admitted for practical use. They are most economically practical when installed into ventilation systems during the building of new houses. Application in existing housing demand extra costs to modify ventilation systems. Further information is desirable on the suitability of these systems for housing systems in South and Central Europe.

124. Acid scrubbers mainly apply sulphuric acid in their recirculation water to bind ammonia as ammonium sulphate and have demonstrated ammonia removal efficiencies between 70 and 95 per cent, depending on their pH-set values. Nitrogen is removed out of the system by controlled discharge of recirculation water that contains an ammonium sulphate solution. In biotrickling filters, ammonia is converted in nitrate by biomass on the synthetic package material and in the recirculation water. Ammonia removal efficiencies of 70 per cent can be guaranteed for properly designed filters. Operational costs of both acid scrubbers and trickling filters are especially dependent on the extra energy use by water recirculation and increased pressure differences. However, the high ammonia removal capacity of scrubbers enables in several parts of Europe scales of farming operations that outweigh the higher operational costs.

125. Table 12 provides an overview of the low emission housing and emission reduction techniques for pig houses, including the emission reduction percentages and the estimated cost of the low-emission techniques. Air scrubbing techniques have not been included in the list of Table 12 yet. Some of the techniques are costly, especially when applied in existing housing systems. Further, the estimated cost show a wide range, because the cost will depend on the farm-specific conditions. Evidently, the choice of the technique and low-emission systems must be considered from a whole-farm perspective (and not from the perspective of a technique). When considered from a whole-farm perspective, low-emission techniques and systems will be much lower than in the case of the summation of individual techniques.

126. Denmark and The Netherlands have obtained a considerable experience with implementation of low-emission techniques and housing systems. A recent study showed that the overall mean cost of $NH_3$ emission reduction from pig housing systems in The Netherlands in 2007 was 0.016 euro per kg of pig produced (Baltussen et al., 2010). By that time all large farms (IPPC farms), had low emission techniques installed with an emission reduction target of 40-60%. These cost relate to the low-emission housing and covered storages. The estimated cost will be 0.036 euro per kg of pig produced (carcass weight) in 2013 when all pig farms (including also small farms) have to fulfill the low-emission targets (and animal welfare restrictions) in The Netherlands. When assuming that about 200 kg of pig meat is produced per pig place per year, the total mean cost of the $NH_3$ emission reduction measures in the Netherlands are 7.2 euro per pig place. This is an upper estimate, as all cost for the $NH_3$ emission reduction measures are transferred to fatteners, while a significant fraction of the $NH_3$ also originates from the sows and piglets. The mean cost of the measures expressed in euro per kg saved are estimated 3 euro per kg N saved. This estimate may be used as a robust mean for the whole sector in The Netherlands.

127. Apart from the cost of low-emission techniques, there are also benefits of low emission housing, in terms of a higher feed conversion rate; the feed costs reduce by 1-3% (Baltussen et al., 2010). These reduced feed costs are approximately equivalent to the operational cost of air scrubbers (about 5 euro per fattening pig place per year). The investment cost of scrubbers are 60-80 euro per pig place or 5-10 euro per fattening pig place per year).

**Table 12:** Category 1 techniques: reduction and costs of low-emission housing systems for pigs

| **Category (Annex IX paragraph no.)** | **(% Reduction)** | **Extra Cost (€/place per year)** | **Extra Cost (€/kg pig produced) (**)** | **Ammonia emission** (kg NH3/place per year) **(*)** | **ExtraCost (€/kg NH3 reduced)** |
|---|---|---|---|---|---|
| | | | | | |
| **Pig housing (Existing)** | | | | | |
| **Gestating Sows** | | | | **2.7** | |
| Partially slatted floor with reduced pit | 20 – 50 | 5.69 – 6.83 | 0.0021 – 0.0030 | | 4.21 - 12.65 |
| Frequent manure removal | 25 | 0 | 0 | | 0 |
| **Lactating Sows** | | | | **3.73** | |
| Combination water manure channel | 52 | 16.74 – 20.09 | 0.0021 – 0.0025 | | 8.63 – 10.36 |
| Manure pan underneath | 32 - 65 | 30.98 – 37.17 | 0.0039 – 0.0046 | | 12.80 – 31.23 |
| **Piglets (6 - 20 kg)** | | | | **0.72** | |
| Manure channel with sloped floor | 30 - 60 | 1.27 – 2.67 | 0.0015 – 0.0031 | | 2.94 – 12.36 |
| Partially slatted floor with reduced pit | 25 - 35 | 0.88 – 2.25 | 0.0010 – 0.0026 | | 3.49 – 12.50 |
| Frequent manure removal | 25 | 0 | 0 | | 0 |
| **Growers - Finishers (20 – 100 kg)** | | | | **3.16** | |
| Manure channel with sloped floor | 10 - 30 | 6.45 – 7.74 | 0.0219 – 0.0263 | | 4.08 – 12.25 |
| Partially slatted floor with reduced pit | 30 - 35 | 3.61 – 4.33 | 0.0123 – 0.0147 | | 4.57 – 3.26 |
| Frequent manure removal | 30 - 60 | 0 | 0 | | 0 |
| **Pig housing (New build)** | | | | | |
| **Gestating Sows** | | | | **2.7** | |
| Partially slatted floor with reduced pit | 20 – 50 | 0 | 0 | | 0 |
| Frequent manure removal | 25 | 0 | 0 | | 0 |
| **Lactating Sows** | | | | **3.73** | |
| Combination water manure channel | 52 | 3.29 – 3.95 | 0.0004 – 0.0005 | | 1.70 – 2.04 |
| Manure pan underneath | 32 - 65 | 17.52 – 21.02 | 0.0022 – 0.0026 | | 17.66 – 7.24 |
| **Piglets (until 20 kg)** | | | | **0.72** | |
| Manure channel with sloped floor | 30 - 60 | 0 – 0.25 | 0 – 0.0003 | | 0 – 1.16 |
| Partially slatted floor with reduced pit | 25 - 35 | 0 | 0 | | 0 |
| Frequent manure removal | 25 | 0 | 0 | | 0 |
| **Growers - Finishers (20 – 100 kg)** | | | | **3.16** | |
| Manure channel with sloped floor | 10 - 30 | 0 – 0.73 | 0 – 0.0025 | | 0 – 2.31 |
| Partially slatted floor with reduced pit | 30 - 35 | 0 | 0 | | 0 |
| Frequent manure removal | 30 - 60 | 0 | 0 | | 0 |

(*) non official data, in revision

(**) % gestating sows = 75% productive sows; Sow production = 20 pigs (100 kg) per sow per year; Pig marketed = 100 kg body weight

## C. Housing systems for poultry

### i. Housing systems for laying hens

128. The evaluation of housing systems for layers has to , in the European Union (EU) Member States, consider the requirements laid down by the European Directive 1999/74/EC, on housing of laying hens. These requirements prohibit the installation of new conventional cage systems and lead to a total ban on the use of such cage systems by 2012, with production thereafter only allowed in enriched cages (called also furniture cages) or non-cage systems, i.e. deep litter housing system or aviary system. In non EU countries conventional cage systems are still allowed.

129. *Reference system for non EU countries: Caged housing systems*. The reference system used for the housing of layers in caged systems is open manure storage under the cages. Most laying hens in non EU states are still housed in conventional cages and most of the information on $NH_3$ emission reduction addresses this type of housing.

130. *Enriched cages*. This system could be used as a replacement of conventional cages without a need for significant changes in design of existing building. Enriched cages offer the laying hens increased space and are equipped by areas for nesting, scratching and perches. Birds are kept in a group of 40 – 60 of hens. A ventilated belt placed under cages is the most common method of manure removal.

131. *Deep litter housing system.* A building equipped with this housing system is characteristic by 80-90 cm high dropping pits covered with wooden or plastic slats or wire mesh. The manure is collected in pits under the slats. Pits take two-third of total floor space. Remaining one third of the floor is covered by litter. As a litter sand, wood shavings, straw or other materials can be used. The litter area is used for scratching and dust-bathing of hens. A stocking density of birds is not more than 9 hens per m² of floor space.

132. *132. Aviary system (perchery).* A building is divided into different functional areas used for feeding and drinking, eggs laying, scratching and resting. All areas are covered with wooden or plastic slats or wire mesh. There could be installed ventilated manure belts for dropping collection and removal. A stocking density up to 18 hens per m² floor area is permitted. The same system of manure ventilation and removal as in cage systems can apply to some aviary systems where manure belts are placed under the tiers to collect the manure where the hens are free to walk around.

133. In some countries, the definition of “free range” includes deep litter housing system or aviary system but with access of birds to outdoors. In other countries, laying hens in “free-range systems” are housed on solid or partly slatted floors. In these systems 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 laying period (about 14 months).

**Category 1 techniques**

134. 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. So-called "stilt houses", where the removal of side walls from the lower areas used to store manures, can provide a highly effective means of ventilation although no data are available to enable a categorization of this approach.

135. 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 is dried on the belts through forced ventilation. The manure should be dried to a dry-matter content of 60–70% to prevent the formation of $NH_3$. If the manure from the belts is collected in an intensively ventilated drying tunnel, inside or outside the building, the dry-matter content of the manure can reach 60 –80 % in less than 48 hours. Weekly removal from the manure belts to covered storage has been shown to reduce emissions by 50% compared with removal every two weeks. In general, emission from laying hen houses with manure belts will depend on (a) The length of time that the manure is present on the belts; (b) The drying system; (c) The poultry breed; (d) The ventilation rate at the belt (low rate = high emissions) and (e) Feed composition.

136. Treatment of exhaust air by acid scrubber or biotrickling filters is an option that has been successfully applied on in several countries. Although highly effective in terms of ammonia removal (90%), the high dust loads in poultry housings can complicate reliable long term functioning of current designs. Compared to pig production, the relatively high costs to treat the fully installed ventilation capacity have delayed wider application of the current generation of scrubbers in laying hens systems.

137. Treating poultry manure in non-caged housing systems with aluminum sulfate (alum) is a technique that is being practiced in Northern America. Regular addition of alum decreases ammonia emissions by up to 70%. This results in lower ammonia levels in the rearing facilities and improves poultry production and make the environment safer for agricultural, also because alum reduces particulate matter ($PM_{2.5}$). The techniques of applying alum has been introduced originally as a procedure to lower phosphorus leaching losses from agricultural land following application of poultry manure. The treatment of poultry manure with alum has been well–researched. Results so far indicate that the benefits are twice as large as the cost of applying alum (http://www.sera17.ext.vt.edu/Documents/BMP_poultry_litter.pdf). However, there is no experience with this technique in other countries.

138. An overview of emission reduction techniques for conventionally caged layers is shown in Table 13, for enriched caged housing systems in Table 14 and for non-caged layers in Table 15.

**Table 13:** Conventional caged housing systems for laying hens: techniques and associated $NH_3$ emission reduction potential

| **Category 1** | **$NH_3$ reduction potential (%)** | **References** |
|---|---|---|
| 1. Non-aerated open manure storage under cages (RT)* | 0* | |
| 2. Manure removal by way of scrapers to open storage | 0 | |
| 3. Aerated open manure storage under cages (deep-pit or high rise systems and channel house) | 30 | |
| 4. Manure removal by way of belts to closed storage | 58–76 | |
| 5. Vertical tiered cages with manure belts and forced air drying | 55 | |
| 6. Vertical tiered cages with manure belts and whisk-forced air drying | 60 | |
| 7. Vertical tiered cages with manure belts and improved forced air drying | 70–88 | |
| 8. Vertical tiered cages with manure belts and inside or outside drying tunnel | 80 | |
| 9. Chemical scrubbing of exhaust air | 75-90 | |

* Reference techniques (RT) and all the other reduction percentages of the other techniques are based on 0.083 kg $NH_3$/year x place. In the warm regions, an emission of the RT of 0.220 kg $NH_3$/year x place has been measured.

**Table 14:** Enriched caged housing systems for laying hens: techniques and associated $NH_3$ emission reduction potential

| **Category 2** | **$NH_3$ reduction potential** (%) | **References** |
|---|---|---|
| Enriched cages (EC), two removals a week (RT) | 0* | BREF 2003 |
| Enriched cages (EC) , three removals a week | 20 | [Revision of BREF - 57, Denmark 2010 ] EF – 0,028 |
| Enriched cages (EC), two removals a day | 42 | [Revision of BREF - 57, Denmark 2010 ] EF – 0,020 |
| Chemical scrubbing of exhaust air | 75-90 | |

*Reference techniques (RT) and all the other reduction percentages of the other techniques are based on 0.035 kg $NH_3$/year x place.

**Table 15:** Non-caged housing systems for laying hens: techniques and associated $NH_3$ emission reduction potential

| **Category 2 techniques** | **$NH_3$ reduction potential (%)** | **References , Emission factor** |
|---|---|---|
| Deep litter, perforated floor, manure Belts (RT)* | 0 | [Revision of BREF – 64,65,66, Germany 2010 ] EF – 0.32 |
| Deep litter, partly slatted, manure belts | 78 | [Revision of BREF – 70 Netherlands 2010 ] EF – 0.052-0.068 |
| Deep litter with forced manure drying | 40 | [Revision of BREF – 39, Germany 2001, 41 Netherlands 2001 ] EF – 0.125 |
| Deep litter with perforated floor and forced manure drying | 65 | [Revision of BREF – 44 Netherlands 2000 ] EF – 0.110 |
| Aviaries, perch design, non ventilated manure belts, | 72 - 85 | [Revision of BREF – [79, Netherlands 2010, 60, 61 , 62 Germany 2010] EF – 0.05 - 0.09 |
| Aviaries, ventilated manure belts, | 81 - 95 | Revision of BREF – [60, 61 , 62, 81 Germany 2010, 73, 76 Netherlands] EF – 0.014 - 0.055 |
| 9. Chemical scrubbing of exhaust air | 75-90 | |

* Reference techniques (RT) and all the other reduction percentages of the other techniques are based on 0.315 – 0.320 kg $NH_3$/year x place.

## ii. Housing systems for broilers

139. Traditionally, broilers are kept in buildings with a solid, fully littered floor. This is taken as the reference. To minimize $NH_3$ emission, it is important to keep the litter as dry as possible. The dry-matter content and the emission of $NH_3$ depend on the:

(a) Drinking-water system (avoiding leakage and spills);
(b) Duration of the breeding period;
(c) Animal density and weight;
(d) Use of air purification systems;
(e) Use of floor insulation;
(f) Feed.

**Category 1 technique**

140. A simple way of maintaining dry manure and reducing $NH_3$ emission is to reduce the spillage of water from the drinking system (e.g. using a nipple drinking system). In Table 16, category 1 techniques are indicated which are BAT under all conditions. In contrast to other category 1 measures, no data are reported of reductions in $NH_3$ emissions. Nevertheless, the effectiveness of inhibiting uric acid hydrolysis in preventing emission is so well established that measures that keep manure dry may be considered as category 1.

141. Air scrubber technology to remove $NH_3$ and fine particles ($PM_{2.5}$ and $PM_{10}$) from ventilation air of broiler houses is effective in ammonia removal (e.g. 90% removal), but has not been widely implemented yet, in part because of the economic costs involved. In The Netherlands, Germany and Denmark packed-bed filters and acid scrubbers for removal of ammonia from exhaust air of animal houses are off-the-shelf techniques for ammonia removal (70 - 95% average removal). At the moment a new generation of so-called "multi-pollutant scrubbers" is being developed and tested that not only removes ammonia but also aims for significant removal of odor and particulate matter (PM10 and PM2.5) from the air. So far, removal efficiencies are much higher for ammonia than for odour and $PM_{2.5}$ and $PM_{10.}$

**Category 2 techniques**

142. Effective emission reduction can be achieved through forced drying and several systems are currently being evaluated (Table 11). These systems are energy-intensive and may increase dust emissions. However, the extra ventilation improves the distribution of heat, giving some savings on heating costs. The Combideck System can also be considered a category 2 technique because it is BAT only if local conditions allow its adoption.

**Table 16:** Housing systems for broilers: techniques and associated $NH_3$ emission reduction potential

| | **$NH_3$ reduction potential (%)** | **BAT assessment#** |
|---|---|---|
| Deep litter; fan ventilated house (RT)* | 0* | Not applicable |
| Naturally-ventilated house with a fully littered floor and equipped with non-leaking drinking system (cat.1) | No data | BAT |
| Well-insulated fan ventilated house with a fully littered floor and equipped with non-leaking drinking system (cat.1) | No data | BAT |
| Perforated forced air drying (cat. 2) | 82 | BAT only for housing systems that are already in place |
| Tiered floor and forced air drying (cat. 2) | 94 | " " " " |
| Tiered removable sides; forced air drying (cat.2) | 94 | " " " " |
| Combideck System (cat. 2) | 44 | Conditional BAT |
| Chemical scrubbing of exhaust air | 90 | BAT |

*Reference techniques (RT) and all the other reduction percentages of the other techniques are based on 0.080 kg $NH_3$/year x place.

# The definition of BAT includes a non-quantified element of cost. Category 1 techniques may not, therefore, have been defined as BAT because of perception of costs, or may only have been defined as BAT where already fitted.

## iii. Housing systems for turkeys and ducks

143. *Reference system turkeys:* Traditionally, turkeys are kept in buildings with a solid, fully littered floor, very similar to the housing of broilers. Birds are housed in closed, thermally insulated buildings with forced ventilation or in open houses with open sidewalls. Manure removal and cleaning takes place at the end of each growing period. $NH_3$ emission has been measured under practical conditions in a commonly used turkey house with a fully littered floor and has been found to be 0.680 kg $NH_3$ per turkey place per year.

144. *Reference system ducks:* The commonly applied duck house is a traditional housing system, very similar to the housing of broilers. Partly slatted/partly littered floor and fully slatted floor are other housing systems for fattening of ducks.

145. Techniques that can be considered as category 1 (which are also considered as BAT) include: (a) Naturally-ventilated house with a fully littered floor and equipped with non-leaking drinking system; and (b) Well-insulated fan ventilated house with a fully littered floor and equipped with non-leaking drinking system;

**146.** The following techniques are considered as category 2, because data on $NH_3$ emission reduction are not currently available : (a) Perforated forced air drying; (b) Tiered floor and forced air drying; (c) Tiered removable sides; forced air drying; and (d) Air scrubber technology to remove $NH_3$ and fine particles.

# VI. MANURE STORAGE TECHNIQUES

147. *Reference technique*. The baseline for estimating the efficiency of an abatement measure is the emission from the same type of store, without any cover or crust on the surface. Table 17 gives an overview of the different emission abatement measures for slurry stores and their efficiency in reducing $NH_3$ emissions.

148. After removal from animal houses, slurry is commonly stored in concrete or steel tanks or silos, or in an earth-banked lagoon (with an impermeable liner – clay or plastic). The latter tend to have a relatively larger surface area per unit volume than the former. Emissions from slurry stores can be reduced by decreasing or eliminating the airflow across the surface by installing a floating cover (different types), by allowing the formation of a surface crust, or by reducing the surface area per unit volume of the slurry store. Reducing the surface area is only a consideration at initial store design or at replacement.

149. Where poultry manure is already dry (e.g. within poultry housing), for any further long term storage elsewhere, it is BAT to provide a barn or building with an impermeable floor with sufficient ventilation; this will keep the manure dry and prevent further significant losses.

150. When using an emission abatement technique for manure stores, it is important to prevent loss of the conserved $NH_3$ during spreading on land by using an appropriate reduced-emission application technique.

**Category 1 techniques**

151. The best proven and most practicable techniques to reduce emissions from slurry stored in tanks or silos is to provide a 'tight' lid, roof or tent structure. The application of these techniques to existing stores depends on the structural integrity of the stores and whether they can be modified to accept the extra loading. Plastic sheeting (floating cover sheeting may be a type of plastic, canvas or other suitable material) is suitable for *small* earth-banked lagoons. Storage bags for slurry on small farms (e.g. < 150 fattening pigs) also provide a system that reduces emissions. While it is important to guarantee that such covers are well sealed or "tight" to minimize air exchange, there will always need to be some small openings or a facility for venting to prevent the accumulation of flammable gases, such as methane.

**Table 17:** Ammonia emission abatement measures for cattle and pig slurry storage.

| Abatement Measure | $NH_3$ emission reduction %[a/] | Applicability | BAT for IPPC pig farms?[#] | Costs (OPEX) (€ per $m^3$/yr)[c/] |
|---|---|---|---|---|
| 'Tight' Lid, roof or tent structure (Cat. 1) | 80 | Concrete or steel tanks and silos. May not be suitable on existing stores. | Yes – but decisions taken on a case by case basis | 8.00[b/] |
| *Plastic sheeting (floating cover) (Cat. 1) | 60 | Small earth-banked lagoons. | Yes – but decisions taken on a case by case basis | 1.25 |
| Natural crust (floating cover) (Cat. 1) | 40 | Higher dry matter slurries only. Not suitable on farms where it is necessary to mix and disturb the crust in order to spread slurry frequently. | Yes – but decisions taken on a case by case basis | 0.00 |
| Replacement of lagoon, etc. with covered tank or tall open tanks (H> 3 m) (Cat.1) | 30– 60 | Only new build, and subject to any planning restrictions concerning taller structures. | Not assessed | 14.9 (cost of tank 6.94) |
| Storage bag (Cat. 1) | 100 | Available bag sizes may limit use on larger livestock farms. | Not assessed | 2.50 |
| *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. | Yes – but decisions taken on a case by case basis | 1.25 |
| "Low technology" floating covers (e.g. chopped straw, peat, bark, LECA balls, etc.) (Cat. 2) | 40 | Concrete or steel tanks and silos. Probably not practicable on earth-banked lagoons. Not suitable if materials likely to cause slurry management problems. | Yes – but decisions taken on a case by case basis | 1.10 – tanks |

* Sheeting may be a type of plastic, canvas or other suitable material.
a/ Emission reductions are agreed best estimates of what might be achievable across the UNECE region. Reductions are expressed relative to emissions from an uncovered slurry tank/silo.
b/ Costs are for the United Kingdom. Costs refer to the cost of the lid/roof only, and do not include the cost of the silo.
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)
# The definition of BAT includes a non-quantified element of cost. Category 1 techniques may not, therefore, have been defined as BAT because of perception of costs, or may only have been defined as BAT where already fitted.

## Category 2 techniques

152. There is a range of floating covers that can reduce $NH_3$ emissions from stored slurries by preventing contact between the slurry and the air. However, the effectiveness and practicality of these covers are not well tested, except for 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, LECA (light expanded clay aggregates) balls or other floating material applied to the slurry surface in tanks or earth-banked lagoons. Floating covers might hinder homogenization of the slurry prior to

spreading; some of the materials used may hinder the spreading process itself, by clogging up machinery, or cause other slurry management problems.

153. Minimizing stirring of stored cattle slurry of a sufficiently high dry matter content will allow the build-up of a natural crust. If this crust totally covers the slurry surface and is thick enough, and slurry is introduced below the crust, such a crust can significantly reduce $NH_3$ emissions at little or no cost. This natural crust formation is an option for farms that do not have to mix and disturb the crust in order to spread slurry frequently. The emission abatement efficiency will depend on the nature and duration of the crust.

154. If shallow earth-banked lagoons are replaced by taller tanks or silos, emissions will be 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). However, the effectiveness of this option is difficult to quantify, as it is strongly dependent on the characteristics of the lagoon and the tank.

155. There are few options for reducing $NH_3$ emissions from stored farmyard manures for cattle and pigs. Experiments have shown that covering farmyard manure piles with plastic sheeting can substantially reduce $NH_3$ emissions, and did not show any significant increase in methane or nitrous oxide emissions (T. Misselbrook, personal communication). At present, this is considered as a category 2 technique, due to the need for more general testing of the abatement efficiency.

# VII. MANURE APPLICATION TECHNIQUES

156. *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. 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.

157. *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 18 represent averages over a wide range of conditions. The absolute magnitude of ammonia emission levels of the reference techniques varies 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.

158. Emissions of ammonia expressed as a percentage of the TAN (total ammoniacal nitrogen) applied are typically in the range of 40-60% following application using the reference technique (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 <u>increased</u> with <u>increasing</u>: evapotranspiration (air temperature, wind speed, solar radiation); and slurry DM concentration. Emissions of ammonia as a percentage of TAN applied are normally <u>increased</u> with <u>decreasing</u>: 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, some soils may become hydrophobic when very dry, which can also reduce infiltration and therefore increase emissions.

**Category 1 techniques**

158. Category 1 techniques include machinery for substantially decreasing the surface area of slurries applied to land and 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 NH3-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 most 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% applied in water irrigation systems

**Table 18(a)**: Category 1 abatement techniques for slurry* application to land. The abatement measures refer to the category 1 techniques listed in provision 158.

| Abatement measure | Land use | Emission reduction (%)† | Factors affecting emission reduction | Limitations to applicability compared with the reference | Estimated costs relative to reference |
|---|---|---|---|---|---|
| (a) Band-spreading slurry with a trailing hose | Grassland<br>Arable | 30-35%% | More crop canopy will increase reduction, depending on placement precision and the extent of herbage contamination. | | 1.0 - 1.3<br>May be cost neutral or net financial benefit if co-benefits considered. |
| Band spreading with trailing shoe | Grassland<br>Arable (pre-seeding) and row crops | 50-60% | More crop canopy will increase reduction, depending on placement precision and the extent of herbage contamination. | Not suitable for growing solid seeded crop or | 1.0 - 1.5<br>May be cost neutral or net financial benefit if co-benefits considered. |
| (b) Injecting slurry (open slot) | Grassland | 70% | Injection depth ≤ 5 cm | Unsuitable where:<br>Slope >15%;<br>High stone content;<br>Shallow soils;<br>High clay soils (>35%) in very dry conditions,<br>Peat soils (>25% organic matter content). | 1.0 - 1.9 |
| (c) Injecting slurry (closed slot) | Grassland<br>Arable | 80 (shallow slot 5-10 cm)<br>90 (deep injection >15cm) | Effective slit closure | | 1.0 - 1.9 |
| (d) Incorporation of surface applied slurry | Arable | Immediately by ploughing = 90% | | | 1.0 - 2.0 |
| | | Immediately by non-inversion cultivation = 70% | | | 1.0 - 1.8 |
| | | Incorporation after 4 hrs = 45-65% | Efficiency depends on application method and weather conditions between application and incorporation | | 1.0 - 1.5 |
| | | Incorporation within 24 hours = 30% | | | 1.0 - 1.1 |
| (e) Active dilution of slurry of >4% DM to <2% DM for use in water irrigation systems | Arable<br>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 water irrigation systems. Not appropriate where irrigation is not required. | ~1.1 |

* 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).
† Average emission agreed to be achievable across the UNECE region.

**Table 18 (b):** 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 | Estimated costs relative to reference |
|---|---|---|---|---|---|
| (d) Incorporation of surface applied manure | Arable | Immediately by ploughing = 90% | Degree of burying the manure | | 1.0 - 2.0 |
| | | Immediately by non-inversion cultivation = 60% | Degree of burying the manure | | 1.0 - 1.8 |
| | | 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; | | 1.0 - 1.1 |
| | | Incorporation within 12 hours = 50% | | | 1.0 - 1.1 |
| | | Incorporation within 24 hours = 30% | | | 1.0 - 1.1 |

* 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.

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

160. Table 18 also summarizes 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.

161. 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 a 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.

162. ***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 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.

163. ***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. 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.

164. ***Trailing shoe:*** This technique is mainly applicable to grassland [Insert: and arable crops 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 grass 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.

165. 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.

166. ***Injection – open slot:*** This technique is mainly for use on grassland. Different shaped knives or disc coulters are used to cut vertical slots in the soil up to 50–60 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 50-75 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 soil, 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.

167. ***Injection – closed slot.*** This technique can be shallow (50–100 mm depth) or deep (150–200 mm). Slurry is fully covered after injection by closing the slots with press wheels or rollers fitted behind the injection tines. 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.

168. ***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 21). 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 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 to solid manures on arable soils. The

technique is also effective for slurries where closed-slot injection techniques are not possible or available.

169. 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 18). Incorporation within 24 hours of spreading will also reduce emissions to a 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 exposed to the atmosphere.

170. ***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 sprinkler or travelling irrigator, 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 6). 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.
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.

171. 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.

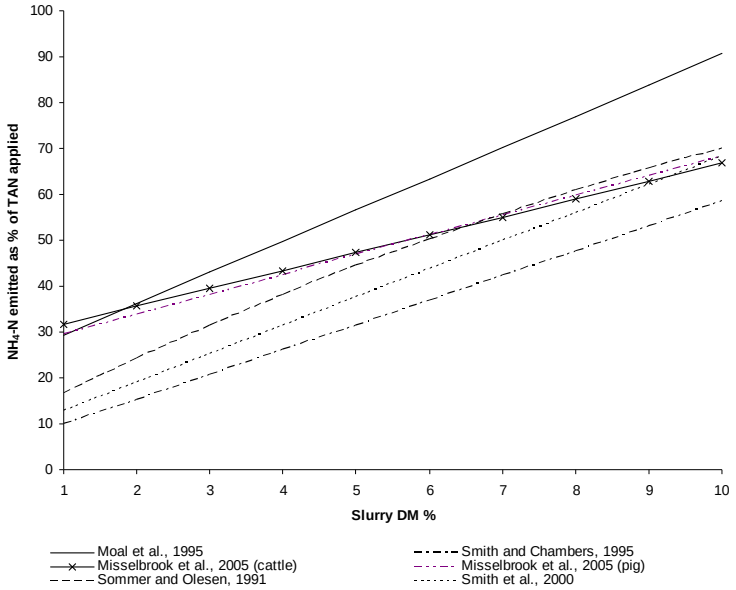


**Figure 6:** Relationship between the percentage of total ammoniacal nitrogen (TAN) emitted as ammonia during the land application of slurry and the dry matter content (DM % weight) of the slurry, according to six estimates. Even though ammonia emissions are still significant at 1% DM content (10-30% of TAN lost through volatilisation), a 50% reduction in DM content will achieve roughly a 30% reduction in average ammonia emissions.

172. ***Additional benefits of techniques to reduce ammonia emissions from the land application of slurry and solid manure.*** The experimental quantification of N fertilizer benefits 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 relatively low application rate of additional N. Although the uptake of the ammonia-N by the crop will vary, the N 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.

173. 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.

174. 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 pollution by avoiding spreading slurry onto adjacent areas such as near water courses.

175. 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. 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.

176. ***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 (Webb et al. 2010). The overall benefit-cost ratio depends especially on equipment costs and abatement efficiency.

177. ***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 esp. 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. 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 high energy costs of nitrogen fertilizer manufacture.

178. 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 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.

179. 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 on microbial metabolism.]

**Category 2 techniques**

180. ***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) presurized 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 Atmospheric Timing Management Systems (ATMS) as described in the paragraph below.

181. ***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.

182. 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.

183. 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.

184. 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.

185. ***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.

186. ***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) (Riedy and Menzi 2007). This is potentially a cost-effective approach as it can be done using broadcast application equipment. 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.

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

188. This approach can be considered as rather different to the technical methods listed as Category 1, such as band spreading, manure incorporation, where the efficiencies reported in Table 21 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) to the actual timing practice.

189. 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.

190. 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 affects the total amounts of manure to be spread.

191. *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.

192. 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 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.

193. *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"*.

194. 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.

195. 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.

196. 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.

197. 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.

198. *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. 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. 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 $N_2O$. 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.

199. 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. 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 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.

**Category 3 techniques**

200. *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 the quantities required are 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

201. 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. 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 focussed 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).

202. 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. Since the measures to reduce ammonia emissions from urea-based fertilizers remain limited, especially on perennial crops, such a change would be expected to significantly increase regional ammonia emissions.

203. 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).

204. *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 19.

**Category 1 techniques**

205. 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.

206. *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).

207. *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.

208. *Incorporation of fertilizer into the soil* either by direct closed-slot injection of 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 fertiliser 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.

209. *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.

210. *Switching from urea to ammonium nitrate* fertilizer is a rather easy way to reduce ammonia emissions, with an effectiveness of around 90%. 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.

211. ***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.

212. ***Impact on N cycle.*** 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 $NH_3$ 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 increase overall nitrate leaching or nitrous oxide loss. The measures focus on retaining nitrogen in the farming system, thereby maximizing productivity.

**Table 19:** Mitigation options (Category 1) for reducing ammonia emissions from urea-based fertilisers.

| **Abatement measure** | **Fertilizer type** | **Emission reduction (%)** | **Factors affecting emission reduction** | **Applicability** | **Estimated costs relative to reference[1]** |
|---|---|---|---|---|---|
| Surface broadcast | Urea-based | Reference | | | |
| Urease inhibitor | Urea-based | 70% for solid urea 40% for liquid urea ammonium nitrate | | All | 1.0 – 2.0 |
| Slow release fertilizer (polymer coatings) | Urea-based | c. 30% | Polymer coating type and integrity; fertilizer application technique (surface or injected) | All | 1.0 – 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 | 1.0 – 1.5 |
| Incorporation | Urea-based fertilizers | 50-80% | Delay after fertilizer application; depth of mixing; soil texture | Tilled land prior to crop establishment | 1.0 – 1.5 |
| 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 | 1.0 -2.0 |
| 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 | 1.0 – 1.1 |

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

**Category 2 techniques**

213. *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, as discussed under the sand application section (Paragraphs 182-193).

214. *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.

**Category 3 techniques**

215. *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 sulfate and ammonium phosphate based fertilizers

**Category 1 techniques**

216. 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 (subject to the result of trials).

**Category 2 techniques**

217. 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

218. 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 often limited by soil type, topography, farm size and structure (distances), climatic conditions, 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.

219. 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 $NH_3$.

## (b) Manure treatment

220. 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 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.

221. 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

222. 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.

## (d) Manure additives

223. A wide variety of manure additives has been suggested to reduce $NH_3$ emissions. They mostly aim at reducing the $NH_3$ content or the pH by chemical or physical processes. Their efficiency in reducing $NH_3$ emissions (up to 70% reduction reported) depends on how well they achieve these aims and on where in the manure management process they are introduced. The gain pig slurry acidification through the addition of sulphuric acids in terms of N saved (less $NH_3$ lost) is equivalent to approximately 35 kg mineral N/ha when using pig manure, this represents €1.13 per kg N prevented to emit in the pig house and during storage (source: Danish Agricultural Advisory Service). Based on the scientifically sound principles and mechanism and the substantial experience in Denmark (and previously also in The Netherlands), acidification of animal slurries outside animal houses may be considered a category 1 technique.

# X. NON-AGRICULTURAL STATIONARY AND MOBILE SOURCES

224. 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).

225. 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

226. *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.

227. *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.

228. 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 $NH_3$.

229. 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.

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

## (b) Techniques suited to selected sectors

231. *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 carburettor 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.

232. *Ammonia slippage in staionary 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.

233. *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.

234. *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).

235. *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 $NH_3$.

236. *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.

237. *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

238. 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.

239. 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.

240. 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 $NH_3$-N/$m^3$ may be achieved through maximizing product recovery and minimizing atmospheric emissions by appropriate maintenance and operation of control equipment.

241. 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.

242. 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).

243. 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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