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Modeling of Emissions of Air Pollutants and Greenhouse Gases from Agricultural Sources in Europe

Klimont, Z. and Brink, C.

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Modelling of Emissions of Air Pollutants and Greenhouse Gases from Agricultural Sources in Europe

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Contents

1. INTRODUCTION 1

1.1. THE RAINS INTEGRATED ASSESSMENT MODEL 2

1.2. SUMMARY OF THE MODIFICATIONS AND EXTENSIONS INTRODUCED SINCE THE PREVIOUS VERSION OF THE RAINS AMMONIA MODULE 4

2. THE STRUCTURE OF THE AGRICULTURAL MODULE IN RAINS 6

2.1. AGGREGATION OF EMISSION SOURCES 6

3. ACTIVITY DATA 8

3.1. AGRICULTURE 8

3.1.1 Livestock data 8

3.1.2 Mineral fertilizer application 11

3.2. STATIONARY COMBUSTION AND TRANSPORT 12

3.3. WASTE TREATMENT AND DISPOSAL 12

3.4. OTHER SOURCES 13

4. METHODOLOGY FOR EMISSION CALCULATION 14

4.1. AMMONIA EMISSIONS FROM LIVESTOCK FARMING 14

4.1.1 Emission factors 16

4.1.1.1. Dairy cows 18

4.1.1.2. Other cattle 21

4.1.1.3. Pigs 22

4.1.1.4. Other livestock categories 24

4.2. NITROUS OXIDE EMISSIONS FROM LIVESTOCK 24

4.2.1 Direct emissions from manure management 25

4.3. METHANE EMISSIONS FROM LIVESTOCK 27

4.3.1 Enteric fermentation 27

4.3.2 Manure management 27

4.4. AMMONIA EMISSIONS FROM MINERAL FERTILIZER APPLICATION 29

4.4.1 Emission factors 29

4.5. NITROUS OXIDE EMISSIONS FROM APPLICATION OF FERTILIZERS 31

4.5.1 Direct emissions from agricultural soils *31*

4.5.2 Indirect emissions after nitrogen deposition *32*

4.5.3 Indirect emissions induced by nitrogen leaching and runoff *33*

4.6. EMISSIONS FROM FERTILIZER PRODUCTION 34

4.6.1 Ammonia *34*

4.6.2 Nitrous oxide *36*

4.7. STATIONARY COMBUSTION SOURCES 36

4.8. MOBILE SOURCES 39

4.9. WASTE TREATMENT AND DISPOSAL 42

4.10. OTHER SOURCES OF AMMONIA EMISSIONS 43

4.10.1 Biomass burning *43*

4.10.2 Industrial processes *44*

4.10.3 Humans and pets *44*

4.10.4 Other sources *45*

4.11. OTHER SOURCES OF NITROUS OXIDE AND METHANE EMISSIONS 45

4.11.1 Rice cultivation *45*

4.11.2 Other anthropogenic sources of nitrous oxide *46*

5. EMISSION CONTROL OPTIONS 47

5.1. OPTIONS TO CONTROL AMMONIA EMISSIONS 47

5.2. IMPACT OF AMMONIA REDUCTION MEASURES ON EMISSIONS OF NITROUS OXIDE AND METHANE 52

5.2.1 Low nitrogen feed (LNF) *53*

5.2.2 Treatment of air ventilated from animal buildings (BF) *53*

5.2.3 Livestock buildings adaptation (SA) *53*

5.2.4 Covered outdoor storage of manure (CS) *54*

5.2.5 Low ammonia application of manure *55*

5.2.6 Urea substitution *56*

5.2.7 End-of-pipe options in fertilizer plants *56*

6. REFERENCES 57

ANNEX 1 61

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Zbigniew Klimont, a graduate of Warsaw Technical University, is an environmental engineer whose scientific interests are in modelling energy supply and demand, global warming, energy systems and air pollution problems. A research fellow at the Polish Academy of Sciences, he joined IIASA in 1992 to contribute to the development of the RAINS model, specifically emission and cost modules for the estimation of ammonia, volatile organic compounds and particulate matter.

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1. Introduction

Atmospheric ammonia (NH_3) is, next to sulphur dioxide (SO_2) and nitrogen oxides (NO_x), an important contributor to acidification and eutrophication of natural ecosystems. For a number of reasons emissions of ammonia have received less attention during the negotiations of recent international agreements on the reduction of emissions of air pollutants in Europe than other pollutants. In the future, the importance of NH_3 is expected to grow, not only because other emissions of acidifying pollutants are declining, but also because its role in the eutrophication of ecosystems and its contribution to the formation of secondary particles receives increasing attention. Thus, it will be important to balance potential measures for controlling ammonia emissions against the remaining potential for further cuts of other pollutants that also contribute to acidification, eutrophication and high levels of fine particles in the atmosphere.

Integrated assessment models have been developed to identify least-cost strategies to control emissions of different pollutants leading a variety of environmental effects. The Regional Air Pollution Information and Simulation (RAINS) model (e.g., Schöpp *et al.*, 1999; Cofala *et al.*, 2000; Alcamo *et al.*, 1990), created at the International Institute for Applied Systems Analysis (IIASA), is a tool for exploring cost-effective emission reductions that improve acidification, eutrophication, ground-level ozone and fine particulate matter (Amann and Lutz, 2000; Amann *et al.*, 1998).

Agricultural emissions of ammonia have been included in the RAINS model for the first time in 1991, when the first version of the ammonia module was developed (Klaassen, 1991ab, 1994). Although some small modifications and model extensions have been carried out since, new approaches to estimate ammonia losses from agriculture required a major revision of the original model concept.

This new approach, often called a “process-based” or “N-flow” approach (Asman *et al.*, 1998; FAL-IUL, 1998; Dämmgen *et al.*, 2002), departs from the classical “emission factor” method and allows for a more accurate assessment of emissions from livestock operations especially in cases where control measures are applied. This new method has recently gained widespread acceptance for calculating national ammonia emission inventories, and several countries (UK, Germany, Denmark, Switzerland, and Norway) have applied it in practice for their year 2000 inventories.

The objective of this paper is to present the recent update of the methodology used in the RAINS model for estimating ammonia emissions in Europe and to document the model extension to include emissions of greenhouse gases from agriculture, i.e., methane (CH_4) and nitrous oxide (N_2O).

The remainder of this introductory section reviews the context of the emission and cost estimates of the RAINS model and provides a summary of the major changes and the new elements introduced in the model. Section 2 gives a brief description of the model structure. Section 3 discusses activity data that are currently contained in the RAINS databases and compares them with the earlier data sets that have been used for the scenarios for the negotiations of the NEC Directive and the Gothenburg Protocol. Section 4 introduces the new methodology for estimating emissions and outlines how emission factors for individual categories were derived for the revised model. A review of abatement options and their characteristics, including cost calculation, is subject of Section 5. The questionnaire distributed in July 2003 to national experts is presented in Annex 1.

1.1. The RAINS integrated assessment model

The RAINS model addresses cost-effective emission control strategies in a multi-pollutant/multi-effect framework. For this purpose, the RAINS model now includes the control of SO_2, NO_x, VOC, NH_3 and fine particulate matter emissions as precursors for acidification, eutrophication, ground-level ozone and aerosols. The issue of health risks due to elevated ambient concentrations of fine particles has been added only recently to the model framework. The search for cost-effective solutions to control the ambient levels of fine particles aims at balancing emission controls over the sources of primary emissions as well as over the precursors of secondary aerosols. Thus, the control problem can be seen as an extension of the “multi-pollutant/multi-effect” concept applied for acidification, eutrophication and ground-level ozone (Table 1.1).

Table 1.1: Air quality management as a multi-pollutant, multi-effect problem.

	SO_2	NO_x	NH_3	VOC	Primary PM emissions
Acidification	√	√	√		
Eutrophication		√	√		
Ground-level ozone		√		√	
Health damage due to fine particles	√	√	√	√	√
	via secondary aerosols				

The present implementation of the RAINS model contains modules to describe emissions and emission control costs for all of the substances listed above. The present structure of the RAINS model is illustrated in Figure 1.1, where the elements related to ammonia are highlighted.

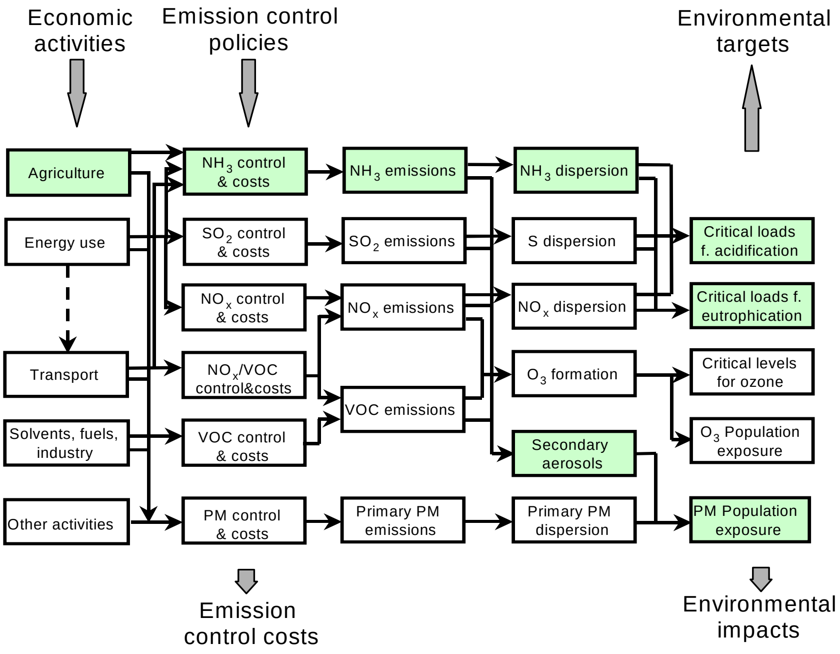

Figure 1.1: Flowchart of the RAINS model.

A central objective of integrated assessment models is to assist in the cost-effective allocation of emission reduction measures across various pollutants, several countries and different economic sectors. Obviously, this task requires consistent information about the costs of emission controls at the individual sources, and it is the central objective of this cost module to provide such information.

The optimal cross-country and cross-sectoral allocation of emission control measures is crucially determined by differences in the emission control costs of the individual emission sources. It is therefore of utmost importance to systematically identify the factors leading to differences in emission control costs among countries, economic sectors and pollutants. Such differences are usually caused, *inter alia*, by variations in the composition of the various emission sources, the state of technological development and the extent to which emission control measures are already applied.

In order to systematically capture these differences across Europe, a methodology has been developed to estimate emissions and emission control costs of standard technologies under the specific conditions characteristic for the various European countries. With a basic assumption about the general availability of control technologies with equal technical properties and costs, a number of country-specific circumstances (level of technological advancement, installation size distribution, labor costs, etc.) are used to estimate the costs for the actual operation of pollution control equipment.

1.2. Summary of the modifications and extensions introduced since the previous version of the RAINS ammonia module

This report documents the changes that have been recently introduced in the RAINS NH_3 module as it is documented in Klaassen, 1991ab and Klaassen, 1994. The revised (interactive) Internet version of the model is available on the RAINS web site (http://www.iiasa.ac.at/rains). Current implementation includes only ammonia; work is ongoing to include greenhouse gases (CH_4 and N_2O).

New sectors

The sectoral aggregation of the RAINS model has been modified and a number of new emission categories have been introduced. This includes fur animals[1], waste treatment, transport, industrial combustion, industrial processes (other than production of N fertilizers) and fuel combustion in the residential sector. Additionally, some animal categories were split to distinguish between different manure systems, i.e., between solid and slurry waste. This was done for cattle and pigs. Finally, emissions from N fertiliser use are calculated separately for urea and other synthetic N fertilizers.

Revisions

Several emission categories and parameters have been revised. This includes updates of emission factors, activity data, removal efficiencies, current application rates of control technologies, as well as revisions of a number of other emission and cost relevant parameters, e.g., average farm size, housing periods, manure storage times and constraints on applicability of control techniques.

Modifications

A significant change (compared with Klaassen, 1991a) was introduced for the emission factors for livestock: at the moment RAINS distinguishes four distinct stages for which emissions are estimated, i.e., housing, storage, manure application and grazing. Work continues to include other stages to better reflect individual practices such as direct spread of manure and emissions from feeding and collecting lots. The emission factors are now calculated within the RAINS initialisation routine, rather than being input directly into the model, which increases transparency and facilitates further adjustments of parameters that are relevant for the estimation of stage specific emission factors.

With respect to the efficiency of control measures, a new algorithm was developed to modify the default stage-specific ammonia removal efficiencies to account for changes in the nitrogen balance in manure due to measures that are applied on preceding stages.

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[1] This category is used in some cases for other animal categories, e.g., rabbits.

New control options

The modifications and extensions of the sectoral structure required definition of new control options, e.g., urea substitution, incorporation of solid waste, distinction between high and low to medium efficiency covered storage and low ammonia application options. Additionally, an end-of-pipe type of option has been included, i.e., incineration of poultry manure, to reflect the practice in some countries.

Links to other pollutants

A link with the RAINS NO_x module was established, so that the impacts of NOx control measures on NH_3, CH_4 and N_2O emissions can be investigated. The characteristics of the livestock production are used to estimate emissions of greenhouse gases (CH_4 and N_2O) including impact of ammonia reduction measures on emission of these gases.

Cost data

The cost data were revised and further developed to reflect the changes in the RAINS module and introduction of new control options. However, the work continues to add the most recent findings and national experience in implementation of various abatement measures. This is done together with the UNECE Expert Group on Ammonia Abatement and final results are expected later in the autumn of 2004.

New model features

The model provides several new features that allow for easier viewing of input data, the assumptions made for several parameters and output. Also a new feature allowing for analysis of the cost curve was added. Another new feature allows for specification of a regression function that describes the relationship between milk yield of dairy cows and N-excretion and consequently making ammonia emission factors time (year) dependent. At the time of writing this report, this feature is available only in the PC implementation.

2. The structure of the agricultural module in RAINS

Emissions of ammonia originate primarily from agricultural activities. In Europe, livestock production is the dominant source (70-90 percent of total emissions) followed by application of mineral fertilizers (up to 20 percent of total) and a number of other non-agricultural sources like wild animals, waste treatment, production of nitrogen fertilizers, combustion of solid fuels, transport (specifically cars equipped with early generation of three-way-catalysts), few other industrial process as well as humans and pets.

Agriculture is also a very important source of greenhouse gases. In Europe, about 60 percent of methane and about 30 percent of nitrous oxide originate from this sector. Cattle is the primary source of methane emissions in Europe and for nitrous oxide the application of N-fertilizers.

2.1. Aggregation of emission sources

In the ideal case, the assessment of the potential and costs for reducing emissions should be carried out at the very detailed level. In reality, however, the necessity to assess abatement costs for all countries in Europe as well as focus on emission levels in 10 to 20 years from now restricts the level of detail which can be maintained. While technical details can be best reflected for individual categories, i.e., farms of different profiles and sizes, the accuracy of estimates on an aggregated national level for future years will be seriously hampered by a general lack of reliable projections of many of these farm-related parameters. For an integrated assessment model focusing on the pan-European scale it is therefore imperative to aim at a reasonable balance between the level of technical detail and the availability of meaningful data describing future development, and to restrict the system to a manageable number of source categories and abatement options. Table 2.1 presents the major sectors included in the RAINS NH_3 module.

Compared to Klaassen (1991a), the current version of the model includes a number of new/modified categories:

- Split of cattle and pigs into animals kept on liquid and solid manure systems;
- Split of nitrogen fertilizer application into urea and other N-fertilizers;
- Fur animals;
- Industrial and domestic combustion;
- Mobile sources;
- Waste treatment and disposal;
- Inclusion of other non-agricultural sources like wild animals, humans, pets, cigarette smoking, etc.

Table 2.1: Main activity groups distinguished in the RAINS NH_3 module and their relation to the UNECE NFR code.

RAINS sector	*Comments*	RAINS code [a)]	NFR Code
Livestock			
Dairy cows	*Excluding suckling cows; Distinguishing between liquid and solid manure systems*	AGR_COWS (DL, DS)	4B1a
Other cattle	*All other cattle incl. bulls, beef cattle, suckling cows, youngstock; Distinguishing between liquid and solid manure systems*	AGR_BEEF (OL, OS)	4B1b
Pigs	*Including fattening pigs and sows; Distinguishing between liquid and solid manure systems*	AGR_PIG (PL, PS)	4B8
Laying hens		AGR_POULT (LH)	4B9
Other poultry	*All poultry except laying hens, including broilers, turkeys, ducks, geese, etc*	AGR_POULT (OP)	4B9
Sheep and goats		AGR_OTANI (SH)	4B3, 4B4
Fur animals	*In some countries this category might be used for other animals, e.g., rabbits*	AGR_OTANI (FU)	4B13
Horses	*Including mules and asses*	AGR_OTANI (HO)	4B6, 4B7
Fertilizer use			
Urea		FCON_UREA (FR)	4Di
Other N-fertilizers	*Refers to other mineral N fertilizers, excluding urea*	FCON_OTHN (FN)	4Di
Industry			
Fertilizer production	*Production of nitrogen fertilizers*	FERTPRO (IN, IND[b)])	2B1, 2B5
Industrial combustion	*Power plants, fuel conversion, combustion in industry*	PP_..., IN_..., CON_COMB (PP_IND_COMB)	1A1, 1A2
Industrial processes	*Includes coking, nitric acid, other production processes*	IO_NH3_EMISS (IO, IND[b)]), IND_PROC)	1A2
Residential combustion	*Emissions from combustion of solid fuels in domestic, residential and commercial sectors*	DOM (DOM)	1A4bi, 1A4ci
Transport	*Road and off-road mobile sources*	TRA_... (TRANSPORT)	1A3, 1A4bii, 1A4cii, 1A5b
Waste treatment	*Treatment and disposal of waste, including sludge application on the fields*	WT_NH3_EMISS (WT)	6A-D
Other	*Various activities reported in national emission reports including humans, pets, cigarette smoking, etc.*	OTH_NH3_EMISS (OT)	

[a)] Codes refer to the Web version of the model and PC implementation (in brackets). The latter are also used in the tables in this document.

[b)] Code "IND" is used for displaying result of emission calculation only and it represents the sum of IN and IO, i.e., N fertilizer production and other industrial process.

3. Activity data

The extension of the structure of the model as well as new developments in agriculture sector require a regular update of the projection data in the RAINS model. A brief characteristic and a summary of the currently used data set are given below.

3.1. Agriculture

Agricultural activities considered in the RAINS model include two major categories, i.e., livestock production and application of mineral N fertilizers. The currently implemented scenario extends from 1990 to 2030 and assumes that the reform of the EU Common Agricultural Policy (CAP) is not implemented. A scenario with the CAP reform is under preparation as well as a set of national scenarios[2].

3.1.1 Livestock data

Historical data from 1990 to 2000 originate from international statistics (FAO, 2003; EUROSTAT, 1997 and 2002), national submissions to the NEC Directive and the UNECE LRTAP Convention as well as discussions with national experts during the consultations carried out within the CAFE program. Besides, a "questionnaire" asking for more detailed characteristics of national agricultural systems was distributed in July 2003 to national agricultural experts (see Annex 1).

Projections of animal numbers are based on results of a number of European and global models. For the EU-15, data for the years 2000 to 2010 are derived from the CAPRI model of the University of Bonn (EC, 2002). For the ten New Member States (NMS), projections originate from DG Agriculture. For other countries and for the period beyond 2010, the projection is based on trends derived from the FAO global study (Bruinsma, 2003). Country-specific data are available from the CIRCA web site (http://forum.europa.eu.int:80/Public/irc/env/Home/main). A summary of the current baseline scenario for the EU-15 and NMS-10 is presented in Figure 3.1 to Figure 3.4. The trends shown for the group of countries are not necessary representative for individual countries. The data referred to as NEC originate from the earlier RAINS database that was used in the negotiations of the Gothenburg Protocol (UNECE, 1999a) and the NEC Directive.

A detailed discussion of these scenarios is not the subject of this work and has been carried out in a series of other studies (e.g., EC, 2002). Therefore, only brief discussion of differences and similarities

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[2] The national projections of activity data are included in the "National scenario" that was prepared within the CAFE project and will be available on the Internet version of RAINS from mid-September 2004.

is given. For cattle in the EU-15, both projections are similar. For historical years differences can be explained by slightly different classifications and aggregations of animal categories. For the NMS, the earlier cattle forecast was more optimistic about how quickly the livestock production will recover to the pre-transition levels of beef production and stabilize the number of dairy cows. A similar picture emerges also for the other livestock categories in the NMS. For the EU-15, the current projection for pigs and poultry assumes slightly faster growth in the beginning of the period and then stabilization at a higher level than in the "NEC" projection.

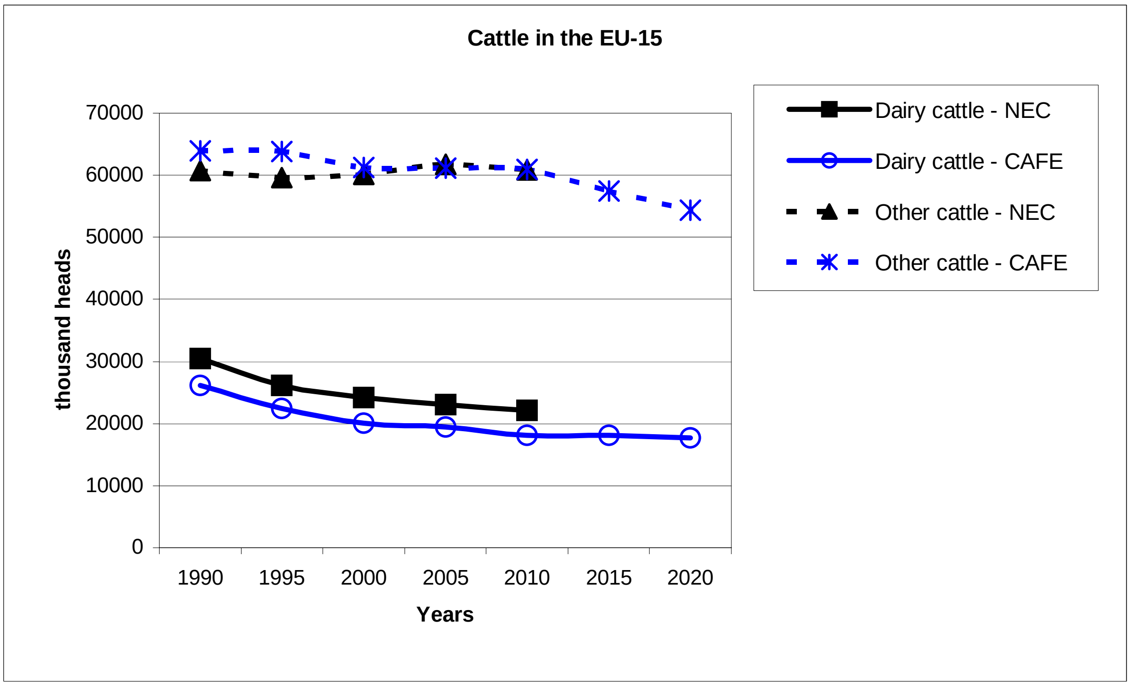

Figure 3.1: Comparison of livestock (cattle) projections for the EU-15 used in the NEC and Gothenburg Protocol and CAFE processes.

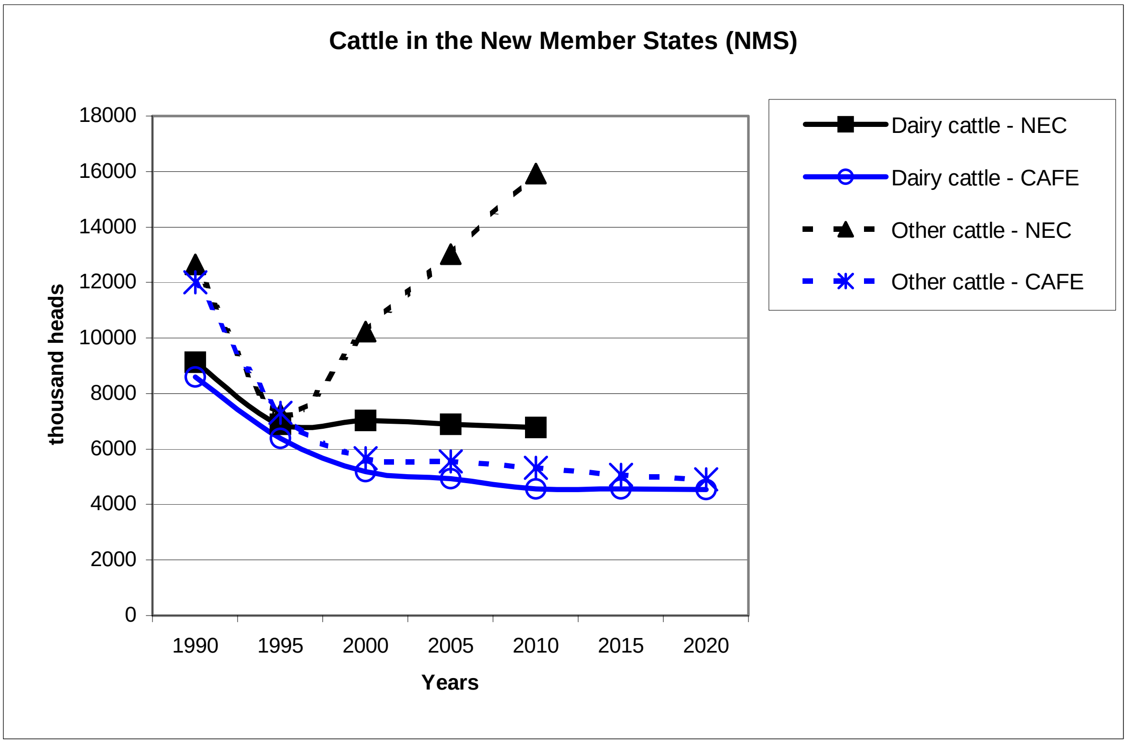

Figure 3.2: Comparison of the livestock (cattle) projections used in the NEC/Gothenburg Protocol and CAFE processes for 10 New Member States (NMS-10).

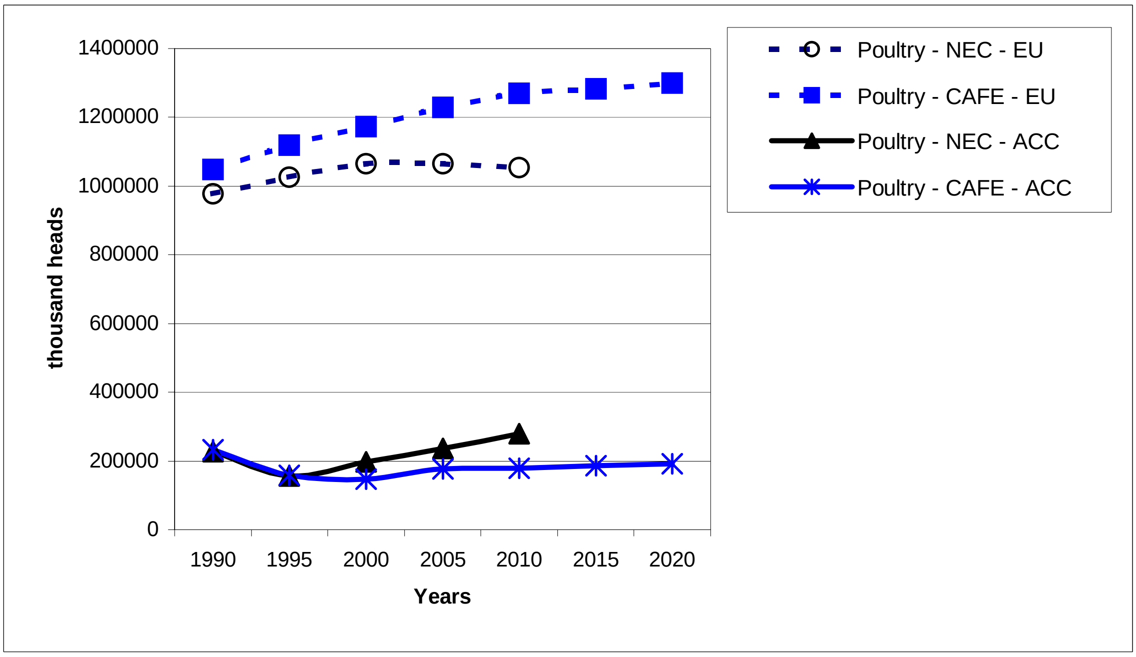

Figure 3.3: Comparison of livestock (poultry) projections used in the NEC/Gothenburg Protocol and CAFE processes for the EU-15 and NMS-10.

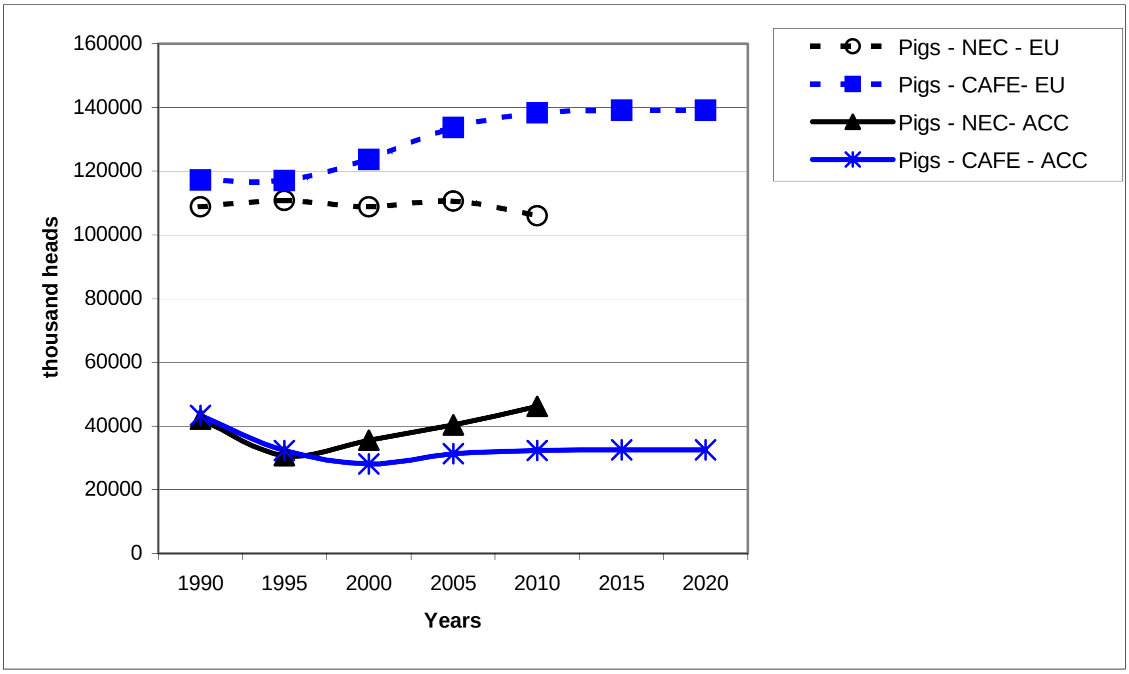

Figure 3.4: Comparison of livestock (pigs) projections used in the NEC/Gothenburg Protocol and CAFE processes for the EU-15 and NMS-10.

3.1.2 Mineral fertilizer application

Historical data for 1990 to 2000 originate from international statistics (FAO, 2003; IFA, 2003) and national submissions to the NEC Directive and UNECE LRTAP Convention as well as discussions with national experts during the consultations carried out within the CAFE program.

The forecast of fertilizer consumption until 2010 for EU-15, Switzerland and Norway is based on a study by EFMA (European Fertilizer Manufacturers Association) (EFMA, 2003). For other countries and for the period beyond 2010, the projection is based on trends derived from the FAO global study (Bruinsma, 2003). Country-specific data are available from the CIRCA web site (http://forum.europa.eu.int:80/Public/irc/env/Home/main). A summary of projections of fertilizer use is presented in Figure 3.5. The trends shown for the selected groups of countries are not necessary representative for individual countries. The “NEC” data refer to the earlier RAINS database used for the analyses of the Gothenburg Protocol (UNECE, 1999a) and the NEC Directive.

A detailed discussion of these scenarios is not the subject of this work and has been carried out in other studies (e.g., EFMA, 2003). Therefore, only brief discussion of differences and similarities is given. For the EU-15, the CAFE projection is essentially a continuation of the NEC projection. For the NMS-10, however, the forecasts look different although both assume growth starting in 1995. The NEC projection shows a faster recovery, in terms of fertilizer use, while the more recent projection anticipates slower growth in fertiliser use, but stronger improvements in the efficiency of mineral fertilizer application.

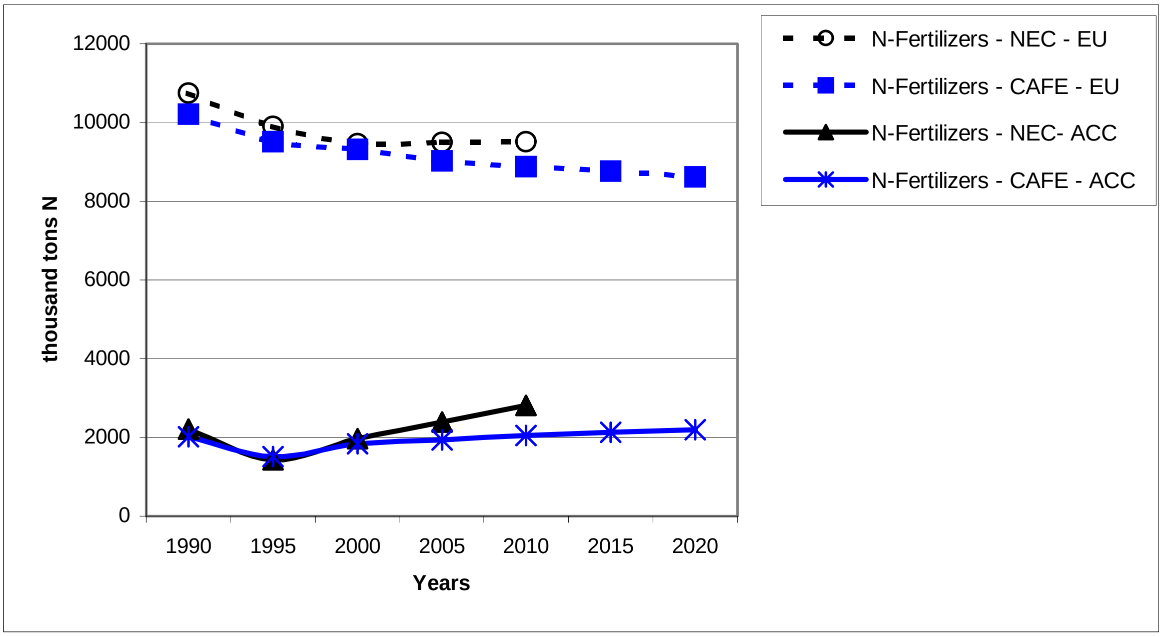

Figure 3.5: Comparison of mineral N-fertilizer use projections used for the NEC/Gothenburg Protocol and CAFE processes for the EU-15 and 10 accession countries.

3.2. Stationary combustion and transport

The forecast of activity data is based on the DG-TREN baseline energy scenario developed with the PRIMES energy model as part of the long-range energy modelling study. This scenario constitutes one of the CAFE baseline projections. Country-specific data can be downloaded from the CIRCA web site (http://forum.europa.eu.int:80/Public/irc/env/Home/main) and from the RAINS web model (http://www.iiasa.ac.at/rains).

3.3. Waste treatment and disposal

Statistical data on the amount of municipal waste incinerated, stored on landfills, composted, and sewage sludge applied to land was collected in the summer of 2003. Data were found for most European countries and originate primarily from EUROSTAT (2001). Supplementary information was collected from UN (2002) and OECD (www.oecd.org). To project this activity into the future, the trends observed for a few countries were extrapolated following the arguments provided in the UK report on non-agricultural sources of ammonia (Handley *et al*., 2001). However, although the database with activity data on waste has been developed, the current version of RAINS continues for the time being to use emissions as the activity level. Thus, emissions reported to the NEC Directive and the UNECE LRTAP Convention are directly used in the model unless other, more up-to-date, information has been provided by national experts. The new methodology will be implemented in the near future, applying specific emission factors for waste treatment and disposal.

3.4. Other sources

Other sources include production of N mineral fertilizers, other industrial processes, humans, pets, cigarette smoking and a number of other small sources that are sometimes included in national inventories. Apart from fertilizer production, where the projection is based on the data that have been compiled for the NEC Directive and the Gothenburg Protocol scenario work, the development of other sources is based on national reports to the NEC Directive and the UNECE LRTAP Convention, assuming in most cases no change for the future.

4. Methodology for emission calculation

This section presents the methodology used in RAINS to estimate emissions of ammonia (NH_3), nitrous oxide (N_2O) and methane (CH_4) from agricultural sources in Europe. The methodology for estimating ammonia is an update of Klaassen (1991a).

The standard concept for calculating emissions from a given activity is to multiply an 'activity level' with a representative 'emission factor'. The crucial question in constructing emission inventories relates to the appropriate level of resolution. On the one hand, the disaggregation should be detailed enough to allow capturing the important differences between emission sources. Only in a very few situations do emission sources represent homogeneous populations. In the majority of cases each source has slightly different characteristics. On the other hand, practical considerations, particularly the availability of reliable statistics on activity rates and emission factors, seriously limit the level of detail that can be meaningfully maintained. Therefore, any emission inventory has to strike a balance between technical detail and practical data availability.

4.1. Ammonia emissions from livestock farming

Livestock farming is the single largest source of ammonia emissions in all European countries, typically representing about 80 percent of all ammonia emissions. Early emission inventories used emission factors per animal per year and have not distinguished between different animal manure systems, e.g., liquid slurry and straw based systems. Since research related to the loss of nitrogen from animal production was carried out in few countries only, most emission inventories relied on these few numbers. However, these are not always representative for all countries and their agricultural practices, since they do not consider differences in diet, N excretion, housing, and manure practices.

More recent inventories rely on country- or region-specific data on N-excretion, management practices. They distinguish between different manure systems to assess losses of nitrogen at the various stages of manure handling (e.g., Pain *et al.*, 1998; Misselbrook *et al.*, 2000; Dämmgen *et al.*, 2002; Asman *et al.*, 1998; FAL-IUL, 1998). This method is often referred to as "N-flow" or "process based". It relies on the assessment of available nitrogen and ammoniacal nitrogen (TAN) at each considered stage (e.g., housing, storage in lagoons, tanks, application, etc.) and its potential loss as NH_3. Recently, this method gained wider acceptance, and was used for the national ammonia emission inventories of the UK, Germany, Denmark, Netherlands, Switzerland, and Norway (see e.g., Webb and Misselbrook, 2003). It has to be stressed, however, that this revised method is very data demanding and in some countries a simplified approach will continue to be used.

Due to limited availability of all necessary data, a European model like RAINS can only work with less detailed livestock categories and regional differences. However, the simplified RAINS methodology needs to consider the major findings from the more detailed approach and attempt capturing their major implications with practical approach, as to reproduce emission estimates from more detailed national analyses. The recent implementation of the RAINS model allows for a two-tier approach: if there is detailed data available, a more detailed approach (Tier-II) can be used, otherwise a simplified (Tier-I) method is applied.

The major differences between these approaches relate to

- the number of emission stages distinguished (e.g., additional stages like hard standings (feeding lots and collecting yards) (Misselbrook *et al.*, 2001), direct spread of manure from the animal house, etc.),
- country-specific parameters related to the amount of time dairy cattle spends in-house (milking) while grazing (default assumption is 20 percent of time spent grazing),
- country-specific data on the proportion of slurry stored in open tanks and lagoons,
- the N-excretion rate, which should originate from national estimates and not from the generic regression (productivity versus N-excretion),
- estimates of TAN amount for each emission stage rather than using N-volatilization rate as suggested for the simplified method (default data originates from the Joint EMEP/EEA Emission Inventory Guidebook (EEA, 2003).

So far the Tier-I approach has been implemented in RAINS. Work is ongoing to incorporate the more detailed Tier-II method. For Tier-I, four NH_3 emission stages are distinguished, i.e., animal house, outside storage of manure, application and grazing period. For Tier-II, additional stages include feeding lots, collecting/exercising yards, direct spread of manure, outside storage in open tanks, outside storage in lagoons. For both approaches, the following general equation is used to calculate NH_3 emissions from livestock in RAINS:

$$EL_{i,l} = \sum_{j} L_{j,l} \sum_{k} \sum_{s=1}^{8} \left[ef_{i,j,l,s} \left(1-\eta_{i,j,k,s}\right) X_{i,j,k,l} \right] \tag{4.1}$$

where:

$EL_{i,l}$	ammonia emissions from livestock farming in country (i) and year (l) [kt NH_3/year],
i,j,k,l	country, livestock category, abatement technique, year;
s	emission stage – four stages for Tier-I and eight stages for Tier-II;
L	animal population [thousand heads];
ef	emission factor [kg NH_3 / animal per year];
	reduction efficiency of abatement technique;
X	implementation rate of the abatement technique.

Another new feature in the model, allows for specification of a regression function that describes relationship between milk yield of dairy cows and N-excretion and consequently making ammonia emission factors year specific (which they are in real life). At the moment, this is only implemented for dairy cattle. The regression can be used to simulate the impacts of increased production efficiency on the emissions of ammonia.

The variables in the equation are discussed in the following sections: activity data in Section 3.1.1, emission factors in Section 4.1.1, application rates and removal efficiencies in Section 5.1.

4.1.1 Emission factors

In order to accurately calculate NH_3 emissions from livestock, quantitative data on several parameters are required to reflect stage-specific N-loss characteristics. Major factors include:

Nitrogen content of feed,
conversion factor between N in animal food and N in products (e.g., milk, meat),
age and weight of animal,
housing system,
type of manure storage,
length of grazing period.

After spreading of manure, the following factors play an important role in determining N-losses:

Meteorological conditions, e.g., temperature, humidity, turbulence, precipitation, etc.,
soil properties, e.g., pH, calcium content, water content, etc.,
manure properties, e.g., pH, viscosity, dry matter content, etc.,
application rate, and
the way manure is applied.

In practice, however, often average emission factors for the considered emission stages are derived for each animal type. The minimum information necessary to arrive at region-specific emission factors for each animal type includes typical N excretion rates, the type of the housing and manure storage systems, the type of manure application, the length of the grazing period, N volatilization rates at the different stages taking into account housing, storage and application practices.

This minimum information is currently used in RAINS for Tier-I method. Default data originate from the relevant sections of the EMEP/EEA Emission Inventory Guidebook (EEA, 2003), replies to the questionnaire (see Annex 1) and discussions with national experts carried out during the CAFE consultation process. However, it was not possible to obtain even this minimum information for all countries, so that a number of own estimates had to be made. These estimates are based on regressions that have been developed based on data available for a number of countries and livestock categories. For example, the relation between milk yield and nitrogen excretion was derived primarily from Klaassen (1991a), ECETOC (1994), and the questionnaire responses. With data on milk production, which are available for all countries from the FAO statistics (FAO, 2003), it was possible to assess N-excretion rate for dairy cows. However, with this approach country-specific production practices could not be fully captured. The regression analysis is based on data collected from the large countries, and their validity for agricultural systems in the smaller countries needs to be confirmed.

For the implementation of the revised approaches, a number of additional parameters needed to be collected and introduced to the model. A questionnaire (see Annex 1) has been developed and distributed to a number of scientific networks, i.e., the UNECE Expert Group on Abatement Techniques and the Agricultural Panel of the UNECE Task Force on Emission Inventories and Projections (TFEIP), the national experts participating the UNECE Expert Group on Techno-economic Issues (EGTEI) and the national emission inventory experts to the TFEIP. By the end of July 2004, 19 countries have provided responses. The first results (based on 16 responses) were presented and discussed at the Agricultural Panel session of the TFEIP meeting in Warsaw (22-24 September 2003).

The approach for deriving stage specific emission coefficients for the Tier-I approach can be summarized with the following four equations:

$$\begin{aligned} ef_1 &= Nx_1 v_1 \\ ef_2 &= Nx_1 (1 - v_1) v_2 \\ ef_3 &= Nx_1 (1 - v_1 - (1 - v_1) v_2) v_3 \\ ef_4 &= Nx_4 v_4 \end{aligned} \tag{4.2}$$

where:

$ef_{1,2,3,4}$ = NH_3-nitrogen loss at distinguished emission stages, i.e., housing (1), storage (2), application (3), and grazing (4),

$Nx_{1,4}$ = N excretion during housing (1) and grazing (4),

$v_{1..4}$ = N volatilization rates at distinguished emission stages (see Table 4.1).

The N excretion rates (Nx) are country- and livestock category-specific. They are discussed in detail in the proceeding sections. Similarly, the volatilization rates (v) are country-specific to reflect differences between management practices and other conditions. The default set (Table 4.1) is used when no such information is found for a given country.

Table 4.1: Default N-volatilization rates [% NH_3-N] (EEA, 2003).

	Emission stage			
Livestock category	*Housing*	*Storage*	*Application*	*Grazing*
Dairy cattle	12	6	20	8
Other cattle	12	6	20	8
Pigs	17	6	20	3
Laying hens	20	4	20	n.a.
Other poultry	20	3	20	n.a.
Sheep and goats	10	0	10	4
Horses	12	0	12	8
Fur animals	12	0	25	n.a.

4.1.1.1. Dairy cows

The Tier-I, emission factors are estimated as given in Equation 4.2 considering, where available, country-specific parameters that were partly collected with the agricultural questionnaire (Table 4.2). Excretion during housing and grazing depends on a number of factors including feed composition, retention of nitrogen in milk and meat, the length of housing period, the time animals spend indoor when milking (during grazing “season”), and the amount of fertilizer applied on pasture. Not all of these elements are considered in the RAINS calculation, because it is assumed that many of these factors will be included in the excretion rates provided by the national experts. For the calculation of the emission factor, RAINS relies on the provided total N-excretion rates and days of grazing (or housing). It is further assumed that for about 20 percent of the time, grazing animals are brought to stalls for milking, unless other country specific data are available. Thus, during that time nitrogen is excreted in houses and an adjustment of the housing and grazing period excretion rate is made accordingly. If no country-specific data on N excretion rates are available, a relationship between milk yield and N-excretion is used:

$$Nx = 0.0178 \times M + 0.2271 \tag{4.3}$$

where

Nx = nitrogen excretion rate [kg N/animal-year],
M = milk yield [kg/animal-year].

This regression (Figure 4.1) is based on data from a number of studies (ECETOC, 1994; Pain and Menzi, 2000; Klaassen, 1991a; FAO, 2003) and on responses to the questionnaire. The available data do not allow conclusions for yields below 3500 kg milk/year. For such low milk yields, an N excretion value of 50 kg N/animal per year was assumed (Table 4.2).

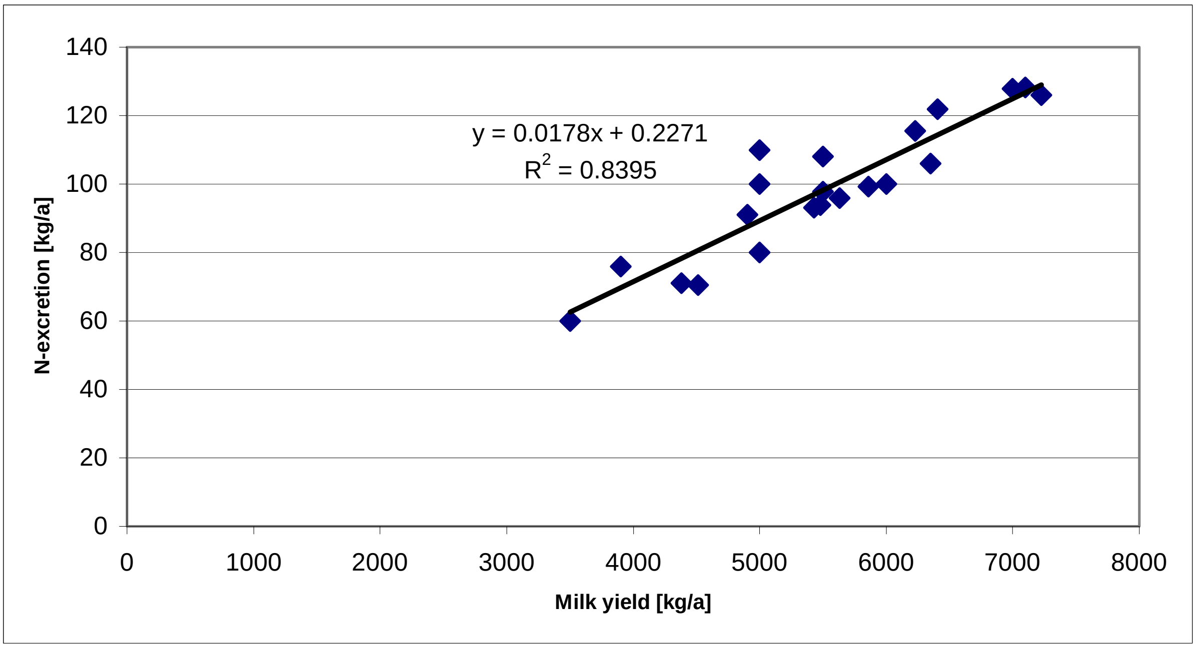

Figure 4.1: Relationship between milk yield and nitrogen excretion in Europe.

Table 4.2: N-excretion rates and NH_3 emission factors for dairy cows in RAINS.

Country	[a]	N-excretion *[kg N/head-year]*	Housing *[days/year]*	N-excretion *housing*	N-excretion *grazing*	Emission factor *[kg NH_3/year]*
Albania		50.0	183	30.1	19.9	14.28
Austria	Q	62.8	275	50.4	12.4	22.45
Belarus		50.0	183	30.1	19.9	14.28
Belgium	Q	108.0	189	66.3	41.7	31.74
Bosnia–H.		50.0	183	30.1	19.9	14.28
Bulgaria		55.4	183	33.3	22.1	15.83
Croatia		50.0	183	30.1	19.9	14.28
Cyprus		87.4	165	49.1	38.3	23.90
Czech Republic	Q	99.9	200	63.8	36.1	29.70
Denmark	Q	125.3	297	106.5	18.8	40.89
Estonia	Q	115.0	220	78.5	36.5	35.77
Finland	Q	96.0	274	76.9	19.1	33.42
France	Q	100.0	165	56.2	43.8	30.76
Germany	Q	115.6	213	77.1	38.5	39.77
Greece		71.4	183	42.9	28.5	20.40
Hungary	Q	80.0	185	48.4	31.6	22.96
Ireland	C	82.1	121	38.2	43.9	21.70
Italy	Q	108.8	321	98.2	10.6	45.88
Latvia	Q	71.0	220	48.4	22.6	22.09
Lithuania	C	70.0	183	42.1	27.9	19.99
Luxembourg		107.0	190	66.0	41.1	31.09
Malta		85.7	165	48.1	37.6	23.41
Netherlands	Q	126.2	200	80.6	45.6	49.05
Norway	Q	82.0	292	68.9	13.1	15.31
Poland	Q	75.9	215	50.9	25.0	29.96
Portugal	C	108.1	234	77.0	31.1	32.32
Republic of Moldova		50.0	183	30.1	19.9	14.28
Romania		57.2	185	34.6	22.6	16.41
Russian Federation		50.0	183	30.1	19.9	14.28
Serbia and Montenegro		50.0	183	30.1	19.9	14.28
Slovakia		60.7	183	36.5	24.2	17.35
Slovenia	QC	105.5	310	92.8	12.7	41.36
Spain	C	85.7	255	65.1	20.6	31.85
Sweden	Q	117.0	225	81.1	35.9	40.80
Switzerland		94.6	339	89.2	5.4	36.64
F.Y.R. of Macedonia		50.0	183	30.1	19.9	14.28
Ukraine		50.0	183	30.1	19.9	14.28
United Kingdom	QC	106.0	182	63.5	42.5	36.45

[a] "Q" indicates that data on excretion and days in housing originate from the questionnaire (Annex 1); "C" refers to data discussed and agreed by national experts during the CAFE consultations.

4.1.1.2. Other cattle

A similar approach has been used for other cattle, with the difference that due to lack of data no regression function has been applied to derive N excretion. Thus, if no country-specific data are available, information from the questionnaire prepared in 1997 by MAFF (UK Ministry of Agriculture Food and Fisheries) and Pain and Menzi (2000) have been used. Minimum total N excretion has been assumed at 40 kg N/animal per year. The summary of submitted data on N-excretion ("Q") and derived emission factors is provided in Table 4.3.

Table 4.3: N-excretion rates and NH_3 emission factors for other cattle in RAINS.

		N-excretion	Housing	N-excretion		Emission factor
Country	$^{a)}$	*[kg N/head-year]*	*[days/year]*	*housing*	*grazing*	*[kg NH_3/year]*
Albania		40.0	199	21.8	18.2	10.72
Austria	Q	40.0	185	20.3	19.7	10.47
Belarus		45.0	225	27.7	17.3	13.07
Belgium	Q	41.0	198	22.2	18.8	11.13
Bosnia and Herzegovina		40.0	199	21.8	18.2	10.72
Bulgaria		45.0	199	24.5	20.5	12.06
Croatia		45.0	199	24.5	20.5	12.06
Cyprus		40.0	165	18.1	21.9	9.56
Czech Republic	Q	45.0	255	31.4	13.6	14.23
Denmark	Q	37.1	232	23.6	13.5	9.84
Estonia	Q	45.0	217	26.8	18.2	12.76
Finland	Q	53.0	237	34.4	18.6	15.94
France	Q	50.0	198	27.1	22.9	13.36
Germany	Q	41.0	246	27.6	13.4	12.88
Greece		45.0	199	24.5	20.5	12.06
Hungary	Q	40.0	185	20.3	19.7	10.24
Ireland	C	45.0	128	15.8	29.2	10.04
Italy	Q	46.9	345	44.3	2.6	22.39
Latvia	Q	51.0	180	25.2	25.8	12.84
Lithuania	C	50.0	199	27.3	22.7	13.41
Luxembourg		42.0	199	22.9	19.1	11.26
Malta		40.0	165	18.1	21.9	9.56
Netherlands	Q	40.0	234	25.6	14.4	15.60
Norway	Q	38.0	292	30.4	7.6	6.23
Poland	Q	35.0	200	19.2	15.8	11.08
Portugal	C	54.0	219	32.4	21.6	14.43
Republic of Moldova		40.0	199	21.8	18.2	10.72
Romania		45.0	199	24.5	20.5	12.06

Table 4.3: Continued.

		N-excretion	Housing	N-excretion		Emission factor
Country	[a]	*[kg N/head-year]*	*[days/year]*	*housing*	*grazing*	*[kg NH_3/year]*
Russian Federation		40.0	210	23.0	17.0	11.10
Serbia and Montenegro		40.0	199	21.8	18.2	10.72
Slovakia		45.0	199	24.5	20.5	12.06
Slovenia	QC	42.0	310	35.7	6.3	15.99
Spain	C	45.0	44	5.4	39.6	7.18
Sweden	Q	39.0	220	23.5	15.5	11.67
Switzerland		42.0	310	35.7	6.3	12.11
F.Y.R. of Macedonia		40.0	199	21.8	18.2	10.72
Ukraine		45.0	199	24.5	20.5	12.06
United Kingdom	QC	49.0	182	24.4	24.6	12.93

[a] "Q" indicates that data on excretion and days in housing originate from the questionnaire (Annex 1); "C" refers to data discussed and agreed by national experts during the CAFE consultations.

4.1.1.3. Pigs

The nitrogen content of the feed and the nitrogen retention in meat are the two main determinants for N excretion. As for cattle, RAINS relies on data submitted by national experts assuming that these factors were considered in the national estimates. If no national information is available, no phase feeding for fatteners was assumed with an average excretion rate of 15 kg N/animal per year. For sows, 30 kg N/animal per year is used. Further, with data on the share of fatteners and sows in total pigs, average N excretion rates were derived (Table 4.4). Reported ("Q") and estimated N excretion rates and total NH_3 emission coefficients for an uncontrolled management system are presented in Table 4.4.

Table 4.4: N-excretion rates and NH_3 emission factors for pigs in RAINS.

Country	[a]	N-excretion *[kg N/head-year]* Average	*fatteners*	*sows*	Emission factor *[kg NH_3/year]*
Albania		12.4	15.0	30.0	5.65
Austria	Q	11.6	15.0	26.9	4.61
Belarus		12.4	15.0	30.0	5.65
Belgium	Q	13.8	12.0	23.7	5.42
Bosnia and Herzegovina		12.4	15.0	30.0	5.65
Bulgaria		12.4	15.0	30.0	5.65
Croatia		12.4	15.0	30.0	5.65
Cyprus		12.4	15.0	30.0	5.65
Czech Republic	Q	12.4	15.0	30.0	5.65
Denmark	Q	9.6	6.2	26.4	4.29
Estonia	Q	12.4	15.0	30.0	5.65
Finland	Q	10.1	11.0	29.0	3.46
France	Q	12.2	12.8	33.0	5.55
Germany	Q	11.9	13.0	36.0	7.09
Greece		11.5	13.0	30.0	5.25
Hungary	Q	8.9	11.6	17.5	4.08
Ireland	C	11.1	13.0	30.0	5.39
Italy	Q	11.5	12.8	24.6	6.15
Latvia	Q	10.0	12.0	25.0	4.57
Lithuania	C	12.4	15.0	30.0	5.65
Luxembourg		9.9	13.0	30.0	4.52
Malta		12.4	15.0	30.0	5.65
Netherlands	Q	9.2	12.1	30.3	6.30
Norway	Q	10.7	11.0	36.6	3.89
Poland	Q	11.1	14.8	20.0	5.83
Portugal	C	12.4	14.9	29.8	5.22
Republic of Moldova		12.4	15.0	30.0	5.65
Romania		12.4	15.0	30.0	5.65
Russian Federation		12.4	15.0	30.0	5.65
Serbia and Montenegro		12.4	15.0	30.0	5.65
Slovakia		12.4	15.0	30.0	5.65
Slovenia	QC	11.9	14.0	36.0	7.67
Spain	C	7.9	13.0	30.0	4.03
Sweden	Q	9.7	10.8	32.0	4.23
Switzerland		11.2	13.0	30.0	6.33
F.Y.R. of Macedonia		12.4	15.0	30.0	5.65
Ukraine		12.4	15.0	30.0	5.65
United Kingdom	QC	12.4	15.6	23.7	5.66

[a] "Q" indicates that data on excretion and days in housing originate from the questionnaire (Annex 1); "C" refers to data discussed and agreed by national experts during the CAFE consultations.

4.1.1.4. Other livestock categories

For other livestock categories distinguished in the RAINS model (poultry, sheep, horses, fur animals) the same approach based on Equation 4.2 and the assumptions listed in Table 4.1 are used. Typically, the contribution of these categories to ammonia emissions is smaller and fewer countries report specific data. This section presents a short summary. Detailed results of the N excretion calculation and NH_3 emissions factors for each category and country can be found on the RAINS web model.

For laying hens the average excretion rate is assumed to be about 0.8 kg N/animal per year (EEA, 2003). Data reported in the questionnaire indicate a range from 0.65 to 1.5 kg N. Estimated ammonia emission rates are between 0.37 and 0.7 kg NH_3/animal per year.

For other poultry the excretion rate of 0.7 kg N/animal per year as given in EEA (2003) is used. However, this is strongly dependent on the composition of this category, as the excretion rates vary between about 0.4 kg N for broilers to nearly 2 kg N for turkey. Data reported in the questionnaire indicate a range from 0.45 to 1.5 kg N. Estimated ammonia emission rates are between 0.32 and 0.7 kg NH_3/animal per year.

For sheep (this category includes also goats), EEA (2003) suggests a default N excretion rate of 20 kg N/ewe (assuming on average 1.8 lamb/ewe) per year. Data reported in the questionnaire indicate a range of about 14 to 23 kg N. Large variations in housing period lengths are reported, i.e., from only few weeks in the UK to about 200 days in Austria. Estimated ammonia emission rates are between 1.33 and 2.6 kg NH_3/animal per year.

For horses and fur animals, only few countries reported specific values while for majority the default excretion rates as given in EEA (2003) of 50 kg N and 4.1 kg N for horses and fur animals were applied. Estimated ammonia emission rates are about 8.1 and 1.7 kg NH_3/animal per year for horses and fur animals, respectively. The country-specific values fall in the same range, i.e., N-excretion for horses ranges from about 42 to 60 kg N. Some countries reported data for rabbits, e.g., Portugal, however, since there is no such class in RAINS these were included in the category "fur animals". The N excretion rate for rabbits is significantly lower than for fur animals, i.e., about 1.5 kg N.

4.2. Nitrous oxide emissions from livestock

Nitrous oxide (N_2O) emissions from agriculture are associated with animal and crop production. These emissions are estimated according to the method described in Mosier *et al.* (1998), which is the basis for the revised 1996 IPCC guidelines. This method distinguishes between:

- direct N_2O emissions from agricultural fields,
- direct emissions from animal production systems and

- indirect emissions, occurring when N is lost from agricultural fields[3] and transported to remote sites, where it is subject to denitrification.

The method in Mosier *et al.* (1998) was adapted, where necessary, in order to use information from the RAINS model as input. This section discusses direct emissions from animal production systems; other items will be discussed further in the document.

As will be explained in more detail in Section 5.2 on emission control options, N_2O emissions are affected by the implementation of several techniques that are applied for reducing NH_3 emissions. In the following, this is indicated by including parameters for the effects of control options in the general equations presented.

4.2.1 Direct emissions from manure management

Direct N_2O emissions from manure management originate from animal waste management systems, application of manure and grazing animals. The agricultural module of RAINS distinguishes already four stages (Tier-I) at which emissions of NH_3 occur. To calculate N_2O emissions from manure management, these are aggregated into three stages, i.e., housing and storage[4] (referred above as animal waste management system), application, and grazing.

The IPCC method distinguishes between different waste management systems for which significant variations in emissions exist. For example, N_2O emissions from solid waste systems are 20 times higher than from slurry systems (Mosier *et al.*, 1998). The RAINS model includes these two systems for cattle and pigs. For the other animal types, the N_2O emission factors were derived based on the default fractions of N excreted in the various waste management systems in Western and Eastern Europe as presented by Mosier *et al.* (1998) (see Brink *et al.*, 2001).

N_2O emissions from manure application depend on the amount of nitrogen that is entering the soils, taking into account the nitrogen that is lost as NH_3 and NO_x during application and preceding stages. The loss of NH_3–N is calculated in the model (taking into account the impact of control measures) while the loss of NO_x–N is estimated using a volatilization rate of 0.3 percent of the N in manure that was applied to soils. This value is based on a dataset reviewed by Skiba *et al.*, 1997. The emission factor used for direct N_2O emissions from agricultural soils (0.0125 kg N_2O-N kg^{-1} N input) originates from Mosier *et al.* (1998).

For grazing, the emission factor reported by Mosier *et al.* (1998) (0.02 kg N_2O-N kg^{-1} N excreted) is used. The excretion rate is estimated in the RAINS model as described in Section 4.1. Finally, N_2O

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[3] In the RAINS model, deposition of nitrogen originating from other sources (traffic, combustion, etc.) is also considered.

[4] N_2O emissions from animal waste management systems as referred to in Mosier *et al.* (1998) include both emissions from animal housing and emissions from outdoor storage of manure.

emissions will depend also on the implementation of control measures that affect N-excretion, i.e., dietary modification.

Table 4.5: Unit N_2O emission rates.

Emission category		Housing	Grazing	Comments
$ef^{(N2O)}_{i,j,s}$ [a]				g N_2O-N per kg N excreted; derived from (Mosier *et al.*, 1998)
Cattle and pigs (liquid systems)		1.0	20	
Cattle and pigs (solid systems)		20.0	20	
Poultry	- Western Europe	4.6		
	- Eastern Europe	3.9		
Sheep and goats	- Western Europe	7.3	20	
	- Eastern Europe	5.0	20	
Other animals		5.0		
$ef^{(NOx)}$		3		g NO_x-N per kg N input (Skiba *et al.*, 1997)
$ef^{(N2O)}_{,s}$ [b]		12.5 [c]		g N_2O-N per kg N input (Mosier *et al.*, 1998)

[a] s = animal housing, grazing; [b] *s* = manure application; [c] Associated with large uncertainty as the reported range was 2.5 to 22.5 g N_2O-N/kg N.

Emissions of N_2O from manure management are calculated using the following equations (4.4):

$$E_{i,s,t}^{(N_2O)} = \left\{ \begin{array}{ll} \sum\limits_{j,k} E_{i,j,k,s,t}^{(N_2O)} = \sum\limits_{j} L_{i,j,t} Nx_{i,j,s} ef_{j,s}^{(N_2O)} \sum\limits_{k} \left[\left(1-\eta_{j,k,s}^{(N_2O)}\right) X_{i,j,k,t} \right], & s=1 \\ \sum\limits_{j,k} E_{i,j,s,k,t}^{(N_2O)} = \left[\begin{array}{l} \sum\limits_{j} L_{i,j,t} NA_{i,j,s,t} \left(1-ef^{(NO_x)}\right) \left[1-ef_{i,j,m}^{(NH_3)} \sum\limits_{k} \left[\left(1-\eta_{i,j,k,m}^{(NH_3)}\right) X_{i,j,k,t} \right] \right] \\ ef_{s}^{(N_2O)} \sum\limits_{k} \left[\left(1-\eta_{k,s}^{(N_2O)}\right) X_{i,j,k,t} \right] \end{array} \right], & s=2, m=3 \\ \sum\limits_{j,k} E_{i,j,k,s,t}^{(N_2O)} = \sum\limits_{j} L_{i,j,t} Nx_{i,j,s} ef_{s}^{(N_2O)} \sum\limits_{k} \left[\left(1-\eta_{j,k,s}^{(N_2O)}\right) X_{i,j,k,t} \right], & s=3 \end{array} \right\}$$

where:

$E^{(N2O)}$	N_2O emissions (N_2O-N);
i,j,k,t	country, activity (e.g., animal category), control technology, year;
s	N_2O emission stages distinguished in RAINS, i.e., housing and storage (s=1), manure application (s=2), grazing (s=3);
m	NH_3 emission stages distinguished in RAINS (tier-I), i.e., housing (m=1), storage (m=2), manure application (m=3), grazing (m=4);
m	NH_3 emission stages distinguished in RAINS (tier-I), i.e., housing (m=1), storage (m=2), manure application (m=3), grazing (m=4);
L	Activity data, i.e., number of animals;
Nx	Nitrogen excretion per animal per year;
$ef^{(N2O)}$	Unabated N_2O emission factor;
$\eta^{(N2O)}$	N_2O emission reduction efficiency of the abatement technique;
X	Implementation rate of the abatement technique;
NA	Nitrogen in manure applied on land;
$ef^{(NOx)}$	Volatilisation of NO_x-N during manure application (kg NO_x-N per kg N input);
$ef_m^{(NH3)}$	Emission factor for ammonia (NH_3-N) during manure application (m=3) (kg NH_3-N per kg N input);
$\eta_m^{(NH3)}$	NH_3 emission reduction efficiency of abatement technique (low ammonia application options, i.e., m=3).

4.3. Methane emissions from livestock

Emissions from enteric fermentation and manure management were estimated following the 'Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories' (IPCC, 1997). The animal categories distinguished in the IPCC guidelines for CH_4 match closely the categories distinguished in the RAINS model. A minor difference is that the RAINS model includes sheep and goats in one category, while the IPCC guidelines make a distinction between the two. Since in most European countries sheep have by far the greatest share in this category (FAO, 2003), the IPCC emission factors for sheep were used.

4.3.1 Enteric fermentation

Methane (CH_4) emission factors for enteric fermentation were directly taken from the IPCC guidelines Tier 1 approach (IPCC, 1997). The default emission factors for cattle differ between Eastern and Western European countries because of differences in animal size, milk production and feeding practices. Emissions are calculated using the following equation:

$$E_{i,l}^{(CH_4)} = \sum_{j} L_{i,j,l} ef_{i,j}^{(CH_4)} \tag{4.5}$$

where:

$E^{(CH4)}$ = CH_4 emissions from enteric fermentation,
i,j,l = country, livestock category, year,
L = number of animals in category j.

4.3.2 Manure management

Emissions of CH_4 from manure management were estimated according to the IPCC guidelines using default values for Western and Eastern Europe (IPCC, 1997). Emissions depend on climatic conditions. The IPCC guidelines provide different emission factors for cool, temperate and warm areas, with annual average temperatures less than 15 C, between 15 C and 25 C, or greater than 25 C. Countries in Europe with temperate climatic conditions are Albania, Greece, Italy, Portugal and Spain.

Manure stored or treated as a liquid tends to produce more CH_4 than manure handled as a solid (IPCC, 1997). Therefore, different emissions factors were used for cattle and pigs kept in solid and liquid waste systems, which are distinguished as separate categories in the RAINS model. Moreover, for the animals in liquid systems, emission factors are different for housing and grazing. Emission factors were derived from the IPCC guidelines (IPCC, 1997), assuming that the solid and liquid systems for cattle and pigs in the RAINS model correspond with the 'solid storage' and 'liquid/slurry' manure management systems in the IPCC method respectively. The fraction of manure that is excreted during housing and during grazing is determined on the basis of information in the RAINS databases on nitrogen excretion rates for housing and grazing.

CH_4 emissions from manure management depend on the amount of manure produced by the animals. The RAINS model includes information on the volume of manure produced by each animal type in each country. This information could be used to calculate country-specific values for manure production for each animal type. The IPCC guidelines require, however, information on manure produced as kg dry matter. Because it is not clear how to convert the information on volume to weight for each country, currently the IPCC default values for manure production in Western and Eastern Europe are used. Estimated emission factors calculated are presented in Table 4.6.

Emissions are calculated using the following formula:

$$E_{i,l}^{(CH_4)} = \sum_j L_{i,j,l} \sum_{c=1}^{2} \sum_k \left[ef_{i,j,c}^{(CH_4)} \left(1 - \eta_{i,j,k,c}^{(CH_4)}\right) X_{i,j,k,l} \right] \qquad (4.6)$$

where:

$E^{(CH4)}$ = CH_4 emissions from manure management,
i,j,c,k,l = country, livestock category, abatement technology, year,
c = methane emission stage, i.e., housing/storage (c=1), grazing (c=2),
L = number of animals of category j,
$ef^{(CH4)}$ = unabated CH_4 emission factor (kg CH_4 per animal),
$\eta^{(CH4)}$ = reduction efficiency of abatement technique *k* for CH_4 emissions.

Table 4.6: CH_4 emission factors for manure management (kg CH_4 animal^{-1} yr^{-1})[a)].

	Western Europe				Eastern Europe			
	Cool		Temperate		Cool		Temperate	
RAINS categories	*housing*	*grazing*	*housing*	*grazing*	*housing*	*grazing*	*housing*	*grazing*
Dairy cattle (liquid system)	29.8	3.0	104.4	4.5	24.2	2.4	84.8	3.6
Dairy cattle (solid system)	3.0	3.0	4.5	4.5	2.4	2.4	3.6	3.6
Other cattle (liquid system)	11.0	1.1	38.6	1.7	11.1	1.1	39.0	1.7
Other cattle (solid system)	1.1	1.1	1.7	1.7	1.1	1.1	1.7	1.7
Pigs (liquid system)	5.5	0.6	19.3	0.8	5.5	0.6	19.3	0.8
Pigs (solid system)	0.6	0.6	0.8	0.8	0.6	0.6	0.8	0.8
Laying hens	0.078		0.117		0.078		0.117	
Other poultry	0.078		0.117		0.078		0.117	
Sheep and goats	0.19		0.28		0.19		0.28	
Horses	1.39		2.08		1.39		2.08	

[a)] Derived from IPCC (1997).

4.4. Ammonia emissions from mineral fertilizer application

Application of mineral N fertilizers is a significant source of ammonia emissions, contributing typically between 10 and 15 percent to national total emissions. Emissions of NH_3 from mineral fertilizers depend on many factors including the type of fertilizer applied, soil properties, meteorological conditions, time of application in relation to a crop canopy, and the method of application (e.g., Bouwman *et al*., 1997; EEA, 2003). Emissions of ammonia from fertilizer use are estimated using the following equation:

$$E_{i,l} = \sum_j (nf_{i,j} FC_{i,j,l}) \tag{4.7}$$

where:

i,j,l = country, fertilizer category (urea and other N-fertilizers), year,
E = emissions of ammonia from fertilizer use [Gg NH_3-N / year],
nf = nitrogen loss (fertilizer category specific) [% of N content /100],
FC = fertilizer use [Gg N / year].

4.4.1 Emission factors

Typically, N losses from synthetic fertilizers used in Europe vary between one and four percent, with the exception of ammonium sulphate (between two and 20 percent) and urea (15 to 20 percent). These large ranges of emission rates which are reported in the literature for the same fertilizer type (Table 4.7) are caused by a number of factors such as the soil pH, cation exchange capacity, temperature, humidity, and the time of application. The RAINS model distinguishes two fertilizer categories, namely urea and other nitrogen fertilizers. Weighted average emission factors, based on the literature data (Table 4.7), available statistics on fertilizer consumption (EFMA, 2003; IFA, 2003; FAO, 2003), and information from national experts are derived for all countries taking into account average temperatures, i.e., distinguishing three groups of countries (ECETOC, 1994).

Table 4.7: NH_3-N loss from synthetic N-fertilizers [percentage of N content].

Fertilizer type	EEA, 2003	ECETOC, 1994	Asman, 1990
Ammonium sulfate	8	5 - 15	8
Ammonium nitrate	2	1 - 3	2
Anhydrous ammonia	4	4	1
Urea	15	15 - 20	15
Combined ammonium phosphates	2-5	5	4
Other complex NK, NPK fertilizers	2	1 - 5	2.5 - 4
Nitrogen solutions	8	8	-

However, this simple approach has been recently criticized for not taking into account the fact that some countries extend through different climatic zones and that the categorization proposed by ECETOC (1994) is too strongly influenced by Western European conditions. New research (Harrison and Webb, 2001; Misselbrook *et al.*, 2000; Sutton *et al.*, 2001) indicates the importance of adjustments for soil pH. The working group of the TFEI Expert Panel on Agriculture and Nature (Sutton *et al.*, 2002) suggested that these factors should be taken into account and proposed modifications to the simple method.

For estimating emission from fertilizer use, a new classification of European climatic regions has been suggested. Based on on Sutton *et al.* (2002), this scheme should distinguish climatological regions rather than entire countries. In reporting data, countries could assign a percentage area of their fertilizer use to the three different categories. As a temperature scalar, spring mean temperature (March, April, May) was proposed, since in this period most fertilizer is applied. In addition, the effect of calcareous soils (pH >7) should be considered using a multiplier on the basic values for the different areas (Table 4.8).

Work is progressing to collect the new information and implement it in RAINS. However, until this will be finalized the model will continue to use weighted averages for urea and other fertilizers considering the new data on N losses (Table 4.8) and the new spatial classes. The new formula to calculate emissions of ammonia from the application of mineral N-fertilizers is:

$$E_{i,l} = \sum_{r=1}^{3} \sum_{j} \left[FC_{i,r,j,l} nf_{j,r} (An_{i,r,j} + Ac_{i,r,j} Cm_j) \right] \tag{4.8}$$

where:

i,r,j,l	country, climatological region (see above), fertilizer category, year,
E	emissions of ammonia from fertilizer use [Gg NH_3-N / year],
nf	nitrogen loss (fertilizer category specific) [% of N content /100] (Table 4.8),
FC	fertilizer use [Gg N / year],
An, Ac	share of a given fertilizer applied on non-alkaline (pH<7) (*Ac*) and alkaline soils (*Ac*),
Cm	calcareous soil multiplier (Table 4.8).

To apply Equation 4.8, new data need to be collected, including information on the amount of fertilizers applied in different climatic zones within countries and the shares of fertilizers applied on non-alkaline (pH<7) and alkaline (pH>7) soils. It is envisaged that this type of information will be made available by some countries during the CAFE program bilateral consultations in 2003 and 2004.

Table 4.8: Revised estimates of ammonia emission rates from cultures as a % of fertilizer N-application (Sutton *et al.*, 2002)[a].

	Emission factor			Calc. soils multiplier	
Fertilizer type	*Region 1*	*Region 2*	*Region 3*		Comment
Ammonium Nitrate	2%	1.5%	1%	x 1	Difficult to justify pH effect based on solubility of all nitrate salts.
Calcium ammonium nitrate	2%	1.5%	1%	x 1	Difficult to justify pH effect, based on similarity of observed emissions to ammonium nitrate.
Urea	20%	17%	15%	x 1	Weak temperature effect; no pH effect expected as urea hydrolysis controls micro-site pH. Basic values from Harrison and Webb (2001) and Misselbrook *et al.* (2001).
Nitrogen solutions [b]	11%	9%	7%	x 1	Temperature effect based on urea and ammonium nitrate.
Anhydrous ammonia	4%	3%	2%	x 4	Weak temperature effect assumed. Expert judgement would suggest a strong pH effect, which is an area of high uncertainty.
Ammonium sulphate	2.5%	2%	1.5%	x 10	Note very strong pH effect supported by measurements and chemical principles (Harrison and Webb 2001).
Ammonium phosphates	2.5%	2%	1.5%	x 10	Expert judgement; some data and based on similarity to ammonium sulphate
Other NK and NPK	2%	1.5%	1%	x 1	For ammonium fertilizers, largely based on ammonium nitrate
Nitrate only (e.g., KNO_3)	0.7%	0.5%	0.5%	x 1	No direct fertilizer emission as no ammonium in this fertilizer. This term accounts for the plant-mediated emission (re-mobilization and senescence), which is also lower than from ammonium-based fertilizers (Sutton *et al.* 2001).

[a] These estimates include the indirect vegetation mediated emissions from grass cutting and senescence of arable crops.

[b] Nitrogen solutions refer to a saturated solution of urea and ammonium nitrate.

4.5. Nitrous oxide emissions from application of fertilizers

4.5.1 Direct emissions from agricultural soils

Direct N_2O emissions from agricultural soils occur after application of organic and synthetic fertilizers and crop residues to agricultural fields and as a result of biological N_2 fixation and cultivation of organic soils (histosols) (Mosier *et al.*, 1998). The present RAINS model does not include relevant information on crop production, emissions from crop residues and biological N_2 fixation. N_2O emissions from these sources are calculated using FAO data on crop production (FAO, 2003). Mosier *et al.* (1998) also provide emission factors for N_2O from cultivated histosols. However, this source was not included here because of insufficient input data.

For fertilizer application, nitrous oxide emissions are calculated according to the following equation:

$$E_{i,l}^{(N_2O)} = \sum_j \left[FC_{i,j,l} \left[1 - ef^{(NOx)}\right] \left[1 - \sum_k \left[nf_{i,j}\left(1 - \eta_{i,j,k}^{(NH_3)}\right) X_{i,j,k,l}\right]\right] ef^{(N_2O)} \right] \tag{4.9}$$

where:

i,j,k,l	country, fertilizer category, abatement technology to reduce NH_3 emissions, year,
$E^{(N2O)}$	emissions of N_2O from fertilizer use [Gg N_2O-N / year],
nf	nitrogen loss (fertilizer category specific) [% of N content /100],
FC	fertilizer use [Gg N / year],
$ef^{(NOx)}$	volatilization of NO_x during fertilizer application (kg NO_x-N per kg N input);
$ef^{(N2O)}$	emission factor for N_2O during fertilizer application (kg N_2O-N per kg N input);
$\eta^{(NH3)}$	emission reduction efficiency of ammonia abatement technique (urea substitution),
X	application rate of ammonia control technology.

4.5.2 Indirect emissions after nitrogen deposition

Nitrogen used in agriculture may also indirectly cause emissions of N_2O. Mosier *et al.* (1998) distinguish three types of indirect N_2O emissions: (*i*) N_2O formation in soils and aquatic systems induced by N deposition, (*ii*) N_2O formation in aquatic systems induced by N leaching and runoff, and (*iii*) N_2O formation from human consumption followed by municipal sewage treatment. Total indirect emissions are the sum of these.

Following Mosier *et al.* (1998), N_2O emissions after deposition of NH_3 and NO_x are accredited in emission inventories to the country where the NH_3 and NO_x emissions occur, despite although the actual N_2O formation takes place at the location of the deposition, which is not necessarily in the same country. However, because N_2O is uniformly mixing in the atmosphere, the location of emissions does not influence their environmental impacts. Mosier *et al.* (1998) assume that one percent of the atmospheric N deposited on agricultural soils is converted into N_2O.

Nitrogen deposition does not only originate from agricultural sources, but also from non-agricultural sources of NH_3 and NO_x. The RAINS model includes emissions and deposition of these nitrogen species. Hence, it is possible to calculate the amount of nitrogen deposited on agricultural and forest soils and consequently to calculate in a consistent way N_2O emissions. Since nitrogen deposition is also a source of NO (Skiba *et al.*, 1997), the same approach can be applied for NO.

The RAINS framework to calculate indirect N_2O and possible NO emissions will allow to assess the impacts of NO_x and NH_3 control strategies.

4.5.3 Indirect emissions induced by nitrogen leaching and runoff

A considerable amount of N fertilizer is lost from agricultural soils through leaching and runoff. This nitrogen enters groundwater and surface waters, where it may enhance biogenic production of N_2O (Mosier *et al.*, 1998). According to Mosier *et al.* (1998), 30 percent of the nitrogen applied to agricultural fields is lost through leaching and runoff, of which about 2.5 percent is converted to N_2O in aquatic systems. The amount of nitrogen applied to soils as organic or mineral fertilizer is calculated by the RAINS model. Therefore, N_2O emissions induced by nitrogen leaching and runoff after application of livestock manure (*mE*) and mineral N-fertilizers (*fE*) can be calculated by:

$$
\begin{aligned}
mE_{i,l}^{(N_2O)} &= \sum_j \left[L_{i,j,l} NA_{i,j,l} \left[1 - ef^{(NOx)}\right] \left[1 - \sum_k \left[ef_{i,j}^{(NH_3)} \left(1 - \eta_{i,j,k}^{(NH_3)}\right) X_{i,j,k,l}\right]\right] ief^{(N_2O)} \right] \\
fE_{i,l}^{(N_2O)} &= \sum_n \left[FC_{i,n,l} \left[1 - ef^{(NOx)}\right] \left[1 - \sum_k \left[nf_{i,n} \left(1 - \eta_{i,n,k}^{(NH_3)}\right) X_{i,n,k,l}\right]\right] ief^{(N_2O)} \right]
\end{aligned}
\tag{4.10}
$$

where:

i,j,n,k,l	country, livestock category, fertilizer category, abatement technology to reduce NH_3 emissions, year,
$mE^{(N2O)}$	indirect emissions of N_2O from livestock manure application [Gg N_2O-N / year],
$fE^{(N2O)}$	indirect emissions of N_2O from fertilizer use [Gg N_2O-N / year],
FC	fertilizer use [Gg N / year],
$ef^{(NH3)}$	emission factor for NH_3 during livestock manure application (kg NH_3-N per kg N input),
$ef^{(NOx)}$	volatilization of NO_x during fertilizer application (kg NO_x-N per kg N input) (
$ef^{(N2O)}$	emission factor for N_2O during fertilizer application (kg N_2O-N per kg N input),
nf	nitrogen loss (fertilizer category specific) [% of N content /100],
$\eta^{(NH3)}$	emission reduction efficiency of ammonia abatement technique,
X	application rate of ammonia control technology,
$ief^{(N2O)}$	emission factor for indirect N_2O emissions induced by nitrogen leaching and runoff .

Recent findings indicate that the IPCC methodology is not satisfactory for estimating of N_2O indirect emissions from soils, and improved approaches are under discussion.

Table 4.9: Emission factors for N_2O and NO_x emissions from fertilizer use and production.

Parameter	Emission factor	Comments
Fertilizer use		
$ef^{(NOx)}$	3	g NO_x-N per kg N input (Skiba *et al.*, 1997)
$ef^{(N2O)}$	12.5 [a)]	g N_2O-N per kg N input (Mosier *et al.*, 1998)
$ief^{(N2O)}$- *indirect*	7.5	g N_2O-N per kg N input; derived from (Mosier *et al.*, 1998)
Fertilizer production		
$ef^{(N2O)}$	27	g N_2O-N per kg HNO_3-N produced (IPCC, 1997)

[a)] Associated with large uncertainty as the reported range was 2.5 to 22.5 g N_2O-N/kg N.

4.6. Emissions from fertilizer production

4.6.1 Ammonia

The production of ammonia and N fertilizers is a potential source of NH_3 emissions. Emission factors for fertilizer plants vary depending on the profile of the plant, its age, the presence and type of abatement equipment, and the type of the process. Ammonia might be lost during various stages of fertilizer production, e.g., conversion of ammonia to nitric acid, formation of ammonium nitrate, solidification of ammonium nitrate, coolers and dryers, release of surplus ammonia at the end of the manufacturing process (Handley *et al.,* 2001; UNEP, 1998a; Battye *et al.*, 1994). A detailed description of production processes and sources of ammonia emissions to the air can be found in UNEP (1998a). Another potentially important source of ammonia emissions are SCR and SNCR (selective catalytic and non-catalytic reduction) units installed to control NO_x emissions. This is due to the so called "ammonia slip" (see also Section 4.7).

ECETOC (1994) provides a range of emission factors for various fertilizers manufactured in Western Europe (Table 4.10), and national inventories collected in the CORINAIR'1990 database provide additional factors. VROM (1983) reported average emission factors for ammonia plants of 0.8 kg NH_3/ton fertilizer produced and for fertilizer plants a range from 0.01 kg to 12.5 kg NH_3 per ton produced. Buijsman *et al.* (1987) assumed an average coefficient of 5 kg NH_3/ton fertilizer produced. Based on the latter reports and assuming after Buijsman *et al.* (1987) that the total production of ammonia plants in each country is proportional to fertilizer production, Klaassen (1991a) derived an average emission factor of 5.8 kg NH_3/ton fertilizer produced. More recently, Handley *et al.* (2001) estimated for 1999 UK ammonia emissions from this source between 1.3 and 3.9 Gg NH_3. According to FAO (2003), fertilizer production in UK was at that time about 400 Gg N, which suggests average emission factors between 3.9 and 11.9 kg NH_3/Mg N fertilizer produced, which falls into the range reported by other countries in the CORINAIR database (Table 4.10).

Table 4.10: Default emission factors for different types of fertilizer plants [kg NH_3/Mg N].

	ECETOC, 1994		CORINAIR'1990
Product	Weighted average	Range	Range
Ammonia	0.006	-	0.6 - 1.3
Ammonium nitrate	0.298	0.01 - 0.49	0.25 - 1.75
Calcium ammonium nitrate	1.370	0.16 - 2.96	-
NPK fertilizers	3.083	0.01 - 9.33	0.2 - 12.5
Nitric acid	0.046	0.02 - 0.23	0.01
Urea	5.075	0.69 - 9.33	0.5 - 5.3

Two reports prepared by experts from IFA (International Fertilizer Industry Association), UNEP (United Nations Environment Programme, Industry and Environment) and UNIDO (United Nations Industrial Development Organization) review environmental issues and legislation associated with manufacturing of fertilizers (UNEP, 1998ab). A summary of reported emission factors for existing and new plants producing N-fertilizers is provided in Table 4.11. These values are generally in good agreement with those discussed above and with the EFMA (European Fertilizer Manufacturers Association) report on BAT in this sector (EFMA, 1995). Battye *et al.* (1994) reviewed US information on emissions from this source and provide a range of emission factors. Based on the information provided in the report, one can derive emission factors for production of ammonia (about 1.7 kg NH_3/Mg N), urea (from 11 to 39 kg NH_3/Mg N; national average[5] about 14 kg NH_3/Mg N), and ammonium nitrate (from 3 to above 100 kg NH_3/Mg N; national average about 91 kg NH_3/Mg N). The upper ranges for ammonium nitrate and urea seem to be very high as is the national average for ammonium nitrate, but could possibly be explained by inconsistencies in the reported units.

Table 4.11: Ammonia emission factors reported in UNEP (1998a) report.

		Emission factor [kg NH_3/Mg N]	
Fertilizer type	Process	*Existing plants*	*New plants*
Urea	Prilling towers	2.14	1.07
	Granulation	1.71	0.54
	Process absorption vents	0.43 – 1.61	0.13
	TOTAL	4.29 – 5.47	1.74
Ammonium Nitrate and Calcium Ammonium Nitrate	Evaporation, granulation, prilling	5.88	0.59
Mixed Fertilizer plants	TOTAL	1.0 [a)]	0.3 [a)]

[a)] Different unit, i.e., kg NH_3 / Mg product.

Emission coefficients for industry should be country-specific and derived from national estimates. The present RAINS data were extracted from the national submission to CORINAIR, the ECETOC (1994) study, Handley *et al.* (2001) and other national reports. Data on the total production of fertilizers were taken from FAO (2003). For most of the countries included in the RAINS model, emission factors for this sector vary between 1.1 to 6.1 kg NH_3/Mg N fertilizers produced. Few countries (France, Spain, Italy, Portugal, and Poland) reported significantly higher numbers (about 20 kg NH_3/Mg N), but also these values are within the ranges presented in Table 4.10 and Table 4.11.

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[5] It is derived from emissions reported in Battye *et al.* (1994) from the NAPAP inventory for 1985 and statistical data on production of respective fertilizers from FAO (2003). The same applies to average estimated for ammonium nitrate.

4.6.2 Nitrous oxide

Another source of N_2O emissions related to agricultural activities is the industrial production of nitric acid (HNO_3), which is mainly produced as an intermediate in the production of nitrate fertilizers (Oonk and Kroeze, 1998). The IPCC guidelines allocate these emissions to the industrial sector. Emissions are estimated based on total production of N fertilizers in each country. Since N_2O emissions occur only during the production of nitrate fertilizers, the fraction of nitrate fertilizers (mainly ammonium nitrate) in total N fertilizer production was estimated on the basis of FAO data (FAO, 2003) and a constant fraction was assumed beyond the year 2000.

N_2O emission rates from nitric acid production depend on technology and operating conditions (IPCC, 1997). No information on these conditions is available for individual countries in Europe. Therefore, a uniform N_2O emission factor of 0.027 kg N_2O-N kg^{-1} HNO_3-N produced was used (Table 4.9). This value has been proposed by Reimer *et al.* (1992) for plants without selective non-catalytic reduction (SNCR) technology, which is representative for European plants. It was also assumed that in Europe most of the nitrate fertilizers are ammonium nitrate and that the fraction of nitrate in its production is 50 percent (factor 0.5 in the equation 4.11):

$$E_{i,l}^{(N_2O)} = 0.5 FP_{i,l} fN_{i,l} ef^{(N_2O)} \qquad (4.11)$$

where:

i,l	country, year,
E^{N2O}	N_2O emissions from N-fertilizer production [Gg N_2O-N/year],
FP	amount of nitrogen fertilizer produced,
fN	fraction of nitrate fertilizers in total N-fertilizer production (factor 0.5 is explained in the text),
$ef^{(N2O)}$	emission factor for N_2O emitted during nitrate fertilizer production processes.

4.7. Stationary combustion sources

Although there is large uncertainty associated with emission factors from fuel combustion in stationary sources, it is generally believed that they are relatively small. Ammonia is released as a by-product of incomplete combustion and during the so called “ammonia slip” from SCR (Selective Catalytic Reduction) and SNCR (Selective Non-Catalytic Reduction) installations.

Most measurements of ammonia emissions from combustion of fossil fuels date back to the 1950’s. They show large variability, and for some type of installations or fuels very few data exist. This makes it difficult to establish robust emission factors for these activities. Battye *et al.* (1994) present an overview of emission factors, including information on performance of SCR and SNCR installations. Also Sutton *et al.* (2000) and Lee and Dollard (1994) summarize emission rates for combustion sources (Table 4.12).

Table 4.12: Ammonia emission factors for stationary combustion sources.

	Emission factor [mg NH_3/MJ][a]			
Emission source	*No control*	*SCR*	*SNCR*	Data source
Coal combustion	0.0112	6.2 [b]	12.6 [c]	Bauer and Andren, 1985; Battye *et al.*, 1994
	0.36			Lee and Longhurst, 1993
	0.61 – 0.92			Möller & Schieferdecker, 1989 (brown coal)
	~ 40			Geadah, 1985 (domestic combustion)
	5			Kubica *et al.*, 2003 (stoves)
Fuel oil combustion	0.64- 5			Muzio and Arend, 1976;
	2.67	4.76 [d]	9.7 [d]	Warn *et al.*, 1990; Battye *et al.*, 1994
Natural gas				
Utility & ind. boilers	1.5 (0.15 – 8.8)	4.3 [e]	8.5 [f]	Warn *et al.*, 1990; Battye *et al.*, 1994
Commercial boilers	0.23			Warn *et al.*, 1990; Battye *et al.*, 1994
Municipal waste	21 (17.5 – 25)			Sutton *et al.*, 2000
			4.5 [e]	Battye *et al.*, 1994
		2.2 (0.55 – 5.5)		IPCC, 1997
Wood combustion		10.3 [e]	20.9 [e]	Battye *et al.*, 1994
	5-10			Kubica *et al.*, 2003 (stoves - fireplaces)

[a] Originally reported in kg/Mg (coal), kg/10^3 liters (oil), kg/10^6 m^3 (gas); [b] small installations about 1 MW;
[c] FBC boiler – mid size boilers (20-60 MW); [d] large boilers >100 MW; [e] unknown size; [f] 110-360 MW

There is large variation in the reported emission rates and it is difficult to derive a consistent set of emission factors. Some data quoted in Battye *et al.* (1994) was omitted, because they refer to one plant only. However, it is interesting to note that emission rates for fuel oil and natural gas are higher than for coal. This is in contrast to European emission inventories, i.e., where emissions from combustion of oil and gas are often neglected and only solid fuels are considered (Handley *et al.,* 2001; Sutton *et al.,* 1995 and 2000).

The release of NH_3 from SCR and SNCR might become in the future a more important source. Both technologies are used to reduce emissions of NO_x from combustion. SCR and SNCR use NH_3 or urea as chemical reduction agents. Some of the NH_3 passes through the SCR/SNCR system without reacting with NO_x after the NO_x reduction reaction (NO_x is reduced to N_2) and is then emitted in the flue gas (the "NH_3 slip"). For both processes, the NH_3-to-NO_x ratio has strong influence on the NO_x reduction efficiency. With a 1:1 ratio, SCR achieves typically about 80 percent NO_x reduction, and the SNCR about 40 percent. Excess NH_3 can lead to greater NO_x reduction efficiency, but causes higher ammonia losses. NH_3 slip can range from below 1 ppm in the flue gas to more than 100 ppm (e.g., Battye *et al.*, 1994; UNEP, 1998a). Typically, quoted values by manufacturers are 5 – 10 ppm for SCR and 20 – 30 ppm for SNCR systems.

Based on Table 4.12 and the above discussion, emission factors for the RAINS model have been developed (Table 4.13). The ammonia module of RAINS is linked with the NO_x module to assure full consistency with assumed NO_x control measures. Emissions of ammonia from stationary combustion sources are calculated:

$$E_{i,l} = \sum_j \sum_m \sum_k A_{i,j,m,l} \left[ef_{j,m} + (Nef_{j,m,k} - ef_{j,m}) XN_{i,j,m,k,l} \right] \qquad (4.12)$$

where:

i,j,m,k,l = country, sector, fuel, abatement option, year,

E = NH_3 emissions from stationary combustion [Gg NH_3/year],

A = fuel consumption [PJ/year],

ef = ammonia emission factor (*No NO_x control)* for combustion sources [g/MJ] (Table 4.13),

Nef = ammonia emission factor for NO_x abatement measures [g/MJ] (Table 4.13),

XN = application rate of NO_x abatement measures (SCR and SNCR).

Table 4.13: Ammonia emission factors for stationary combustion sources used in RAINS.

		Emission factor [mg NH_3 / MJ]		
Sector	Fuel	*No control*	*SCR*	*SNCR*
Power plants and industrial combustion	Coal	0.01	6.2	12.6
	Coke	0.01	n.a.	n.a.
	Fuel oil	0.64	4.8	9.7
	Natural gas	0.15	4.3	8.5
	Biomass	5.0	10.3	20.9
	Waste	1.5	2.2	4.5
New power plants	Coal	0.01	3.1	n.a.
	Coke	0.01	n.a.	n.a.
	Fuel oil	0.01	2.4	n.a.
	Natural gas	0.01	2.1	n.a.
	Biomass	1.0	5.1	n.a.
	Waste	0.65	1.1	2.3
Domestic and residential combustion	Coal	40/0.02 [a)]	n.a.	n.a.
	Coke	0.5	n.a.	n.a.
	Fuel oil	0.98	n.a.	n.a.
	Natural gas	0.23	n.a.	n.a.
	Biomass	9.0/5.0 [a)]	n.a.	n.a.

[a)] Different values for domestic stoves, boilers and residential/commercial installations, respectively.

4.8. Mobile sources

Ammonia emissions from gasoline cars equipped with three-way catalytic (TWC) converters are higher than from cars without emission controls, but there is no agreement on the size of these emissions. Previous studies (McInnes, 1996) reported values of around 5 mg NH_3/MJ, while some more recent measurements (e.g., Fraser and Cass, 1998; Baum *et al.*, 2000 and 2001; Durbin *et al.*, 2001ab; Huai *et al.*, 2003) indicate a range between 14 to 29 mg NH_3/MJ (Table 4.14). The increase in emissions of NH_3 for catalyst cars is associated primarily with the fuel-rich combustion in the engine (<1) when hydrogen is produced due to an insufficient supply of oxygen for a complete combustion. The hydrogen is then available in the catalytic converter for further reaction with NO to form ammonia (Handley *et al.*, 2001 after Rototest, 1998). During stoichiometric (=1) and air-rich (>1) combustion conditions, only very small amounts of ammonia form. Therefore, efforts of car manufacturers are concentrating on measures to keep close to one. Modern vehicles achieve this through computerized engine control units, which are required to meet EURO III and higher emission standards. Additionally, manufacturers of catalytic converters experiment with other catalysts than platinum (or a combination of catalysts) that would also result in lower emissions of NH_3. Therefore, it is expected (Handley *et al.*, 2001) that emissions of ammonia from gasoline cars will decline in the future. This seems to be confirmed by studies that included vehicles from the end of 90's (e.g., Kean *et al.*, 2000; Durbin *et al.*, 2001a; Huai *et al.*, 2003) and industrial sources (TRL, 2000)[6] that show lower NH_3 emission rates for such vehicles (Table 4.14).

Although a variety of technological developments is contributing to the reduction of emissions, the introduction of gasoline direct-injection engines (GDI) might actually lead to increased emissions of ammonia (and particulate matter) due to their fuel-rich operation. The share of these vehicles is steadily increasing as more manufacturers offer this type of engines. Owing to problems with controlling the air to fuel ratio in CNG (compressed natural gas) fuelled cars, they might be also a source of increased NH_3 emissions. Another factor, having possibly a negative impact on NH_3 emissions, is introduction of low sulphur gasoline. Baum *et al.* (2000) tested the vehicles with gasoline at varying sulphur content (up to a factor 10). It was found that emissions of ammonia might increase by up to 40 percent for catalyst vehicles run on low sulphur blends (Table 4.14). Similar findings emerge from Durbin *et al.* (2001a), where 1992-built passenger cars complying with the Tier 0 regulations had 25 – 30 percent higher ammonia emissions for 30 ppm S fuel compared to using 330 ppm S fuel. Similar tests performed for 1997 TLEV vehicles showed increases between 35 and 85 percent, depending on the driving pattern test. Handley *et al.* (2001) suggests, based on industrial sources, that improvements in controlling the air to fuel ratio ( ) could counter the 'sulphur' effect.

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[6] Quoted after Handley *et al.*, 2001

Less information is available for diesel vehicles. As indicated in Table 4.14, they emit significantly lower levels of ammonia. Diesel engines are run air-rich and are not (yet) equipped with catalysts to reduce NO_x emissions. However, in order to meet more stringent emission limits a number of control options (especially for heavy-duty vehicles) are being discussed. These include SCR-like controls where urea would be injected into the exhaust gases, which could lead to an ammonia slip. Another option is the use of NO_x traps, which would require fuel-rich conditions that could possibly promote the formation of ammonia. The latter option is considered a viable solution especially for light duty diesel vehicles and might be commercially available as early as 2003 (Handley *et al.*, 2001).

The following equation is used in RAINS to calculate emissions of ammonia from transport:

$$E_{i,l} = \sum_j \sum_m \sum_k A_{i,j,m,l} \left[ef_{j,m} + (Tef_{j,m,k} - ef_{j,m}) XT_{i,j,m,k,l} \right] \qquad (4.13)$$

where:

i,j,m,k,l	country, sector, fuel, abatement option, year,
E	NH_3 emissions from mobile sources [Gg NH_3/year],
A	fuel consumption [PJ/year],
ef	ammonia emission factor (*No control)* for transport [g/MJ] (Table 4.15),
Tef	ammonia emission factor for abatement measures in transport [g/MJ] (Table 4.15),
XT	application rate of abatement measures for mobile sources (EURO–IV and beyond).

Table 4.14: Literature ammonia emission factors from mobile sources.

	Emission factor			
Vehicle/control	*mg NH_3/km*	*mg NH_3/MJ*	Source	Region
GASOLINE VEHICLES				
Non-catalyst	2.5 – 5	0.53 – 1.06	Dickson, 1991	US
	n.a.	1.49 [a)]	Battaye *et al.*, 1994	US
	2.2 (1.5 – 2.8)	0.73 (0.48 – 0.92)	VW, 1989; Sutton *et al.*, 2000	Europe
EURO-I/TWC	72	14	Fraser and Cass, 1998	US
	138 [193 [b)]]	29 [41 [b)]]	Baum *et al.*, 2000	US
	85 (31 – 140)	28.4 (10 – 46)	VW, 1989; Sutton *et al.*, 2000	Europe
	100	30	Handley *et al*, 2001; COPERT III	Europe
	63 (2 – 97)	20 (0.6 – 23)	Durbin *et al.*, 2001a (91-93 models) [d)]	US
	75 (48 – 98)	25 (16 – 33)	Durbin *et al.*, 2001a (95-96 models) [d)]	US
EURO II/III	90	34	Rototest, 1998	Europe
	10	4	TRL, 2000	Europe
	32	12	Handley *et al.*, 2001 (weighted)	Europe
	31 (24 – 39)	10 (8 – 16)	Durbin *et al.*, 2001a (97 models) [d)]	US
LEV [c)]	38 (1.3 – 137)	8.1 (0.27 – 29)	Huai *et al.*, 2003	US
ULEV [c)]	29 (1.6 – 73)	6.7 (0.36 – 17)	Huai *et al.*, 2003	US
EURO-IV	5	2.1	Handley *et al.*, 2001 (ind.sources)	Europe
SULEV [c)]	8.1 (1.2 – 41)	2.4 (0.37 – 12)	Huai *et al.*, 2003	US
Motorcycles	1.46 (1.1 – 2.2)	1.09 (0.8 – 1.6)	Sutton *et al.*, 2000	Europe
Average fleet	61	11	Fraser and Cass, 1998	US
	94 8	20 1.7	Baum *et al.*, 2001 (on-ramp in 1999)	US
	29	7.5	Huai *et al.*, 2003 (post 91 models) [d)]	US
	n.a.	2.23 [e)]	Battaye *et al.*, 1994	US
	49 3	14 0.9	Kean *et al.*, 2000 (>94% catalysts)	49 3
ALTERNATIVE FUEL VEHICLES (LEV or more stringent emission limits)				
Car – CNG	13	4.9	Durbin *et al.*, 2001b (99 model) [d)]	US
LDT – CNG	76	11 – 14	Durbin *et al.*, 2001b (94 models)	US
LDT – LPG	49 - 338	9 – 60	Durbin *et al.*, 2001b (99-00 models) [f)]	US
DIESEL VEHICLES				
Heavy duty truck	2.9 (0.1 – 5.9)	0.29 (0.1 – 0.6)	Sutton *et al.*, 2000	Europe
Diesel passenger car and LDT	n.a.	3.08	Battaye *et al.*, 1994	US
	1.2 (0.36 – 2.06)	0.42 (0.12 – 0.71)	VW, 1989; Sutton *et al.*, 2000	Europe
	2.0 (0.4 – 10.9)	0.47 (0.1 – 2.6)	Dickson, 1991	US

[a)] Tests done on only two old (1956 and 1972) US vehicles running on unleaded fuel.
[b)] About 40 percent increase in emissions with a switch to low sulfur fuel (10-fold reduction in S content).
[c)] LEV – low emission vehicles (US); ULEV – ultra LEV; SULEV – super ULEV.
[d)] Data presented in the table are averages of small to medium size European and Japanese makes only.
[e)] No detailed information on proportion of the catalyst vehicles and age of the fleet is given but since it is an older study one can suspect that the majority are non-catalyst vehicles.
[f)] Tested vehicles are bi-fuel models and were tested on LPG.

Based on the above discussion, emission factors for the RAINS model were developed (Table 4.15).

Table 4.15: Ammonia emission factors for mobile sources used in RAINS.

		Emission factor [mg NH_3 / MJ]	
Vehicle category	Control technology	*Gasoline*	*Diesel*
Light duty vehicles (4 – stroke)	No control	0.73	0.45
	EURO I	30	0.45
	EURO II	12	0.4
	EURO III	12	0.4
	EURO IV	2.1	1.0
Heavy duty vehicles	No control	0.26	0.29
	EURO I	11	0.29
	EURO II	n.a.	0.25
	EURO III	n.a.	0.25
	EURO IV	n.a.	0.45
Motorcycles (2 – stroke)	all	0.87	n.a.
Off-road	No control	0.73	0.3
	EURO I	30	0.3
	EURO II	12	0.3
	EURO III	12	0.3
	EURO IV	2.1	0.6
		Fuel oil	*Diesel*
Shipping	No control	0.98	0.3
	SCR	4.8	3.0

4.9. Waste treatment and disposal

This sector includes ammonia emissions from sewage (treatment plants and spreading of treated sewage onto agricultural land) and municipal waste (landfills and incineration).

There are only few studies reporting emissions from sewage treatment plants (Lee and Dollard, 1994; Battye *et al.*, 1994; Sutton *et al.*, 1995; Handley *et al.*, 2001), and their estimates are associated with large uncertainties. For the UK, it is estimated that emissions from this source contribute about two percent to the non-agricultural ammonia. (Sutton *et al.*, 2000 and Handley *et al.*, 2001). A significantly larger contribution (about 10 percent of non-agricultural sources) comes from sewage spreading (Sutton *et al.*, 2000; Handley *et al.*, 2001). This estimate considers the UK practice of incorporating (injecting) large proportions of the sewage sludge, which leads to lower emissions of ammonia compared to spreading on the field. The present RAINS implementation relies on the nationally reported numbers and does not estimate them within the model. Work is in progress to collect data on activities, projections and emission rates so that in the future emissions of ammonia, nitrous oxide and methane will be estimated within RAINS in a uniform way.

Municipal refuse contains significant quantities of nitrogen. Part of it is lost as ammonia. Munday (1990) found that N emissions amount to about 7.3 percent of methane losses from landfill. About 10 percent of that nitrogen can be emitted in the form ammonia. These estimates provide the basis for later work by Sutton *et al.* (1995, 2000), Handley *et al.* (2001), Eggleston (1992), and Battye *et al.* (1994). While Sutton *et al.* (2000) emphasize the uncertainty of this estimate, they suggest these sources to contribute about five percent to non-agricultural ammonia emissions. Owing to the EU Landfill Directive, emissions of ammonia from this source are expected to decline in the EU as the share of biodegradable municipal waste (reach in nitrogen) will be declining. The alternative to landfill, composting of biodegradable waste, does however not necessarily lead to lower ammonia emissions (Handley *et al.*, 2001)

Incineration of municipal waste causes much lower emissions of ammonia than landfill. The number of waste incinerators across Europe is expected to rise because of the Landfill Directive. While NH_3 emissions from waste incineration are not large, the stringent requirements on emissions of NO_x for these installations might require SCR and SNCR installations, which in turn will inevitably lead to higher NH_3 emissions. In the RAINS model, emissions from waste incineration are calculated using statistical data on the amount of waste incinerated and the emission factors presented in Table 4.13.

With the exception of municipal waste incineration, RAINS currently relies on national reported amount of emissions from waste treatment and disposal. Work is in progress to collect data on activities, projections and emission rates so that in the future emissions of ammonia, nitrous oxide and methane from these sources will be estimated within RAINS in a uniform way.

4.10. Other sources of ammonia emissions

Many other anthropogenic sources/processes release small amounts of ammonia. They typically contribute only a small fraction to the total emissions in a country and are far less important than the emissions from livestock breeding and nitrogen fertilizer application.

4.10.1 Biomass burning

This category includes burning during forest clearing and agricultural waste burning. There is evidence that significant amounts of ammonia are released during biomass burning. Nitrogen in biomass is in a reduced chemical state, typically as amides and amines. Under combustion conditions, the products of this fuel nitrogen are elemental nitrogen (N_2) and nitrogen oxides (NO and NO_2, or NO_x). Because of its initial "reduced" state and poor mixing conditions that characterize biomass combustion, biomass nitrogen can be released as ammonia (Battye *et al.*, 1994). Bouwman *et al.* (1997) reviewed several global estimates of NH_3 emissions from this source, they vary between 2.5 and 7 Tg NH_3, which amounts to approximately 10 to 20 percent of global emissions from animals.

Burning crop residues on fields is forbidden in several European countries. RAINS does not include emissions from this source yet. It is planned to make use of the available land use data as well as recent improvements in biofuel use statistics to estimate regional emissions from biomass.

4.10.2 Industrial processes

Many other industrial processes were found to release small amounts of ammonia. They include beet sugar production, cement industry, explosives manufacturing, coke production, pulp and paper industry, use of ammonia as refrigerant, and a number of other processes (Handley *et al.*, 2001; Battye *et al.*, 1994). All these sources are believed to be small contributors, but they should not be forgotten. For the UK, Handley *et al.* (2001) estimated that about 5-10 percent of total non-agricultural ammonia emissions might originate from these sources, which would represent about one percent of total national UK ammonia emissions in the 1990's.

At this stage, the RAINS model does not include a procedure to calculate emissions from these sources, but relies on national emission inventories and puts these estimates into the category "Other", so that they are part of the national total. Unless additional information is available, the future emissions from these sources in RAINS are considered constant at the level of the last reported year.

4.10.3 Humans and pets

As a result of normal metabolic processes, NH_3 is released from humans (breath, sweat, excretion). There is, however, large variation in the estimates of emissions from this source, i.e., from 0.04 to 1.3 kg NH_3-N/person per year. One of the reasons for this wide range is possibly the inclusion/exclusion of different sources, i.e., breath, perspiration, cigarette smoking, pets. Battye *et al.* (1994) proposed the largest contribution to come from perspiration (about 0.25 kg NH_3-N/person); smaller amounts are associated with breath (4.1 – 5.4 g NH_3-N/person) and cigarette smoking (0.82 g NH_3-N/person). Atkins and Lee (1993) measured household concentrations of ammonia and derived emission factors of about 0.1 – 0.2 kg NH_3/person. A more recent and exhaustive review of emissions from human sweat, breath, smoking, infant nappies, and pets was prepared by Sutton *et al.* (2000). A "best estimate" average UK emission factor was of about 110 g NH_3-N per person per year has been found. The largest contribution to this comes from pets, i.e., dogs (about 75 g) and cats (about 15 g), followed by human sweat (14 g) and breath (3 g), cigarette smoking (3.5 g), nappies (0.5 g).

For RAINS, an emission factor of 0.13 kg NH_3 per person per year has been adopted after Sutton *et al.* (2000). This emission factor includes emissions from human breath and perspiration, pets (dogs and cats), cigarette smoking, and nappies. Emissions from this source are calculated using population data from the UN statistics and projections (UN, 2002).

4.10.4 Other sources

According to Handley *et al.* (2001) and Sutton *et al.* (2000), emissions from wild animals and birds might contribute comparable or even higher quantities of ammonia than other sectors discussed in this section. For UK, Handley *et al*. (2001) estimated emissions of about 6.3 Gg NH_3, which is nearly two percent of the national total and 10-15 percent of the non-agricultural sources emissions.

The RAINS model does not include a procedure to systematically estimate these emissions, but rather relies on the nationally reported data and adds these emissions to the category "Other". If national estimates are not available, the UK per area emission factor is used.

Emissions from horses are not always fully included in emission inventories. Although many emission inventories (and the RAINS model) contain a category for horses, statistical information applies in some cases only to agricultural horses. Sutton *et al.* (2000) and Handley *et al.* (2001) claim that pleasure riding horses and racing horses can account for a large proportion of horses. Sutton *et al.* (2000) estimated overall UK ammonia emissions from horses at about 9 Gg NH_3, of which about 30 percent are from racing horses. It is not clear to what extent emissions from racing horses and pleasure horses are included in the individual national inventories. In RAINS, emissions from horses are estimated on the basis of FAO statistics on the number of animals (FAO, 2003). The applied emission factors are more representative for pleasure horses than racing breeds. If country-specific estimates for these categories exist, the RAINS database can be adjusted accordingly. At the moment, the model does not include a formal procedure for calculating these emissions.

4.11. Other sources of nitrous oxide and methane emissions

4.11.1 Rice cultivation

Information on rice production in Europe has been recently included in the RAINS databases in the context of its extension to greenhouse gases. Following the IPCC guidelines, CH_4 emissions from rice cultivation are calculated for different water management techniques (IPCC, 1997). In Europe, all rice fields are irrigated. Information on annual harvested area is obtained from FAO and default emission factors are taken from the IPCC guidelines. Emissions are calculated applying the following equation:

$$E_{i,l}^{(CH_4)} = RH_{i,l} ef_{i,l}^{(CH_4)} \tag{4.14}$$

where:

i,l = country, year,
$E^{(CH4)}$ = methane emissions from rice cultivation,
RH = annual harvested area for rice cultivation,
$ef^{(CH4)}$ = CH_4 emission factor for rice cultivation on irrigated fields.

4.11.2 Other anthropogenic sources of nitrous oxide

Other sources include biological N fixation by certain crops (pulses and soybeans), which afterwards causes N_2O emissions from these soils. These crops add nitrogen to the soils by fixation of atmospheric N_2. Large uncertainties exist both for the amount of N fixed by biological N fixation in agricultural systems and for the N_2O conversion coefficient (Mosier *et al.*, 1998). This source is not included in RAINS.

Nitrous oxide emissions from crop residues also occur when crop residues are returned to the soils after harvest or crop residues are burnt. Burning of crop residues is forbidden in Western Europe and in a number of Eastern European countries. Currently emissions of N_2O from these sources are not included in RAINS.

5. Emission control options

5.1. Options to control ammonia emissions

For each of the major sources of ammonia emissions (livestock farming, fertilizer use, and chemical industry), RAINS considers a number of emission control options.

Ammonia emissions from livestock occur at four stages, i.e., in the animal house, during storage of manure, its application and during the grazing period. At every stage, emissions can be controlled by applying various techniques. RAINS cannot distinguish all of the control options available in 'real life', but considers groups of techniques with similar technical and economic characteristics. Efficiencies and applicability area of the considered options are given in Table 5.1. The major categories of abatement techniques considered in RAINS are:

- Low nitrogen feed [LNF] (dietary changes). Lower nitrogen (N) content of fodder reduces N excretion by animals and consequently NH_3 emissions. This can be achieved by (Klaassen, 1991a; Wijnands and Amadei, 1991, UNECE, 1999b):
    - reductions in the level of N applied to grassland or substitution of grass by silage (dairy cows),
    - a better tuning of compound feed to the nutrient needs of the animals (multi-phase feeding for pigs and poultry),
    - changes in the composition of the raw materials (pigs and poultry),
    - supplementing diets with synthetic amino acids (pigs and poultry), and
    - replacement of grass and grass silage by maize (dairy cows).

  Changes in the diet are restricted, since the productivity of the animals should not decrease. It is assumed in the RAINS model that this control option may reduce NH_3 emissions by 10-20 percent (Table 5.1).

- Biofiltration (air purification): treatment of air ventilated from animal buildings by applying various techniques such as bio-filtration, bio-scrubbing and chemical scrubbers. These techniques can only be applied in animal houses equipped with mechanical ventilation, which is often the case for poultry and pigs. In bio-filters and air scrubbers, NH_3 in the air is absorbed in the process water, converted into nitrite and then into nitrate (Scholtens and Demmers, 1991). These measures can reduce NH_3 emissions from housing by 80-90 percent (Klaassen, 1991a; UNECE, 1999b).

- Animal house adaptation: Design modifications of animal houses are possible to prevent or reduce emissions of NH_3 (Klaassen, 1991a; Monteny and Erisman, 1998; UNECE, 1999b). This is achieved if either the surface area of the slurry or manure exposed to the air is reduced or the waste is frequently removed (e.g., flushed with water or diluted with formaldehyde) and placed in covered storages. The RAINS model includes different control options for various livestock categories. Ammonia emissions from cattle housing can be reduced through regular washing or scraping the floor, frequent removal of manure to a closed storage system and modification of floor design. This may reduce NH_3 emissions from animal housing typically by 20-50 percent. Monteny and Erisman (1998) give an extensive review of options for dairy cattle buildings and conclude that, in the Netherlands, an emission reduction of 50 percent seems technically feasible applying available techniques. There are control options that can potentially reduce emissions from housing by up to 80 percent. For pig housing, a 30-40 percent reduction of NH_3 emissions can be obtained by combining good floor design (partly slatted floor, metal or plastic coated slats, inclined or convex solid part of the floor) with flushing systems. Even higher reduction efficiencies can be achieved when flushing systems with clarified aerated slurry or manure cooling systems are used (UNECE, 1999b). NH_3 emissions from housing systems for laying hens can be reduced by drying of manure, either through the application of a manure belt with forced drying or by drying the manure in a tunnel. For other poultry, NH_3 emissions from housing systems can be reduced by regularly removing the manure using a scraper or continuously blowing heated air under a floating slatted and littered floor to dry the litter. For both categories, NH_3 emissions from housing systems can be reduced by 60-80 percent (Klaassen, 1991a). It is important to note that for all measures listed above it is assumed that the manure will be moved to a closed storage that is constructed along with the modifications or construction of new animal houses. This will bring also reductions of NH_3 emissions during storage. Preventing loss of ammonia from housing and storage will result in a higher N concentration in the remaining manure than without these measures applied. Hence, the emissions of NH_3 during application of manure will increase if no preventive measures are taken (e.g., Klaassen, 1994; Monteny and Erisman, 1998). The reduction efficiencies assumed in RAINS for this category of measures are summarized in Table 5.1.

- Covered outdoor storage of manure [**CS**] (available for liquid slurry) distinguishing between:
  - low to medium efficiency [CS_low] options using floating foils or polystyrene, and
  - high efficiency options [CS_high] using tension caps, concrete, corrugated iron or polyester.

- Low ammonia application techniques [**LNA**]: Several techniques are available to reduce the amount of NH_3 emissions during and after application of manure to arable land or grassland. The RAINS model distinguishes between techniques with a high NH_3 removal efficiency, e.g., immediate incorporation, injection of manure, and techniques with a low efficiency, e.g., slit injection, trailing shoe, band spreading. All techniques involve placement of manure in the soils as opposed to spreading it over the surface (broadcasting). The NH_3 reduction efficiency is different for solid and liquid manure (Table 5.1):

    - medium to low efficiency [**LNA_low**] techniques, including slit injection, trailing shoe, slurry dilution, and band spreading for liquid slurry and incorporation of solid manure by ploughing into the soil the day after application, and
    - high efficiency [**LNA_high**] options, including immediate incorporation by ploughing (within four hours after application), deep and shallow injection of liquid manure and immediate incorporation by ploughing (within 12 hours after application) of solid manure.

- End-of-pipe techniques in chemical industry [**STRIP**]: Ammonia emissions from fertilizer plants depend on the type of fertilizer produced with majority originating from mixed fertilizer plants and nitrogenous fertilizer plants, inter alia, manufacturing NH_3 and urea (UNECE, 1999b). NH_3 from industrial sources is emitted into the atmosphere either as straight NH_3 gas or as dust or particles containing NH_4^+ or urea originating from various stages of fertilizer manufacturing process (ECETOC, 1994). These emissions can be reduced by about 95 percent through introduction of such techniques as stripping, absorption, cyclones and fabric filters[7] (UNECE, 1999b). The applicability of these techniques is limited (Tangena, 1985) and so the overall reduction of NH_3 emissions from fertilizer industry will be typically lower depending on fertilizers produced and process involved.

- Substitution of urea [**SUB**]: The proportion of N lost as NH_3 is higher for urea than for other mineral N fertilizers (ECETOC, 1994). Substituting urea [$CO(NH_2)_2$] with, for example, ammonium nitrate [NH_4NO_3] would result in reduction of NH_3 emissions by about 80 to 90 percent, depending inter alia on climate and soil characteristics.

- Incineration of poultry manure [**PM_INC**]: In some countries, surplus poultry (broilers) manure is incinerated instead of applying it on the field. This option allows for a very efficient reduction of emissions from application stage (nearly 100 percent efficiency) but its application is limited due to a number of reasons and overall efficiency about 60 percent.

An addition, **combination**s of the above options are defined in the model and their reduction efficiencies are calculated for all four emission stages distinguished (housing, outside storage, application, grazing). Most of the options do not really remove ammonia but merely preserve nitrogen in the manure, so that more of it is available at later stages. This effect is considered for each of the combinations[8]. Thus, the stage and country-specific removal efficiencies are estimated taking into account controls applied up to a given stage, N-volatilization rates, and stage-specific efficiency of the considered option (Table 5.1).

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[7] Scrubbers, cyclones and bag-houses are often an integral part of the modern mixed fertilizer plants.

[8] In fact this is done first for two categories of “single” options listed in Table 5.1, namely, CS (high and low) and SA where a level of control affects actual emissions at a later stage (assuming no further controls are applied).

The reduction efficiencies used in the RAINS calculation are estimated in two steps. First, reduction efficiencies for storage and application stages are recalculated for animal house adaptation and covered storage. Thereby, the amount of nitrogen available for further emissions is tracked through the entire chain, and the emission factors of subsequent stages are adjusted accordingly using the following formula for covered storage (application stage):

$$\eta_3' = -\frac{(1-v_1)v_2\eta_2}{1-v_1-v_2(1-v_1)} \tag{5.1}$$

where:

1,2,3,4	index for emission stages, i.e., housing (1), storage (2), application (3), grazing (4);
η_s'	recalculated reduction efficiency at stage *s*;
η_s	assumed reduction efficiency at stage *s* (see Table 5.1);
v_s	N-volatilization rate for stage *s* (see Table 4.1).

For animal house adaptation, the correction is calculated for the storage and application stages with the following formulas:

$$\eta_2' = \eta_2 - v_1\eta_1\frac{(1-\eta_2)}{(1-v_1)} \tag{5.2}$$

$$\eta_3' = -\frac{v_1\eta_1+(1-v_1)v_2\eta_2}{1-v_1-v_2(1-v_1)}$$

where:

1,2,3,4	index for emission stages, i.e., housing (1), storage (2), application (3), grazing (4),
η_s'	recalculated reduction efficiency at stage *s*,
η_s	assumed reduction efficiency at stage *s* (see Table 5.1),
v_s	N-volatilization rate for stage *s* (Table 4.1).

The N volatilization rates and stage-specific reduction efficiencies are treated in the model as country-specific parameters. The values provided in Table 4.1 and Table 5.1 include default assumptions. For urea substitution in Table 5.1, the efficiency is always country (region)-specific.

These adjusted values of reduction efficiencies are then used to calculate efficiencies for combination of options. As indicated before, the reduction efficiency of a given emission stage depends on what was done at previous stages. The following equations are used to calculate the efficiency for a given stage for a combination of two (A_B) and three (A_B_C) options:

$$\eta_{A\_B} = \eta_A + (1-\eta_A)\eta_B$$

$$\eta_{A\_B\_C} = \eta_A + (1-\eta_A)\eta_B + \left[1-(\eta_A + (1-\eta_A)\eta_B)\right]\eta_C \qquad (5.3)$$

where:

A,B,C = control technologies included in the combination,
$\eta_{A,B,C}$ = reduction efficiency of a given control option.

Table 5.1: Emission control options for NH_3 considered in the RAINS model and their assumed removal efficiencies (based on the UNECE, 1999b: EB.AIR/WG.5/1999/8 Rev.1)[a].

Abatement option	Application areas	Removal efficiency [%]			
		Animal house	*Storage*	*Application*	*Grazing*
Low nitrogen feed (LNF)	Dairy cows	15	15	15	20
	Pigs	20	20	20	n.a.
	Laying hens	20	20	20	n.a.
	Other poultry	10	10	10	n.a.
Biofiltration (BF)[b]	Pigs, poultry	80	n.a.	n.a.	n.a.
Animal house adaptation (SA)	Dairy cows	25	80	n.a.	n.a.
	Other cattle	25	80	n.a.	n.a.
	Pigs	40	80	n.a.	n.a.
	Laying hens	65	80	n.a.	n.a.
	Other poultry	85	80	n.a.	n.a.
Covered storage (CS_low/high)	Dairy cows, other cattle, pigs, poultry *[liquid manure]*	n.a.	40/80	n.a.	n.a.
Low NH_3 application (LNA_low/high)	Dairy cows, other cattle, pigs, poultry, sheep *[solid waste]*	n.a.	n.a.	20/80	n.a.
	Dairy cows, other cattle, pigs *[liquid manure]*	n.a.	n.a.	40/80	n.a.
Urea substitution (SUB)	Fertilizer use	80 – 93			
Stripping/adsorption	Industry	95			
Manure incineration	Other poultry	~60 [c]			

[a] For some countries changes to these numbers where made as RAINS allows for country-specific reduction efficiencies, these was based on consultations with national experts during the work on the scenarios for Gothenburg Protocol. [b] Although some countries indicated that this option is also available for cattle (because some animal houses are equipped with mechanical ventilation), it has not been implemented in RAINS, yet. [c] Based on the example for UK, the values might vary from country to country.
n.a.: not applicable

Additionally, the impact of NO_x control measures (e.g., SCR and SNCR for stationary combustion sources, three-way catalysts in mobile sources) is considered through the link of the RAINS ammonia module with the NO_x module.

5.2. Impact of ammonia reduction measures on emissions of nitrous oxide and methane

Some measures for reducing ammonia emissions influence emissions of CH_4 and N_2O. Table 5.2 provides a qualitative assessment of such interactions, while Table 5.3 summarizes the quantitative assumptions.

Table 5.2: Direction of effects of NH_3 control options on emissions of N_2O and CH_4 a).

	Sources of CH_4 b)	Sources of N_2O			
				Indirect emissions	
NH_3 control options	Manure management	Animal production	Direct soil emissions	*N deposition*	*N leaching*
Low nitrogen feed	0	–	–	–	–
Air purification	0	+	0	–	0
Animal housing adaptations	–	+	+	–	+
Covered storage of manure	+	–	+	–	+
Injection of manure	0	0	+	–	+
Urea substitution	0	0	0	–	0
Stripping/absorption	0	0	0	–	0

a) ‘+’, ‘ ’ and ‘0’ indicate an increase, decrease and no change in emissions after application of control option.
b) There are no effects of NH_3 abatement on CH_4 emissions from enteric fermentation and rice cultivation.

Table 5.3: Impacts of NH_3 control options on emissions of N_2O and CH_4 (percentage changes in emissions).

		Sources of CH_4 b)	Sources of N_2O			
					Indirect emissions	
Control options	Livestock category	Manure management	Animal production	Direct soil emissions	*N deposition*	*N leaching*
Low nitrogen feed	dairy cows, pigs, poultry	0	– a)	– a)	– a)	– a)
Air purification		0	+ a)	0	– a)	0
Animal housing adaptations	pigs	–10	900	+ a)	– a)	+ a)
	poultry	–90	900	+ a)	– a)	+ a)
Covered storage of manure	cattle, pigs, poultry	10	–10	+ a)	– a)	+ a)
Low NH_3 application (low/high)	cattle, pigs, poultry, sheep	0	0	60/100	– a)	+ a)
Urea substitution	fertilizer use	0	0	0	– a)	0
Stripping/absorption	industry	0	0	0	– a)	0

a) The effect is calculated on the basis of changes in the N flow due to changes in excretion rates and N-volatilisation rates; b) There are no effects of NH_3 abatement on CH_4 emissions from enteric fermentation.

5.2.1 Low nitrogen feed (LNF)

Emissions of CH_4 are influenced by the daily feed intake and the digestibility rate, but they do not directly depend on the N content of the feed (IPCC, 1997). However, these factors may be affected by changes in the N content of the feed, which, in turn, may result in different levels of CH_4 emissions from enteric fermentation and from manure management. Since it is not clear to what extent and in what direction reductions in the N content of the fodder will affect CH_4 emissions, it is tentatively assumed that there is no effect on CH_4.

As described in Section 1, N_2O emissions depend on the amount of N excreted by animals. A lower N content of the fodder reduces the N excretion per animal and, as a consequence, N_2O emissions from livestock (assuming a constant livestock population). While emissions of NH_3 only depend on the mineral N in the manure, N_2O emissions also depend on the organic N in the manure. Use of low nitrogen feed will result in lower amounts of mineral N, while organic N in the manure will be less affected. Therefore, the reduction rate for N_2O emissions may differ from the rate for NH_3. The qualitative effect on N_2O, however, is not well known for the livestock categories included in RAINS. Therefore, at this stage, it was assumed that low nitrogen feed has the same potential effect on N_2O as on NH_3, reducing emissions by 10-20 percent depending on the animal type. This may potentially overestimate the reduction potential for N_2O emissions.

5.2.2 Treatment of air ventilated from animal buildings (BF)

Ventilated air from animal houses is cleaned using nitrifying bacteria to oxidize ammonium to nitrate. This nitrification process may lead to N_2O emissions, either directly or through consecutive denitrification. No information is available on the amount of N_2O produced during the purification of the ventilated air. Nevertheless, it is likely that N_2O formation is similar to that resulting from nitrification and denitrification in soils. As a conservative estimate it is tentatively assumed that one percent of the total amount of NH_3-N removed in this process will be converted to N_2O. Because the fate of the nitrate formed during the cleaning of the air from animal houses is unclear, it is not taken into account in this study.

It is assumed that these control techniques have no effect on bacterial processes underlying the production and consumption of CH_4 in animal production.

5.2.3 Livestock buildings adaptation (SA)

The effect of housing measures on CH_4 from manure management differs for the animal categories. For dairy cows, washing the floors with water will not affect CH_4 emissions. However, if acid is used, emissions will decrease because of a change in pH. Considering the risks involved with the use of acid, it is more likely that water will be used. For pigs, the effect on CH_4 from manure management depends on the efficiency of separating the manure into liquid and solid fractions. If this separation process is carried out efficiently, there will be no change in the emissions of CH_4, since all manure will be in the solid fraction and thus remain under anaerobic conditions. However, if the separation is not carried out efficiently, a fraction of manure will be in the liquid part that will be aerated. In this case, CH_4 emissions will decrease. No information was found on the quality of the separation process. Since urine, faeces and flushing liquid are mixed before being separated into a liquid and a solid fraction it will be very difficult to achieve a perfect separation. Therefore, CH_4 emissions from manure management were roughly estimated to decrease by 10 percent (Table 5.3).

Housing adaptations for poultry mainly implies drying of manure. During drying, the manure tends to decompose aerobically and little or no CH_4 is produced (IPCC, 1997). Therefore, emissions of CH_4 were assumed to decrease by 90 percent (Table 5.3).

Similar to CH_4, the effect of housing adaptations on N_2O emissions from animal waste management systems is also different for the various animal types. For dairy cows, there is no change in N_2O emissions since the system remains anaerobic. The effect on N_2O emissions from pig housing depends on the efficiency of the separation of manure into a liquid and a solid fraction. N_2O emissions from manure in aerobic systems appear to be 20 times higher than from anaerobic systems (Mosier *et al.*, 1998). Therefore, emissions from the manure that remains in the liquid fraction and will be aerated may be up to 20 times higher than without the aeration process. If the solid fraction is stored, it may start to compost. This may also produce more N_2O than if the slurry is not separated. Adaptations for poultry housing may also largely affect the N_2O emissions, since they imply aeration and heating of the manure. For pigs and poultry, it is assumed that the modifications of housing systems will cause N_2O emissions from waste management systems to increase by a factor of ten (Table 5.3). This value is deduced from the IPCC emission factors (Mosier *et al.*, 1998).

The total amount of N applied to soils will increase if NH_3 emissions from housing are reduced since the amount of N contained in the manure that is applied to soils will increase. Hence, direct N_2O emissions from agricultural soils and indirect N_2O emissions induced by N leaching and runoff will increase.

5.2.4 Covered outdoor storage of manure (CS)

CH_4 emissions from manure storage depend on manure type and conditions in the storage. If covering the manure storage changes conditions from aerobic to anaerobic, CH_4 emissions may increase (IPCC, 1997). The practice of storing manure varies across Europe, in particular between Western and Eastern European countries (Safley *et al.*, 1992). However, sufficiently detailed information on the country-specific conditions was not found. This study assumes an increase of 10 percent in CH_4 emissions from manure management after introducing covers on manure storage (Table 5.3).

As for CH_4, the effect on N_2O emissions also depends on manure storage conditions. Contrary to CH_4, though, the possible change in storage conditions from aerobic to anaerobic will lead to a decrease of N_2O emissions. A decrease of 10 percent in N_2O emissions from animal waste management systems is assumed (Table 5.3).

As discussed earlier (Section 5.1), the reduction of NH_3 emissions at one stage results in increase of N contained in manure that is later applied to soils and hence an increase in N_2O emissions after application.

5.2.5 Low ammonia application of manure

Changes in the way the manure is applied to agricultural soils are not likely to affect emissions of methane.

The effect of low NH_3 manure application on N_2O emissions is unclear. Without doubt, these techniques increase the availability of N in agricultural soils, which in turn may affect N_2O production. In a way, low NH_3 application of manure resembles urine patches, which are known to have high N_2O emission rates per kg of N added (De Klein, 1994). Although the overall effect on N_2O formation is not well understood, Kroeze (1994) assumed for the Netherlands that after surface application of manure 0.2 - 1.25 percent of manure-N is lost as N_2O, while manure injection may result in losses of 1.25 - 2.5 percent. Velthof and Oenema (1997) used an emission factor for N_2O that is 67 percent higher for slurry applied with a technique that minimizes NH_3 emissions than the emission factor for surface applied slurry. In RAINS it is assumed that 1.25 percent of the nitrogen applied to soils by surface application is lost as N_2O (Section 4.2.1). Recognizing that manure injection may resemble the impact of manure produced by grazing animals, for which Mosier *et al.* (1998) used an emission factor of two percent, it is assumed that low efficiency (LNA_low) manure injection techniques may increase N_2O emissions from agricultural soils by 60 percent and high efficiency techniques (LNA_high) by 100 percent (Table 5.3). These tentative assumptions need to be carefully looked at and reviewed in the near future, as these effects are currently subject to scientific debate within the IPCC review process.

When NH_3 emissions during application of manure are reduced, more N will be subject to leaching and the related N_2O emissions will increase (Section 4.5.3).

5.2.6 Urea substitution

There are indications that N_2O emissions are relatively high for fertilizers based on organic N or anhydrous NH_3, and relatively low for fertilizers based on urea, ammonium or nitrate (of which urea seems to give rise to the lowest N_2O emissions). However, Bouwman (1996) argued that statistical analysis of the available experimental data does not allow for deriving fertilizer type-specific emission factors for N_2O that are applicable world-wide. This was the major reason why in the IPCC methodology emissions are calculated as 1.25 percent of the N input to soils, regardless the type of fertilizer used. Therefore, at this stage, no effect of urea substitution on N_2O emissions from agricultural soils is assumed in RAINS.

Substituting urea with ammonium nitrate does not affect emissions of CH_4, because synthetic fertilizer use is not a source of CH_4.

5.2.7 End-of-pipe options in fertilizer plants

There is no effect of stripping and absorption techniques on CH_4 emissions. Although it is likely that this option will affect emissions of N_2O, it is not clear to what extent. Therefore, no effect was taken into account.

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ANNEX 1

Agricultural QUESTIONNAIRE

QUESTIONNAIRE (For explanation of terms refer to glossary at the end of this document)

DAIRY CATTLE

Farm characteristics

Parameter	*Small*	*Large*	*Units*
Share			%
Average herd size			heads
Percentage of animals kept on liquid manure system			%
Percentage of animals kept on solid manure system			%
Milk production			kg head^{-1}year^{-1}
N-excretion			kg head^{-1}year^{-1} N
C-excretion			kg head^{-1}year^{-1} C
Days/hours per day grazing		/	days / hours

Storage/waste management

Type	*Share*[*]	*of which covered:*	*Units*
Lagoons			%
Open tanks			%
Closed tanks			%
Daily spreading			%
Solid storage and dry lot			%
Pasture			%
Other (specify)			%
Storage capacity			months
Slurry for anaerobic digestion			%

Application of manure

Application technique	*Slurry*[*]	*Solid waste*[*]	*Units*
Broadcasting			%
Low efficiency			%
Medium efficiency			%
High efficiency			%

[*] All categories in the indicated column should add to 100%

OTHER CATTLE

Farm characteristics

Parameter	*Small*	*Large*	*Units*
Share			%
Average herd size			heads
Percentage of animals kept on liquid manure system			%
Percentage of animals kept on solid manure system			%
Slaughter weight			kg
Production cycles per year			-
N-excretion			kg head^{-1}year^{-1} N
C-excretion			kg head^{-1}year^{-1} C
Days/hours per day grazing		/	days / hours

Storage/waste management

Type	*Share*[*]	*of which covered:*	*Units*
Lagoons			%
Open tanks			%
Closed tanks			%
Daily spreading			%
Solid storage and dry lot			%
Pasture			%
Other (specify)			%
Storage capacity			months
Slurry for anaerobic digestion			%

Application of manure

Application technique	*Slurry*[*]	*Solid waste*[*]	*Units*
Broadcasting			%
Low efficiency			%
Medium efficiency			%
High efficiency			%

[*] All categories in the indicated column should add to 100%

FATTENING PIGS

Farm characteristics

Parameter	*Small*	*Large*	*Units*
Share			%
Average herd size			heads
Percentage of animals kept on liquid manure system			%
Percentage of animals kept on solid manure system			%
Slaughter weight			kg
Production cycles per year			-
N-excretion			kg head^{-1}year^{-1} N
C-excretion			kg head^{-1}year^{-1} C
Days/hours per day outside		/	days / hours

Storage/waste management

Type	*Share**	*of which covered:*	*Units*
Lagoons			%
Open tanks			%
Closed tanks			%
Daily spreading			%
Solid storage and dry lot			%
Pasture			
Other (specify)			%
Storage capacity			months
Slurry for anaerobic digestion			%

Application of manure

Application technique	*Slurry**	*Solid waste**	*Units*
Broadcasting			%
Low efficiency			%
Medium efficiency			%
High efficiency			%

*All categories in the indicated column should add to 100%

SOWS

Farm characteristics

Parameter	*Small*	*Large*	*Units*
Share in total pigs on the farm			%
Percentage of animals kept on liquid manure system			%
Percentage of animals kept on solid manure system			%
Piglets (<20kg) per sow per year			heads
N-excretion			kg head^{-1}year^{-1} N
C-excretion			kg head^{-1}year^{-1} C

Storage/waste management

Type	*Share**	*of which covered:*	*Units*
Lagoons			%
Open tanks			%
Closed tanks			%
Daily spreading			%
Solid storage and dry lot			%
Other (specify)			%

Application of manure

Application technique	*Slurry**	*Solid waste**	*Units*
Broadcasting			%
Low efficiency			%
Medium efficiency			%
High efficiency			%

*All categories in the indicated column should add to 100%

LAYING HENS

Farm characteristics

Parameter	*Small*	*Large*	*Units*
Share			%
Average herd size			heads

Percentage of animals kept on liquid manure system		%
Percentage of animals kept on solid manure system		%
Egg production		kg(egg) year^{-1}
Production cycles per year		-
N-excretion		kg head^{-1}year^{-1} N
C-excretion		kg head^{-1}year^{-1} C

Storage/waste management

Type	*Share*[*]	*of which covered:*	*Units*
Lagoons			%
Open tanks			%
Closed tanks			%
Daily spreading			%
Solid storage and dry lot			%
Other (specify)			%

Storage capacity		months
Slurry for anaerobic digestion		%

Application of manure

Application technique	*Slurry*[*]	*Solid waste*[*]	*Units*
Broadcasting			%
Low efficiency			%
Medium efficiency			%
High efficiency			%

[*] All categories in the indicated column should add to 100%

CHICKEN (BROILERS)

Farm characteristics

Parameter	*Small*	*Large*	*Units*
Share			%
Average herd size			heads

Percentage of animals kept on liquid manure system		%
Percentage of animals kept on solid manure system		%
Slaughter weight		kg
Production cycles per year		-
N-excretion		kg head^{-1}year^{-1} N
C-excretion		kg head^{-1}year^{-1} C
Days/hours per day outside	/	days / hours

Storage/waste management

Type	*Share*[*]	*of which covered:*	*Units*
Lagoons			%
Open tanks			%
Closed tanks			%
Daily spreading			%
Solid storage and dry lot			%
Other (specify)			%

Storage capacity		months
Slurry for anaerobic digestion		%

Application of manure

Application technique	*Slurry*[*]	*Solid waste*[*]	*Units*
Broadcasting			%
Low efficiency			%
Medium efficiency			%
High efficiency			%

[*] All categories in the indicated column should add to 100%

OTHER POULTRY – Geese (*if important*)

Farm characteristics

Parameter	*Small*	*Large*	*Units*
Share			%
Average herd size			heads
Percentage of animals kept on liquid manure system			%
Percentage of animals kept on solid manure system			%
Slaughter weight			kg
Production cycles per year			-
N-excretion			kg head^{-1}year^{-1} N
C-excretion			kg head^{-1}year^{-1} C
Days/hours per day outside		/	days / hours

Storage/waste management

Type	*Share**	*of which covered:*	*Units*
Lagoons			%
Open tanks			%
Closed tanks			%
Daily spreading			%
Solid storage and dry lot			%
Other (specify)			%
Storage capacity			months
Slurry for anaerobic digestion			%

Application of manure

Application technique	*Slurry**	*Solid waste**	*Units*
Broadcasting			%
Low efficiency			%
Medium efficiency			%
High efficiency			%

*All categories in the indicated column should add to 100%

OTHER POULTRY – Ducks (*if important*)

Farm characteristics

Parameter	*Small*	*Large*	*Units*
Share			%
Average herd size			heads
Percentage of animals kept on liquid manure system			%
Percentage of animals kept on solid manure system			%
Slaughter weight			kg
Production cycles per year			-
N-excretion			kg head^{-1}year^{-1} N
C-excretion			kg head^{-1}year^{-1} C
Days/hours per day outside		/	days / hours

Storage/waste management

Type	*Share**	*of which covered:*	*Units*
Lagoons			%
Open tanks			%
Closed tanks			%
Daily spreading			%
Solid storage and dry lot			%
Other (specify)			%
Storage capacity			months
Slurry for anaerobic digestion			%

Application of manure

Application technique	*Slurry**	*Solid waste**	*Units*
Broadcasting			%
Low efficiency			%
Medium efficiency			%
High efficiency			%

*All categories in the indicated column should add to 100%

OTHER POULTRY – Turkeys (*if important*)

Farm characteristics

Parameter	*Small*	*Large*	*Units*
Share			%
Average herd size			heads
Percentage of animals kept on liquid manure system			%
Percentage of animals kept on solid manure system			%
Slaughter weight			kg
Production cycles per year			-
N-excretion			kg head^{-1}year^{-1} N
C-excretion			kg head^{-1}year^{-1} C
Days/hours per day outside		/	days / hours

Storage/waste management

Type	*Share**	*of which covered:*	*Units*
Lagoons			%
Open tanks			%
Closed tanks			%
Daily spreading			%
Solid storage and dry lot			%
Other (specify)			%
Storage capacity			months
Slurry for anaerobic digestion			%

Application of manure

Application technique	*Slurry**	*Solid waste**	*Units*
Broadcasting			%
Low efficiency			%
Medium efficiency			%
High efficiency			%

*All categories in the indicated column should add to 100%

SHEEP

Farm characteristics

Parameter	*Small*	*Large*	*Units*
Share			%
Average herd size			heads
Percentage of animals kept on liquid manure system			%
Percentage of animals kept on solid manure system			%
Slaughter weight of lamb			kg
N-excretion			kg head^{-1}year^{-1} N
C-excretion			kg head^{-1}year^{-1} C
Days/hours per day grazing		/	days / hours

Storage/waste management

Type	*Share**	*of which covered:*	*Units*
Lagoons			%
Open tanks			%
Closed tanks			%
Daily spreading			%
Solid storage and dry lot			%
Pasture			%
Storage capacity			months
Slurry for anaerobic digestion			%

Application of manure

Application technique	*Slurry**	*Solid waste**	*Units*
Broadcasting			%
Low efficiency			%
Medium efficiency			%
High efficiency			%

*All categories in the indicated column should add to 100%

General questions:

1. Are you able to comment on projected changes in the efficiency of production (milk yields, slaughter (off-take) weights, etc.)?

   YES ☐ NO ☐

2. Are you able to comment/review the projections of agricultural activities?

   YES ☐ NO ☐

3. Are you aware of the National Plan/Legislation of reducing emissions of air pollutants from agriculture?

   YES ☐ NO ☐

4. Are you aware of national reports/studies about pilot/commercial installations describing efficiency, applicability and costs?

   YES ☐ NO ☐

   if yes attempt to fill-in the table below (indicate availability of information by "X":

	Efficiency	*Costs*	*Language*	*Availability*	*Contact (e-mail)*
Feeding strategies					
Buildings					
Storage					
Manure application					
N-fertilizer application					

5. If you are not able to give details asked above are you in position to comment on the data currently used in modeling that is available from http://www.iiasa.ac.at/~rains/nh3_review.html (A "pdf" file is available for every country)

   YES ☐ NO ☐

GLOSSARY

Farm characteristics

Small/large – We do not define a threshold size for small or large farms (there are stark differences between countries), please define the size yourself (*average herd size*) and give a *share* of animals kept in relevant farms.

Liquid manure – A general term that denotes any manure from housed livestock that flows under gravity and can be pumped.

Solid manure – Manure from housed livestock that does not flow under gravity, cannot be pumped but can be stacked in a heap (*Percentage of animals kept on solid manure systems* refers here to straw based system and tied housing systems).

N-, C- excretion – Total amount of nitrogen/carbon in animal excreta (faeces plus urine).

Slaughter weight – Weight of a live animal immediately prior to slaughter.

Storage/waste management

Lagoon – Normally a large rectangular or square shaped structure with sloping earth bank walls (earth banked lagoon) with large surface area to depth ratio. May be lined with water- impermeable material. Used for storing liquid manures, slurry. Emptied with a pump or by a mechanised digger.

Tank – A vessel for holding liquid manure, slurry.

Daily spreading – Manure is taken from the building and spread directly to land without prior storage.

Slurry for anaerobic digestion – Percentage of slurry that is used for biogas production.

Application of manure

The data should refer to the share (percent) of manure applied with a given method.

Broadcasting – The default (reference) method of manure application, i.e., manure is spread over the whole surface of an area of land.

Low efficiency – Efficiency refers to reduction of ammonia emissions. For liquid slurry low efficiency application refers to band spreading and incorporation (ploughing) on the next day and for solid waste refers to incorporation on the next day (>12 hours after application).

Medium efficiency – Efficiency refers to reduction of ammonia emissions. For liquid slurry medium efficiency application refers to trailing shoe, open slot injection, incorporation within 4 to 12 hours (the same day); For solid waste only high and low efficiency technologies are considered.

High efficiency – Efficiency refers to reduction of ammonia emissions. For liquid slurry high efficiency application refers to closed slot injection, immediate incorporation (within 4 hours after application) and for solid waste refers to incorporation on the same day (within 12 hours after application).