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Emission estimates for some acidifying and greenhouse gases and options for their control in Finland

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ABSTRACT

This thesis presents estimates and options for control of anthropogenic ammonia (NH_3), methane (CH_4), nitrous oxide (N_2O) and some halocarbon emissions in Finland.

Ammonia is an air pollutant which contributes to both acidification and nitrogen eutrophication of ecosystems. Its emissions are mainly caused by livestock manure. In Finland the anthropogenic emissions of NH_3 have been estimated to be approximately 44 Gg in 1985 and 43 Gg in 1990. In the 1990's the emissions have declined due to the reduced number of cattle and voluntary implementation of emission reducing measures. The impact of NH_3 emissions on acidification is serious but in Finland it is less than the impact of the other acidifying gases sulphur dioxide (SO_2) and nitrogen oxides (NO_x). All three gases and their transformation products are transported by the atmosphere up to distances of hundreds or even more than a thousand kilometres.

NH_3 emissions can be reduced with relatively cost-effective measures and the measures can partly replace the implementation of more costly abatement measures on SO_2 and NO_x emissions needed to lower the acidifying deposition in Finland.

The other gases studied in this thesis are greenhouse gases. Some of the gases also deplete stratospheric ozone. Finnish anthropogenic CH_4 emissions have been estimated to be around 250 Gg per year during the 1990's. The emissions come mainly from landfills and agricultural sources (enteric fermentation and manure). The significance of other CH_4 sources in Finland is minor. The potential to reduce the Finnish CH_4 emissions is estimated to be good. Landfill gas recovery offers an option to reduce the emissions significantly at negligible cost if the energy produced can be utilised in electricity and/or heat production. Measures directed at reducing the emissions from livestock manure management are more costly, and the achievable reduction in the emissions small.

The potential to reduce the CH_4 emissions from enteric fermentation in Finland is not known. If measures to reduce these emissions prove efficient and economically promising in future studies, the total reduction in the Finnish CH_4 emissions will be higher and in the long run the halving of the emission level of 1990 seems achievable.

The anthropogenic N_2O emissions in Finland are considerably smaller than the CH_4 emissions, around 20 Gg per year during the 1990's, but the greenhouse impact of the Finnish N_2O emissions is of similar magnitude as that of the Finnish CH_4 emissions. The most important anthropogenic N_2O emission sources in Finland are nitrogen fertilisation, nitric acid production and burning processes in the energy sector. The indirect emissions caused by nitrogen deposition due to NH_3 and NO_x emissions are also of significance. The N_2O emissions are estimated to grow due to the increasing use of fluidized bed combustion and catalytic converters in the energy sector. These otherwise environmentally friendly technologies produce significantly more N_2O than the corresponding conventional technologies.

Measures for N_2O emission control are not known very well and many of the measures are still at an experimental stage. Promising measures to reduce the N_2O emissions from nitric acid production and fluidized bed combustion have been put forward but plant scale applications of the measures are still lacking. If the measures can be implemented on plant scale, emission reductions of the same order of magnitude as the estimated growth in the emissions are anticipated.

The CFCs and other considered halocarbons are already partly phased out. The halocarbons that destroy stratospheric O_3 are subject to regulations under the Montreal protocol and in Finland most of the consumption ceased in 1996. The O_3 depleting substances are partly substituted with substances that are effective greenhouse gases, the most important of which are the HFCs. The emission estimates and impact analyses suggest that the importance of the HFCs could become more significant in the next century if the emissions are allowed to grow unrestricted.

The Finnish non-CO_2 greenhouse gas emissions contribute significantly to the anthropogenic greenhouse impact caused by the Finnish emissions. In the future the impact caused by the CO_2 emissions will grow in importance compared with the non-CO_2 greenhouse gases. The warming impact caused by methane, CFCs and HCFCs is estimated to decrease, whereas that of N_2O and HFCs is expected to grow.

PREFACE

This work has been carried out in the Technical Research Centre of Finland (VTT). The Finnish research programmes on Acidification (HAPRO) and Climate Change (SILMU) have initiated the studies and enabled the writing of the scientific articles which this thesis is based on. Much of the work has been performed in research projects for the Ministry of the Environment and the National Research Programme on Energy and Environment (SIHTI) funded by the Technological Development Centre of Finland (TEKES) and the Ministry of Trade and Industry. I wish to express my gratitude for all concerned, and especially to Ms Maija Pietarinen, Ms Pirkko Heikinheimo and Mr Seppo Sarkkinen from the Ministry of the Environment and Mr Jaakko Ojala from the Ministry of Trade and Industry (currently working at the Ministry of the Environment).

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My mother, Ms Carita Ikonen and Mr Harvey Benson have revised the English language in the thesis. I wish to express my sincere thanks to both of them for this, and to my mother also for lifelong support and love.

My dearest thanks are due for my husband Esko and my children Petri and Jonna for love and understanding.

LIST OF PUBLICATIONS

This thesis is based on the following publications and on some additional studies reported in the summary part:

I Niskanen, R., Keränen, S. & Pipatti, R. 1990. Ammonia Emissions in the 1980s. In: Kauppi, P., Anttila, P. & Kenttämies, K. (eds.). Acidification in Finland. Berlin-Heidelberg: Springer-Verlag, pp. 31 - 39.

II Johansson, M., Kämäri, J., Pipatti, R., Savolainen, I., Tuovinen, J.-P. & Tähtinen, M. 1990. Development of an Integrated Model for the Assessment of Acidification in Finland. In: Kauppi, P., Anttila, P. & Kenttämies, K. (eds.). Acidification in Finland. Berlin-Heidelberg: Springer-Verlag, pp. 1171 - 1193.

III Tähtinen, M., Lehtilä, A., Pipatti, R., Wistbacka, M. & Savolainen, I. 1997. Economic reduction of acidifying deposition in Finland by decreasing emissions in Finland, Estonia and Russia. The Science of the Total Environment 204, pp. 177 - 192.

IV Pipatti, R., Savolainen, I. & Sinisalo, J. 1996. Greenhouse Impacts of Anthropogenic CH_4 and N_2O Emissions in Finland. Environmental Management, Vol. 20, No. 2, pp. 219 - 233.

V Pipatti, R. & Savolainen, I. 1996. Role of energy production in the control of greenhouse gas emissions from waste management. Energy Conversion and Management, Vol. 37, Nos 6 - 8, pp. 1105 - 1110.

VI Pipatti, R. & Sinisalo, J. 1994. Scenarios for Halocarbon Emissions in Finland and Estimates of their Impact on Global Warming and Chlorine Loading in the Stratosphere. Journal of Environmental Management, 40, pp. 259 - 275.

The disputant is the leading author of publications IV - VI. In paper I the disputant has written the text on ammonia emissions from the manure of fur animals and industry, and in papers II and III the text on ammonia emissions. The disputant’s work has in all papers dealt with emission estimates, scenarios for future emissions and mitigation options and costs. The environmental impact calculations (acidifying deposition, radiative forcing and chlorine loading) presented in the publications have been made by the other authors.

CONTENTS

PAPERS I - VI

Appendices of this publication are not included in the PDF version. Please order the printed version to get the complete publication (http://www.inf.vtt.fi/pdf/publications/1998/)

1 INTRODUCTION

Acidification and global warming are human-introduced threats to the environment though the causes and impacts of the phenomena are complicated results of interactions between various pollutants, conditions and processes of both natural and man-made origin.

1.1 ACIDIFICATION

Atmospheric emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x) and ammonia (NH_3) cause deposition, which can acidify soils and surface waters. Emissions of NO_x and NH_3 contribute also to the nitrogen eutrophication of ecosystems. In addition NO_x emissions play an important role in the formation of photochemical smog and ground-level ozone (O_3) together with emissions of volatile organic compounds (VOC). High concentrations of the pollutants in the air can also threaten human health and cause damage to vegetation and materials.

SO_2 is emitted to the atmosphere mainly from coal and oil combustion plants and to a minor extent from some process industries. Road transport and other combustion sources cause the bulk of NO_x emissions, whereas NH_3 emissions come mainly from agriculture. The pollutants can remain for days in the atmosphere before being deposited by wet and dry removal processes at distances up to hundreds or thousands of kilometres from the emission sources. The average atmospheric transport distances vary by emitted pollutant. For example, only about 20 per cent of the NO_x emitted in Finland is deposited within the Finnish area, and correspondingly about 30 per cent in the case of SO_2 and more than 50 per cent in the case of NH_3 (Amann et al. 1996; Kangas et al. 1991; Sandnes 1993 and Savolainen et al. 1996).

The environmental impact of the acidifying emissions depends on the amount of deposition and the sensitiveness of the ecosystems to the deposition. The science-based concept of critical loads is used to indicate the sensitivity of a particular environment to the deposition. By definition the critical load expresses a quantitative estimate on the exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur (UN 1994).

The acidifying emissions have decreased in Europe, but the acidifying impact has not declined as much and the area where the critical loads for acidification and eutrophication are exceeded is still large. One reason for this is that the neutralising base cation emissions and deposition have also declined as for instance end of pipe technologies like electrical filters have become more common in power stations reducing the particle emissions. Further reductions in the acidifying emissions are therefore needed in order to protect the ecosystems (Amann et al. 1996; Hedin et al. 1994; Hedin & Likens 1996).

The acidifying emissions do not respect national borders, and international co-operation is essential in reducing the impacts of the emissions in a sensible and cost-efficient way. Several international agreements have been reached in order to reduce the emissions. In Europe the most important agreement is the Convention on Long Range Transboundary Air Pollution (LRTAP), which was adopted in Geneva in 1979. The emission control protocols under the convention are

- the Helsinki Sulphur Protocol (1985)
- the Sofia NO_x Protocol (1988)
- the Geneva VOC Protocol (1991) and
- the Oslo Sulphur Protocol (1994).

The strongest reduction requirements have concerned the sulphur emissions, which have decreased substantially in Europe since the adoption of the convention. In Finland the SO_2 emissions have decreased by more than 80 per cent since 1980, even if the output of energy production and process industry has grown substantially (Savolainen et al. 1996; Kosunen 1997). Hence the importance of the nitrogen emissions has increased and it is estimated that they will soon exceed those of sulphur as the principal acidifying pollutant in Europe (Barrett et al. 1995).

The requirements on NO_x emission reduction have been less stringent but a goal of a 30 per cent reduction in the emissions of the level of 1980 has been set. In Finland this target is estimated to be met in the beginning of the next century (Savolainen et al. 1996; Kosunen 1997). The emissions of NH_3 have not been regulated under any protocol.

The UN ECE (United Nations' Economic Commission) is preparing a new nitrogen protocol under the Convention on Long-Range Transboundary Air Pollution. The goal is to agree upon national ceilings for future emissions of NO_x, NH_3 and also VOCs. The VOCs are as NO_x major precursors of ground level O_3.

In the negotiations the critical load approach is used to estimate the effect-based and cost-effective abatement of the emissions. The area in Europe, where the critical loads are exceeded, is estimated, and a target to reduce this area will be set (so called gap closure approach). The cost-effective way to achieve the target is calculated with the RAINS (Regional Air Pollution Information and

Simulation) model developed at IIASA (International Institute of Applied Systems Analysis). The model calculates national ceiling values for the emissions of the various pollutants, which should be met to achieve the target. This multi-pollutant and multi-effect approach makes the approach complex and difficult and the sources of uncertainties are numerous but will not be addressed here further (Amann et al. 1996; Heyes et al. 1996).

1.2 GLOBAL WARMING

The Earth's energy balance is determined largely by solar heating. Some of the incoming solar radiation is reflected by the atmosphere and surface back to space but the largest part reaches the surface. The Earth's surface is warmed and radiates thermal energy itself and on average the incoming energy is balanced by outgoing terrestrial radiation. Part of the outgoing radiation is absorbed by gases in the atmosphere. The energy absorbed by the gases is re-emitted and the effect of this is to warm the surface and the lower atmosphere. The effect is often called the greenhouse effect. The natural greenhouse effect is caused mainly by water vapour and carbon dioxide (CO_2). The Earth's mean temperature is about 33 degrees higher than it would be without the natural greenhouse effect (IPCC 1990 and 1992; Wayne 1991).

The concentrations of the greenhouse gases in the atmosphere have grown significantly since the pre-industrial time. According to the Intergovernmental Panel on Climate Change (IPCC 1996a) the enhancement in the concentrations of the greenhouse gases is almost entirely caused by human activities. The increasing greenhouse gas concentrations in the atmosphere are changing the radiative energy balance of the Earth and enhancing the natural greenhouse effect.

The growing concentrations of the greenhouse gases in the atmosphere cause a perturbation in the global radiation energy balance (called radiative forcing and expressed in terms of radiation energy per area of the Earth's surface, Wm^{-2}) which is warming the climate of the Earth. The IPCC mid-range emission scenario, IS92a, gives as the best estimate value an increase of about 2 ^{o}C by 2100 in the global mean surface air temperature relative to 1990 (IPCC 1996a).

The most important anthropogenic greenhouse gas is CO_2 but methane (CH_4), nitrous oxide (N_2O) and halocarbons like the CFCs (chlorofluorocarbons) are also important greenhouse gases. CH_4 presently causes about 30 per cent, N_2O about 9 per cent and halocarbons (CFCs + HCFCs) about 10 per cent of the radiative forcing estimated to be caused by CO_2 (values for 1992) (IPCC 1996a).

Ozone (O_3) is also an important greenhouse gas, present both in the stratosphere and troposphere. Changes in O_3 cause radiative forcing by influencing both solar and terrestrial radiation and the net radiative forcing is strongly dependent on the vertical distribution of O_3 change (IPCC 1996a).

Aerosols in the atmosphere influence the radiation balance of the Earth in two ways: by scattering and absorbing radiation (the direct effect) and by modifying the optical properties, amount and lifetime of clouds (the indirect effect). Although some aerosols, such as soot, tend to warm the surface, the net climatic effect of the aerosols is estimated to be a negative radiative forcing that is cooling the Earth's surface (IPCC 1996a).

In the future the absolute value of the radiative forcing is estimated to increase. Most of the increase will be due to increasing CO_2 concentrations in the atmosphere but the expected increase in the radiative forcing of the non-CO_2 greenhouse gases is also important.

The environmental impacts of the predicted global warming are associated with large uncertainties. Sea level rise, changes in precipitation, increasing climate variability and extreme weather events are expected, although especially the local changes are very poorly known. Loss of land area, even devastation of whole islands and low-lying coastal nations in some parts of the Earth, is a possible consequence of sea level rise. How the ecosystems can adapt to the predicted climate change is unknown: reduced crop yields and forest damage may result. The realisation of the predicted global warming would put the well-being of both humans and the environment at risk.

The UN Framework Convention on Climate Change (FCCC) was signed by 165 countries in Rio in 1992. The ultimate objective of the convention is 'the stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner' (UN FCCC 1992).

The concentration levels of the greenhouse gases that would lead to dangerous interference with the climate system are not defined in the convention. The first agreement on binding emission reduction commitments was signed in Kyoto in December 1997. The emission reductions will at first concern only the industrialised countries (Annex I countries of the Convention) as the convention recognises the poor nations' right to economic development.

According to the Kyoto protocol the Annex I countries are required to reduce their anthropogenic carbon dioxide equivalent emissions of CO_2, CH_4, N_2O, HFCs (hydrofluorocarbons), PFCs (perfluorocarbons) and SF_6 (sulphur hexafluoride) by more than 5 per cent below 1990 levels in the commitment period 2008 to 2012. The individual Annex I countries are given specified emissions limitation or reduction commitments in the protocol. For Finland and other member states of European Union the emission reduction commitment is 8 per cent of the base year emissions (UN FCCC 1997).

The commitments of the Kyoto protocol can be fulfilled individually or jointly by the Annex I countries. The member states of the European Union seek to fulfil their commitments jointly and negotiations on burden sharing between the member states have started.

1.3 THE CONTENTS AND OBJECTIVES OF THE THESIS

In the control and mitigation of acidification and global warming knowledge of the anthropogenic emissions and emission reduction measures and their costs are needed. In this thesis Finnish emission and emission reduction estimates for some acidifying and greenhouse gases, namely ammonia (NH_3), methane (CH_4), nitrous oxide (N_2O) and some halocarbons, are presented. NH_3 is an acidifying and eutrophicating air pollutant and the other substances considered are greenhouse gases. N_2O and some of the halocarbons are also ozone depleting substances. Both past and current, as well as scenarios for future emissions, have been estimated. The estimated acidifying and greenhouse impacts of the emissions and emission scenarios are also presented.

The NH_3 emission estimates have been used as input data in the Finnish integrated acidification assessment model (HAKOMA) and an optimisation model developed at the Technical Research Centre of Finland (VTT) for calculation of cost-optimal deposition control polices (papers I - III). The importance of NH_3 emissions to the acidification problem and the abatement of the emissions are discussed in the summary part of the thesis.

The non-CO_2 greenhouse gas emission estimates have been used to assess the radiative forcing caused by anthropogenic greenhouse gas emissions in Finland. A rough estimate of the impact of the Finnish halocarbon emissions on ozone depletion has also been made. The estimates are presented in papers IV and VI and discussed in the summary part.

The potential of the abatement measures to control the greenhouse gas emissions has been estimated as a rule on a single pollutant - single effect basis. An example of a more integrated approach is given for the waste sector in paper V, in which the greenhouse impact of alternative waste treatment strategies is estimated. The uses, advantages and limitations of the different approaches are discussed.

The summary part of the thesis is divided into four main parts. The first part summarises the basic features of the estimation methodologies used in all the papers. The second part deals with acidification and the significance of the NH_3 emissions (papers I - III). The third part addresses global warming and the importance of the non-CO_2 emissions to the greenhouse impact and its control (papers IV - VI). In the fourth part the emission and emission reduction estimates, the uncertainties and issues for further studies are discussed.

The objectives of the emission estimates presented in the thesis have been to provide data for both scientific and administrative purposes and decision-making. The use of the emission estimates determines largely what is required of them. The national emissions inventories are used as material in the control and development of international agreements and also in regional and global research. Therefore the transparency and comparability of the methodologies used are of vital importance and deviating national features in both emissions and methodologies used in their assessment should be documented clearly.

Establishment of environmental policies and decision-making needs data, apart from emissions, also on reduction potential, control measures and costs of emission reduction. In the thesis mitigation of the emissions has as a rule been studied only for a single pollutant at a time. The objective has been to identify the sectors where the mitigation potential is of importance and the emissions can be reduced cost-effectively on a national scale. National data has been used as much as possible as input data in the assessments, whereas in the development of assessment methods international studies and their results have been used primarily.

Control of acidification and global warming are challenges that no country can solve alone, and international co-operation is needed in the mitigation of these environmental detriments. National features can, however, be very different concerning the emissions, possibilities to control them and seriousness of the impacts.

2 METHODOLOGIES FOR ASSESSING EMISSIONS AND EMISSION REDUCTION POTENTIALS

2.1 EMISSION ESTIMATES

In this thesis methods for estimating national anthropogenic emissions of ammonia (NH_3), methane (CH_4), nitrous oxide (N_2O) and some halocarbons and the calculation of the Finnish emission inventories for the mentioned gases are presented. All the emissions are estimated using a bottom-up modelling methodology in which the emissions from individual emission source categories are identified and aggregated to obtain an estimate of the total national emissions.

The general method for estimating the emissions can be described as

$$E_{ij}(t) = \sum_{k} \left(EF_{ijk}(t) \times A_{jk}(t) \right) \tag{1}$$

where E = emission
EF = emission factor
A = activity variable
i = air pollutant considered
j = emission source category (emission sector)
k = fuel or technology type or other factor affecting the emissions
t = year.

This simple methodology has not been used for all emission sources. E.g. the CH_4 emissions in landfills and CFCs emissions from various applications are calculated with dynamic models, which are described in papers IV and VI. The total national emissions for the air pollutant in question are obtained as the sum of the emissions from all the emission sectors.

Acidification has both local and regional dimensions. Near the emission sources the concentrations in the air and also the deposition of the pollutants can be high and severe environmental impacts can result. Part of the emissions are transported in the atmosphere and deposited in ecosystems far from the original source. The sensitiveness of the ecosystems determines the response to the deposition and hence the environmental damage. The geographic distribution of the emissions and resulting deposition is of vital importance in estimating the environmental impact caused by the emissions and also in establishing effective emission reduction strategies.

The geographic distribution of the NH_3 emissions is taken into account by calculating the emissions from municipal data and assuming the emissions to be distributed evenly throughout the area of the municipality considered. The most significant source of NH_3 is agriculture, where most of the emissions come from area sources. The accuracy of the distribution model is therefore satisfactory for national and regional impact assessment studies. Local scale studies need more detailed data on the distribution of the emissions but these are not considered in the thesis.

The anthropogenic enhancement of the natural greenhouse effect of the Earth is a global environmental problem. The greenhouse gas emissions can be assumed to be distributed evenly in the atmosphere as their atmospheric lifetimes are on the order of tens or even hundreds of years. The geographic distribution of the emissions therefore becomes less important in the impact analyses and emission estimates on national scale are sufficient.

Default emission factors given in the IPCC Guidelines (1995), the CORINAIR Guidebook (McInnes 1996) and other similar international sources have been used in the Finnish emission inventories only for emission sources, which are of minor importance in Finland. Most of the emission factors used are determined in accordance with the detailed methodologies given in the guidebooks, other literature or developed in the projects that are the basis of this thesis. The methodologies used are described in detail in the papers I - VI and in the chapters concerning the emission estimates of the individual gases.

Activity data of various kinds are needed in the emission estimates: amounts of fuels burned, vehicle mileage (distances travelled), industrial production, fertiliser use, animal numbers, milk production per dairy cow, consumption data of halocarbons in different applications, waste composition and treatment etc. Most of the activity data has been obtained from national statistics, other public information sources and enquiries. The estimation of activity data not available in the above mentioned sources is largely based on methods given in the IPCC and CORINAIR guidelines.

The emissions of ammonia, methane and nitrous oxide are often linked closely to the natural carbon and nitrogen cycles. This complicates the distinction of anthropogenic and natural emissions and causes uncertainties in the emission estimates. CFCs and the other halocarbons addressed in this thesis come from man-made sources and quantification of the emissions is more easy. None of the studied halocarbons are manufactured in Finland, and the emission estimates are based on imports figures.

2.2 PAST AND FUTURE EMISSIONS

The past and future emissions are calculated in principle with the same methodologies as the present emissions. Historical activity data are more scarce and uncertain for many of the emission sources and have been estimated proportional to factors like Gross Domestic Product (GDP), population, urbanisation, index of industrial production etc.

The scenarios for the future emissions are based as much as possible on official projections of volume changes of the activities producing the emissions and also on existing regulations and plans that will cause volume, structural and technical changes in the emission sectors.

The emission factors are time dependent: technologies and other factors that influence the emissions change with time. The time dependency of the emission factors has in most estimates been omitted due to lack of quantitative data. If the emission factors have incorporated the effect of abatement measures, this has been taken into account when estimating past emissions. The future emissions have been estimated using current emission factors and the impact of new technologies on the emission factors has been considered only in the emission reduction estimates.

2.3 POTENTIAL AND COST-EFFECTIVENESS OF EMISSION REDUCTION MEASURES

The estimates on the potential emission reduction of the air pollutants presented in the papers II and IV are tentative. In paper III and a recent study by the disputant (Pipatti 1997) the reduction potentials and also the cost-effectiveness of the reduction measures have been estimated in more detail. The goal of the studies on the reduction potential and costs of emission abatement has been to summarise the current knowledge on abatement techniques and to analyse to what extent they can be implemented in Finland, how much the emissions can be reduced with the techniques and at what cost.

The general form of the potential emission reduction achieved with an abatement measure is described in equation (2)

$$E_{red} = F \times A \times E \tag{2}$$

where E_{red} = potential emission reduction
F = efficiency of abatement measure (%)
A = applicability of abatement measure (%)
E = unabated emission.

The efficiency (percentage) describes how much the emissions can be reduced by the implementation of the measure, and the applicability (percentage) to what extent the measure can be applied to actual emission sources in Finland. The reduction efficiencies possible at site-specific projects vary and mean values considering the conditions in Finland have been used in the estimates. The applicability of an abatement measure depends on prevailing conditions, techniques and measures that are already in use. Applicability figures have been defined with the help of statistics, queries and expert opinions.

3 ACIDIFICATION AND AMMONIA

3.1 ENVIRONMENTAL IMPACTS OF AMMONIA EMISSIONS

NH_3 is the most common alkaline gas in the air. NH_3 is reactive and the dry deposition of NH_3 near the emission sources can be significant. NH_3 also reacts readily with acidic species in the atmosphere and forms ammonium (NH_4^+) aerosols, which are less easily deposited and transported longer distances in the atmosphere than NH_3. Both NH_3 and NH_4 aerosols are readily soluble in water and efficiently removed from the atmosphere by precipitation. The transportation distances of NH_3 emissions are therefore largely determined by climatic factors and the presence of species in the atmosphere that enhance the conversion of NH_3 to NH_4 (Department of the Environment 1994).

Although alkaline, the NH_3 emissions enhance the acidification of soils and waters (ECETOC 1994; Finnish Ammonia Working Group 1991).

- Microbes in the soils oxidise ammonium (NH_4^+) to nitrite (NO_2^-) and further into nitrate (NO_3^-) releasing hydrogen ions to the soil:

  $NH_4^+ + 2\,O_2 \rightarrow NO_3^- + H_2O + 2\,H^+$

  The nitrification process is dependent on soil characteristics and climate (microbe population, pH, humidity, temperature, nitrogen availability and chemical form etc.). Nitrous oxide (N_2O) is also formed in the process as a by-product. The influence of the deposition caused by NH_3 emissions on N_2O emissions is discussed in more detail in chapter 4.

- Plants and microbes take up ammonium (NH_4^+) from the soil and use it as a nitrogen source. The conversion of ammonium into organic compounds, in which nitrogen appears mostly as amine nitrogen, also releases hydrogen ions into the soil:

  $NH_4^+ + R\text{-}OH \rightarrow R\text{-}NH_2 + H_2O + H^+$

  Usually there is deposition of both NH_4^+ and NO_3^- and the plants preferably take up NH_4^+ ions, thus the excess deposition is mainly NO_3^- with roughly similar acidifying features as SO_4^{2-}.

NH_3 emissions also cause eutrophication of soils and waters. Large concentrations of NH_3 near the emission sources can also damage vegetation directly. The environmental impacts of NH_3 emissions are many and depend very much on the strength of the emission source, presence of other pollutants and characteristics of the ecosystem receiving the deposition (Kauppi et al. 1990; Posch et al. 1995; ECETOC 1994; Sutton et al. 1996; etc.).

3.2 AMMONIA EMISSION SOURCES AND FACTORS AFFECTING THE EMISSIONS

More than 90 per cent of NH_3 emissions in Europe are related to agriculture. Livestock manure is the most important emission source and causes about three quarters of the emissions. Other important sources are fertiliser application and fertiliser production. Crops can both take up and emit NH_3 from the leaves. The net emissions can be significant but vary much. Smaller amounts of NH_3 are emitted from various miscellaneous sources like wastewater treatment, human waste, combustion etc. (ECETOC 1994; Amann et al. 1996; Warn et al. 1990).

NH_3 emissions from livestock waste are influenced by many factors, and the estimation of the emissions is a complex task. The main factors are the amount and chemical form of nitrogen in the waste and the way the waste is managed. Temperature and also other weather conditions like wind, humidity and rain influence the emissions, especially during application of manure in the fields.

The conversion of feed nitrogen into animal protein is low and hence most of the feed nitrogen, usually more than 75 per cent, is excreted (ECETOC 1994; Rodehutscord 1994). The nitrogen is excreted mostly as urine. The nitrogen in the urine is up to 90 per cent soluble and most of it in the form of urea. Urea is easily hydrolysed to NH_3 through the action of microbial urease:

$$CO(NH_2)_2 + H_2O \rightarrow 2\ NH_3 + CO_2.$$

Only about 25 per cent of the nitrogen in the faeces is soluble and the rest of the nitrogen is in the form of proteins and other similar compounds, which decompose more slowly (ECETOC 1994; Keränen & Niskanen 1987).

Poultry manure differs from the manure of the other animals, and the nitrogen is excreted mainly as uric acid ($C_5H_4N_4O_3$) and proteins, which decompose more slowly than urea (ECETOC 1994).

The feed composition largely determines the productivity of the animal and also the amount and composition of nitrogen in the manure. High productivity of animals usually leads to smaller NH_3 emissions per milk and meat production even if the emissions per animal are larger than for less productive animals. In practice animals are often given excess nitrogen in the feed to maintain high productivity (Finnish Ammonia Working Group 1991; Rodehutscord 1994). This increases the NH_3 emissions and so diminishes the total benefits.

Livestock waste management systems are many and vary from country to country, farm to farm and one animal category to another. A general and simplified description of livestock waste management and the nitrogen flow from one stage to the other in the system is given in Fig. 1.

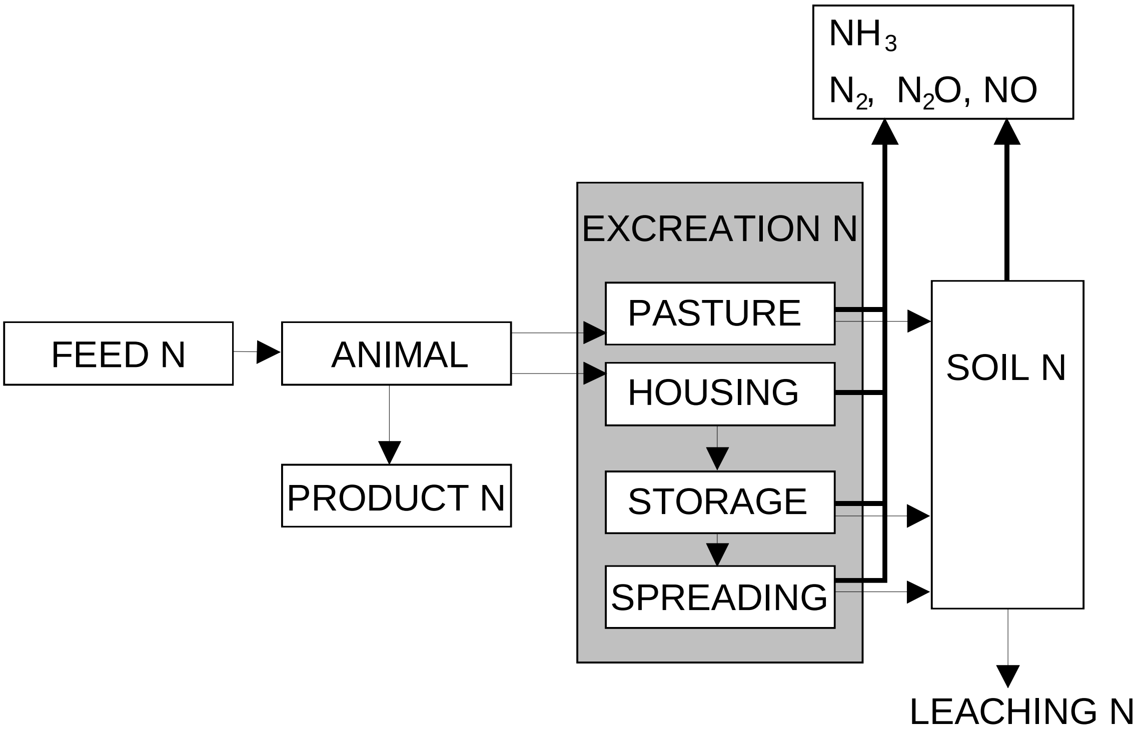

Fig. 1. A simplified diagram of nitrogen flow in livestock waste management systems.

Livestock manure can be treated as solid or liquid. In solid treatment the manure can be removed from the stables frequently and stored before spreading or be accumulated with deep litter within the stables. The urine can either be bound to dry matter like straw or peat or be separated and stored in urine wells. In liquid systems the manure usually drops beneath the floor of the stable and is flushed or pumped into slurry tanks for storage. The spreading of solid and liquid manure requires different types of equipment.

The total NH_3 emissions from solid and liquid manure systems are about the same for unabated systems. The emissions from the various treatment stages vary as well as the options and possibilities to control the emissions (see Fig. 2 - 3).

NH_3 emissions from the application of artificial nitrogen fertilisers are also of significance. The emissions vary by fertiliser type and application technique and timing.

Industrial NH_3 emissions are less important on a regional scale but can be significant locally. The emissions can best be estimated from individual plant data even if average emission factors per production unit are given in literature (ECETOC 1994 etc.).

NH_3 emissions from other sources (crops, wastewater treatment, etc.) are not usually included in national or multinational emission inventories because reliable methods for their estimation are not available or because their importance is minor. Totally the input from these sources is estimated to be less than 10 per cent of the total anthropogenic NH_3 emissions in most countries but the reliability of the figure is low (ECETOC 1994; Lee & Dollard 1994).

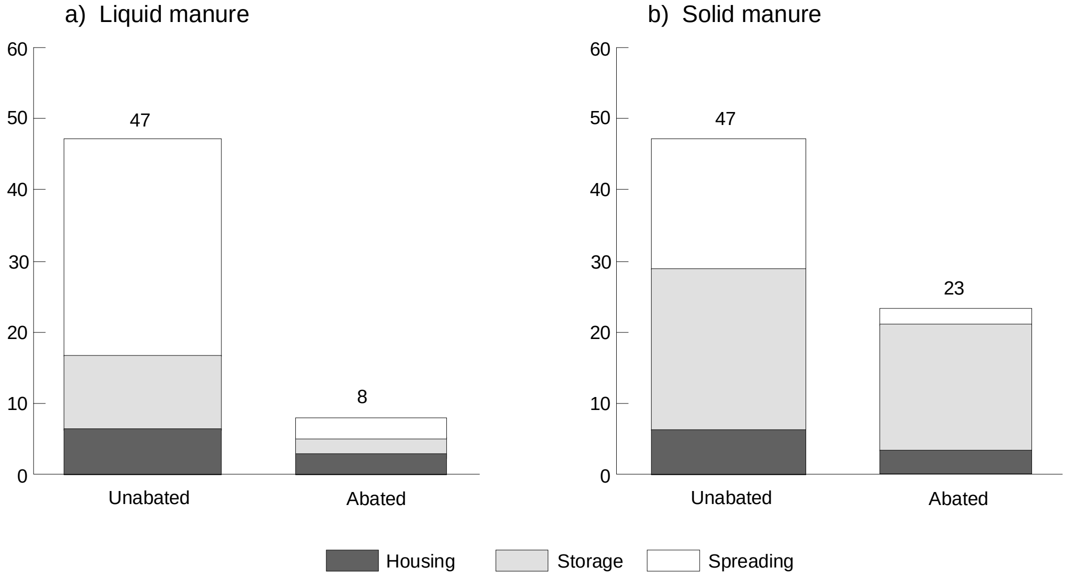

Fig. 2. Estimated NH_3 emissions in liquid and solid manure treatment of cattle manure as percentage of the nitrogen content in manure. The abatement potential for liquid manure systems is estimated to be higher than for solid manure systems (Finnish Ammonia Working Group 1991).

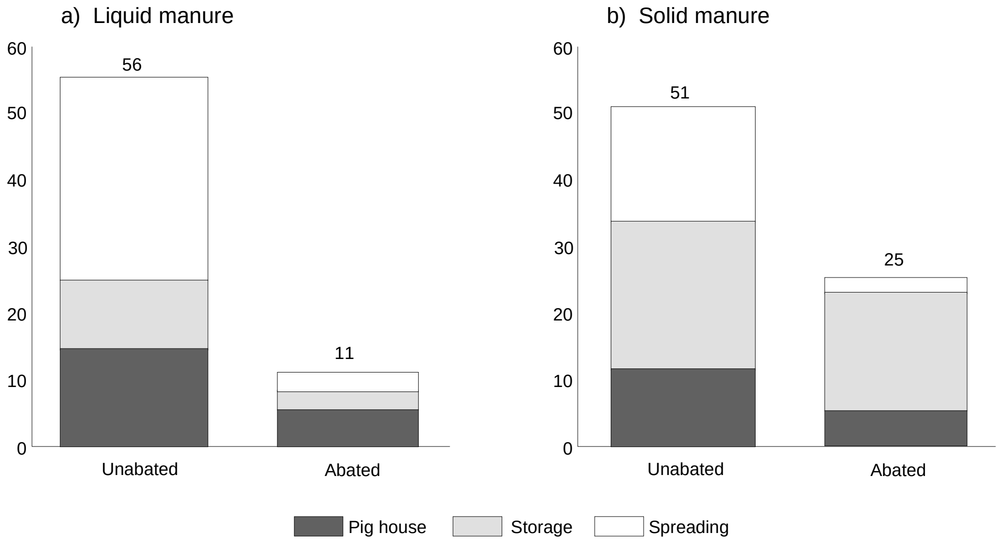

Fig. 3. Estimated NH_3 emissions in liquid and solid manure treatment of pig manure as percentage of the nitrogen content in manure. The abatement potential for liquid manure systems is estimated to be higher than for solid manure systems (Finnish Ammonia Working Group 1991).

3.3 AMMONIA EMISSIONS IN EUROPE

The problems with NH_3 emissions were first realised in countries with an intense agriculture and livestock industry like the Netherlands and Denmark. Many of the studies that have laid the groundwork for NH_3 emission modelling have been performed in these countries. The first European inventory on NH_3 emissions was presented in the mid 1980's in the Netherlands (Buijsman et al. 1985 and 1986; Buijsman 1986).

Buijsman (et al. 1985 and 1986) calculated the emissions from estimated nitrogen content in animal manure and estimated the volatilisation from the different stages of livestock waste management. The calculations were mainly based on the results of Dutch measurements and studies, and made for five animal categories: cattle, pigs, poultry, horses and sheep. For countries, in which the distribution of animal subcategories was known, normalisation factors which made allowances for animal age and weight distribution were used. This way Buijsman et al. (1985 and 1986) could define default emission factors for individual countries in Europe.

The emission factors derived by Buijsman et al. (1986) were long used as default values by many countries in fulfilling their reporting requirements under LRTAP and other international agreements.

National and regional NH_3 emission inventories have been updated and improved in the course of time. The basis for the calculations is essentially the same but current methodologies use country specific data increasingly, take into account the nitrogen flow from one stage to another in livestock manure systems more precisely and hence, allow for a better estimation of the abatement potentials and costs (Klaassen 1991 and 1994; Asman 1992; ECETOC 1994; Cowell & ApSimon 1996; Amann et al. 1996 etc.).

Buijsman's (et al. 1986) estimate on European NH_3 emissions for the year 1980 was 6.4 Tg but he concluded later that the emissions could be up to 40 per cent higher (Personal communication 20.12.1988). The trend in the NH_3 emissions from the beginning of the century to the 1980's has been rising (Buijsman et al. 1986; Klaassen 1991). In the 1990's the emissions have stabilised and even decreased in some countries.

The European NH_3 emissions in 1990 have been estimated to be about 6 - 8 Tg. In current scenarios the emissions are estimated to decrease somewhat by the year 2010 due to a decreasing number of animals and lowered fertilisation use. Some countries have also included NH_3 emission reduction plans in their environmental policies. The reduction potential of the European NH_3 emissions by abatement measures has been estimated to range up to 40 per cent (Amann et al. 1996; Cowell & ApSimon 1996).

3.4 AMMONIA EMISSIONS IN FINLAND

3.4.1 The Finnish Integrated Acidification Model (HAKOMA)

The first studies on NH_3 emissions in Finland were part of the Finnish Acidification Research Programme (HAPRO 1985 - 1990). Keränen & Niskanen (1987) made a literature study on NH_3 emissions in agriculture and applied the data to agricultural practices in Finland in order to estimate the Finnish emissions. The emission inventory was complemented with data on industrial emissions and emissions from fur animals by the disputant (Pipatti 1990). The estimation methodologies and resulting estimates for NH_3 emissions in Finland in the 1980's are presented in paper I.

The NH_3 emissions were included in the Finnish Integrated Acidification Model (HAKOMA) developed by the Technical Research Centre of Finland (VTT) in co-operation with the International Institute of Applied Systems Analysis (IIASA) and several Finnish institutes and universities. The HAKOMA model considers the acidifying emissions in Finland and the rest of Europe and their impact on forest soils and lakes in Finland (see Fig. 1 in paper II).

The main objective in the development of the model was to produce a tool for studies on future acidifying emissions and their impact on soils and waters in Finland. The effect of various scenarios on volume and structural changes in the emission producing sources and effectiveness of control strategies could in this way be evaluated with the model. Estimates of historical emissions are also included in the model. The historical emission estimates give information on the trends in the changes in the emission producing sources and are also needed in studies on accumulation of acidifying deposition in the ecosystems.

The HAKOMA model requires as input data yearly emission estimates of the acidifying pollutants SO_2, NO_x and NH_3. The geographical distribution of the Finnish emissions is given in about 14 km x 14 km squares (1/4^o longitude, 1/8^o latitude), whereas emissions from the rest of Europe are covered with the grid square size of 150 km x 150 km used by EMEP (Co-operative programme for monitoring and evaluation of the long range transmission of air pollutants in Europe). The HAKOMA model and basis for the emission estimates used in the model are described in paper II.

3.4.2 Modelling of Finnish ammonia emissions in the HAKOMA model

Emission estimate for the reference year

In papers I - II the Finnish NH_3 emissions are estimated from the following sources:

- cattle, pig and poultry manure
- fur animal manure
- fertiliser use and
- industrial processes.

The method for the estimation of the Finnish NH_3 emissions from livestock manure is similar to the method used by Buijsman (et al. 1995): the nitrogen content in the manure is determined and the nitrogen flow from one stage to the other in the waste management system is followed. The NH_3 emissions from the different stages in livestock manure treatment are estimated using the data on volatilisation rates given in literature. Emissions from the pasture period are calculated separately from those when the animals are fed inside.

In paper II the emission factors for the reference year 1985 were determined from the above data for the main animal categories: cattle, pig and poultry (laying hens and chickens only). Emissions from the other animal categories were omitted. Table 1 shows the emission factors estimated by Buijsman (et al. 1996) and those obtained from the studies of Keränen & Niskanen (1987) and those used in the HAKOMA-model (Pipatti 1990 and 1992a).

Table 1. Ammonia emission factors (kg NH_3/animal/year) for main animal categories.

	Buijsman et al. (1986)	Keränen & Niskanen (1987)	HAKOMA-model (paper II)
Cattle	25.2	18.5	20
Pigs	3.9	3.7	3.5
Poultry*	0.36	0.22	0.25

* laying hens and chickens

In the late 1980's there were many fur farms in Finland situated very close to one another. The observed disturbances in the growth of the forests near the fur farm areas were mostly blamed on the high concentration of NH_3 due to emissions from the fur animal waste (Ferm et al. 1988). The need to include the NH_3 emissions from fur farms in the HAKOMA-model was obvious.

Data on the nitrogen content in fur animal manure was obtained from a Finnish study (Helin 1982). During the waste treatment 40 - 50 per cent of the total nitrogen content in the manure was estimated to volatilise as NH_3. A mean emission factor of 0.65 kg NH_3/produced fur was obtained from data on the fur animal distribution in 1988 (paper I).

The use of artificial fertilisers also cause emissions of NH_3. The emissions are dependent on the type of fertiliser, application technique and also on soil characteristics. In fertilisers used most commonly in Finland the nitrogen is in the form of ammonium and nitrate, of which only ammonium causes NH_3 emissions (Keränen & Niskanen 1987; ECETOC 1994). The emissions are dependent on temperature and pH of the soil (low temperature and low pH mean low emissions). In urea fertilisation the hydrolysis reaction releases NH_3 into the soil and the pH is increased. The NH_3 emissions can therefore be high. Urea is used only in small amounts in Finland.

The most common application technique in Europe is to apply the fertilisers on the surface of the fields. In Finland, on the contrary, most of the fertilisation is done at seeding time as a band below the surface of the soil (placement fertilisation) and hence the emissions from NH_3 volatilisation are low. Surface spreading is used mostly only on grasslands and fall planted crops in spring in Finland.

The emission estimate by Keränen & Niskanen (1987; also presented in paper I) yields an emission factor of about 4 per cent of the total nitrogen of fertilisers applied in the fields in 1985 in Finland. Using the estimates of Buijsman (et al. 1986) on NH_3 emissions from fertilisers of different types, an overall emission factor of 1.5 per cent of the total nitrogen in fertilisers applied in the fields in 1985 in Finland was obtained. The emission factor derived from Buijsman's (et al. 1986) estimates was used in the HAKOMA-model (paper II).

Newer research data suggest that the NH_3 evaporation during placement fertilisation is negligible (Ammoniakförluster från jordbruket 1994; ECETOC 1994).

The reference year in the HAKOMA-model (paper II) was 1985. Municipal data on the animal numbers and cultivated areas were obtained from the agricultural data base MALTIKA with information on animal statistics, and from the Association of Finnish Fur Animal Breeders. The data on fertilisers sold in agricultural districts in Finland during the fertiliser year 1985/86 were obtained from the company Kemira Oy (Takamäki 1985). As municipal data on the fertiliser use was not available, it was estimated by multiplying the cultivated area in the municipalities with the mean fertiliser use per hectare in the agricultural district to which the municipality belonged.

The industrial NH_3 emissions were obtained from the Ministry of environment which keeps a registry on the air emissions based on obligatory notifications from the industries.

The NH_3 emissions in Finland in 1985 (paper II) were calculated from municipal activity data using the simple methodology presented in chapter 2. The calculations were done with a FORTRAN model and the outputs of the model were converted to NH_3 emissions in 14 x 14 km grids and used as input data in the HAKOMA-model.

The estimate on NH_3 emissions in Finland given in paper I is about 20 per cent higher than the estimate used in the HAKOMA-model in paper II. The largest differences in the estimates are in the emissions from fertiliser application. The use of a lower emission factor than that derived by Keränen & Niskanen (1987) was deemed justified as the fertilisation practices, acidic soils and climate conditions in Finland do not favour the emissions. The other differences in the estimates are smaller and can be attributed to the rounded emission factors used in the HAKOMA model and some differences in the data on animal numbers.

A comparison of the estimates by main source categories in 1985 (papers I and II) and an update of the emissions in 1990 (Tähtinen & Pipatti 1992) is given in Table 2.

Table 2. Ammonia emissions in Finland in 1985 and 1990.

Source	Emission (Mg NH_3)		
	1985 (paper I)	1985 (paper II)	1990
Cattle	28 900	28 200	27 200
Pigs	4 900	4 400	4 800
Poultry	1 800	1 900*	2 100
Sheep	NE	300*	300
Horses	570	550*	550
Fur animals	4 900	3 900	1 800
Fertiliser application	9 100	3 700	4 600
Industry	1 300	1 300	1 200
TOTAL	52 000	44 000	43 000

* Up-dated by Tähtinen & Pipatti (1992); see text for more information.

Due to rounding errors given totals are not always equal to the sums of the given numbers. The uncertainties in the estimates are considerable and the numbers should be given with one or two meaningful digits. However, to show the differences in the estimates this manner of presentation was chosen..

The NH_3 emissions in Finland in 1990 were calculated in a study for the Ministry of the Environment (Tähtinen & Pipatti 1992) with the same model. The estimate was complemented with the emissions from sheep and horses using emission factors (3 kg NH_3/sheep/year and 12.1 kg NH_3/horse/year) given by Klaassen (1991) and emissions from broilers. The emission factor for broilers was taken as 0.3 times the emission factor for laying hens. This emission factor was used in the calculations for chickens also. The emission factor for fur animals was split into two and emissions for minks and polecats (emission factor 0.4 kg NH_3/fur produced) and for foxes and racoons (emission factor 0.75 kg NH_3/fur produced) were calculated separately.

The total Finnish NH_3 emissions in 1990 are about 5 per cent smaller than in 1985/86. This is due to a decline of about 50 per cent in the fur production. The other emission sources have undergone only slight changes. Emissions from cattle have declined, whereas emissions from pigs, poultry and fertiliser application have somewhat increased.

The geographical distribution of the NH_3 emissions from livestock manure in 1985 and 1990 calculated with the HAKOMA-model are given in Fig. 4. The emissions are largest in the western parts of Finland. Most of the pig and poultry farms are located in the south-western areas of Finland and almost all fur farms are situated further north on the west coast. Milk production (dairy cows) is also intensive along the northern west coast, but the production is not concentrated there to the same degree as the fur production.

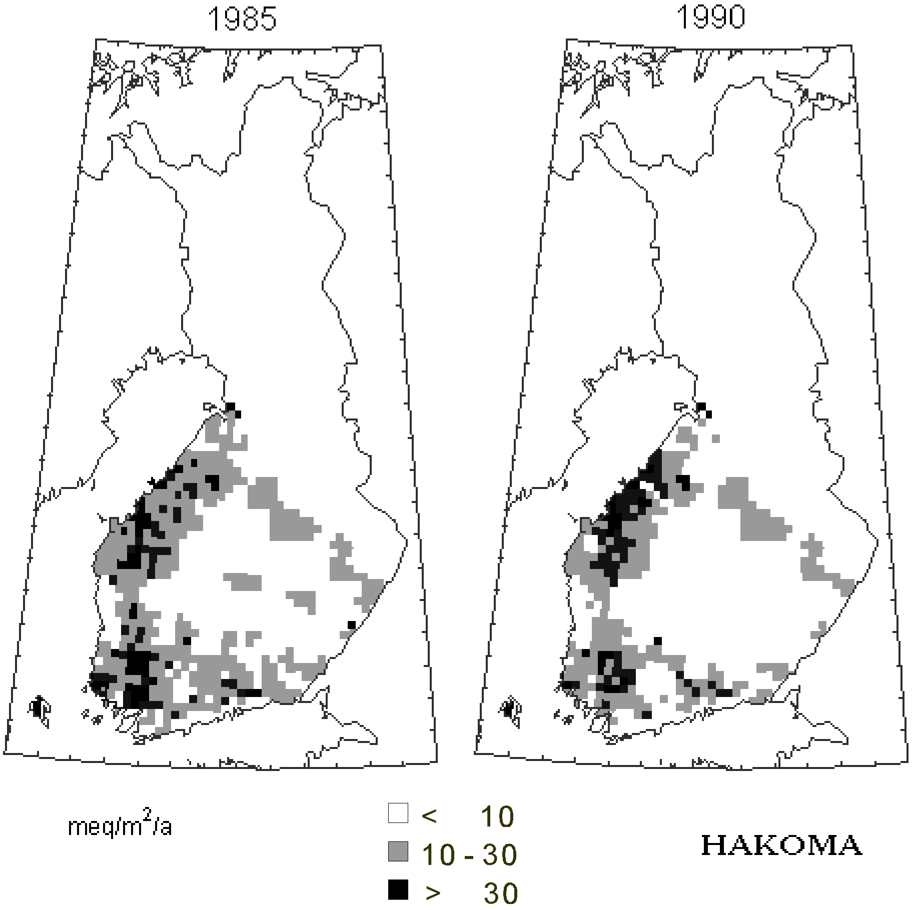

Fig 4. Geographical distribution of ammonia emissions from livestock manure (including manure of fur animals) in Finland in 1985 and 1990.

During 1985 to 1990 the emission densities have declined in many parts of Finland due to reductions in animal numbers. In the northern west coast the emission densities have increased despite the decline in fur production. This is due to increasingly centralised milk production in the areas. In the northern part of Finland agricultural activities and also NH_3 emission densities are very low.

Historical and future emissions

The NH_3 emissions in Finland for the years 1950 to 1985 were calculated as input data for the HAKOMA-model. Municipal data on the animal numbers and fertiliser use was not available for the whole period and the emissions were therefore calculated from provincial data. The animal distributions within the provinces were assumed to be the same as in the reference year. The data on the industrial emissions were taken from Buijsman's (1986) estimate which was based on the NH_3 and fertiliser production in Finland.

Estimates for future NH_3 emissions were given in two scenarios: the reference scenario and the reduction scenario (paper II). In the reference scenario expected changes in the emissions without additional reduction measures were considered. In the reduction scenario the potential to control the emissions compared with the reference scenario was estimated. The basis for the chosen reduction potential (25 per cent) was based on expert opinions. The knowledge on the efficiencies and applicability of abatement measures for NH_3 emission reduction in Finnish conditions was limited.

The scenarios on future NH_3 emissions were based on expected changes in agricultural production (animal numbers and fertiliser use) and in agricultural practices (Ministry of Agriculture 1987). Projections on future agricultural production volumes are uncertain and depend largely on agricultural policy and especially on how agricultural subsidies are handled.

Both the past and future emissions were calculated using the emission factors derived for the reference year (Table 1). The historical emissions may be overestimated as the feeding and waste handling practices have changed much during the time period (Pipatti 1992a). Likewise more effective feeding strategies in the future may increase the emission factors.

Ammonia emissions and acidifying deposition in Finland

The NH_3 emission estimates for the HAKOMA-model were part of the integrated assessment of acidification in Finland. The model served as the main instrument in the assessment and integration of the results of the studies in the Finnish Acidification Programme (HAPRO 1985 - 1990). The objective of the programme was to contribute to air pollution abatement and management of natural resources by obtaining and processing information and understanding of the acidification issue (Kauppi et al. 1990). The impact of acidifying emissions in other countries was also considered in the model. The NH_3 emission estimates were based on Buijsman's estimates (paper II).

At the end of the 1980's the acidifying deposition was about 1.3 - 1.4 times larger than the acidifying emissions in Finland. The nitrogen deposition was about 40 per cent of the total acidifying deposition and almost half of that was reduced nitrogen deposition (NH_3 and NH_4). The Finnish NH_3 emissions contributed to the total Finnish acidifying emissions only with about 12 per cent, and of the acidifying deposition in Finland 6 - 7 per cent was due to Finnish NH_3 emissions. Of the ammonium deposition about one third was due to Finnish emissions, even though more than 50 per cent of the Finnish NH_3 emissions were deposited within Finnish boarders (Kangas et al. 1991; Pipatti 1992a).

The Finnish NH_3 emissions contribute only a little to the total acidifying deposition in Finland but they can be locally important. The impact in the areas with high emissions in Finland can be seen in Fig. 5, which illustrates the total deposition of reduced nitrogen in Finland and the deposition caused by Finnish emissions.

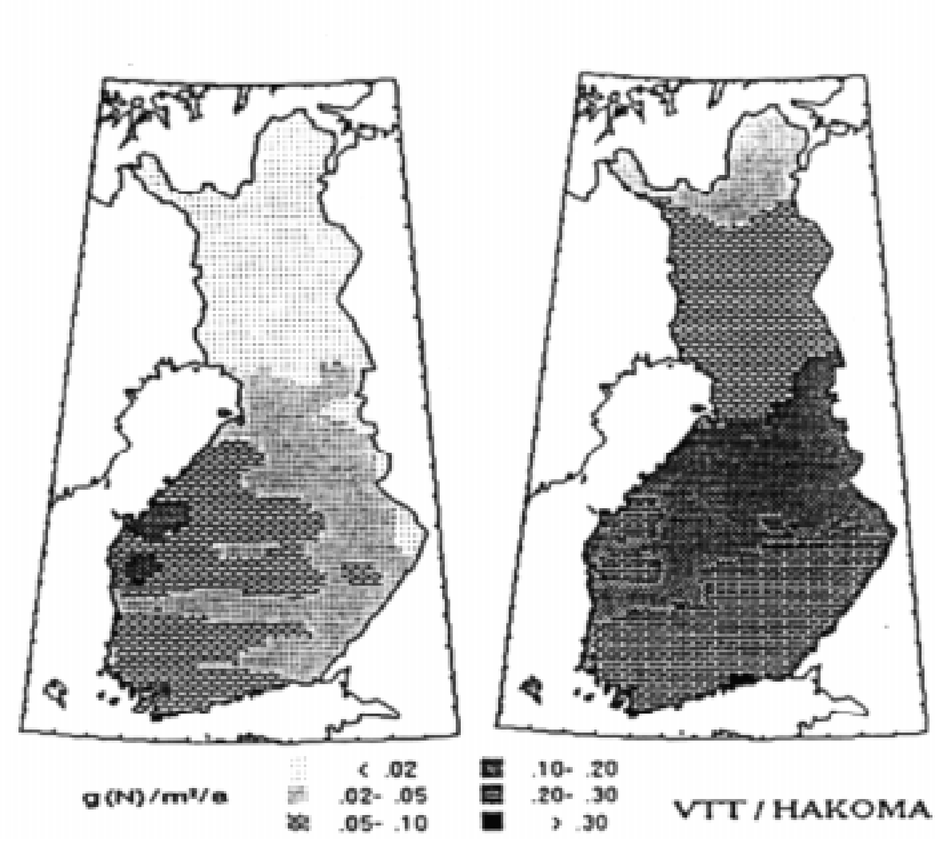

Fig. 5. Nitrogen deposition from ammonia emissions in Finland in 1985. The left map shows the deposition from Finnish emissions, the right the total deposition (Pipatti 1992a).

3.4.3 Ammonia emissions and economic reduction of acidifying deposition in Finland

The significance of the different polluters to acidifying deposition in Finland

In the 1990's the acidifying emissions in Finland have been decreasing. The SO_2 emissions have decreased more than 80 per cent whereas the NO_x and NH_3 emissions have decreased less (10 - 20 per cent) from the values of 1980 (Savolainen et al. 1996). The trend in the European emissions has also been declining and hence the acidifying deposition in Finland has decreased. The critical loads for acidification and eutrophication are, however, still exceeded in many ecosystems, especially in the southern part of Finland (Posch et al. 1995).

The importance of the different air pollutants and emission sources has changed in the 1990´s. The nitrogen emissions (NO_x and NH_3) and the emissions in other countries have become more important causes of acidifying deposition in Finland. This issue is addressed in paper III, where the economic reduction of acidifying deposition in Finland by decreasing emissions in Finland and nearby areas in Russia (St. Petersburg, Karelia and Murmansk) and Estonia is studied.

In Finland NO_x emissions with the transportation sector as their main source have been the most important acidifying emissions in the 1990's. The acidification potential of the Finnish SO_2 emissions is about half that of the NO_x emissions and about twice that of the NH_3 emissions. In the nearby areas the SO_2 emissions dominate as the acidifying polluter and cause more than 80 per cent of the total acidifying emissions. The significance of the different polluters is illustrated in Fig. 6.

Cost-effective reduction of the ammonia emissions

The NH_3 emissions from livestock waste in 1994 in Finland were estimated with a new model. The calculation method is in principle the same as in paper I but newer data on nitrogen content in the livestock waste and waste treatment practices in Finland have been used. The emissions from animal housing and storage have been estimated separately and the emission reducing measures already in use have been incorporated in the model. The emissions from other sources (fur animals and industry) in Finland have not been up-dated but taken from earlier studies (Tähtinen & Pipatti 1992; Pipatti 1994a).

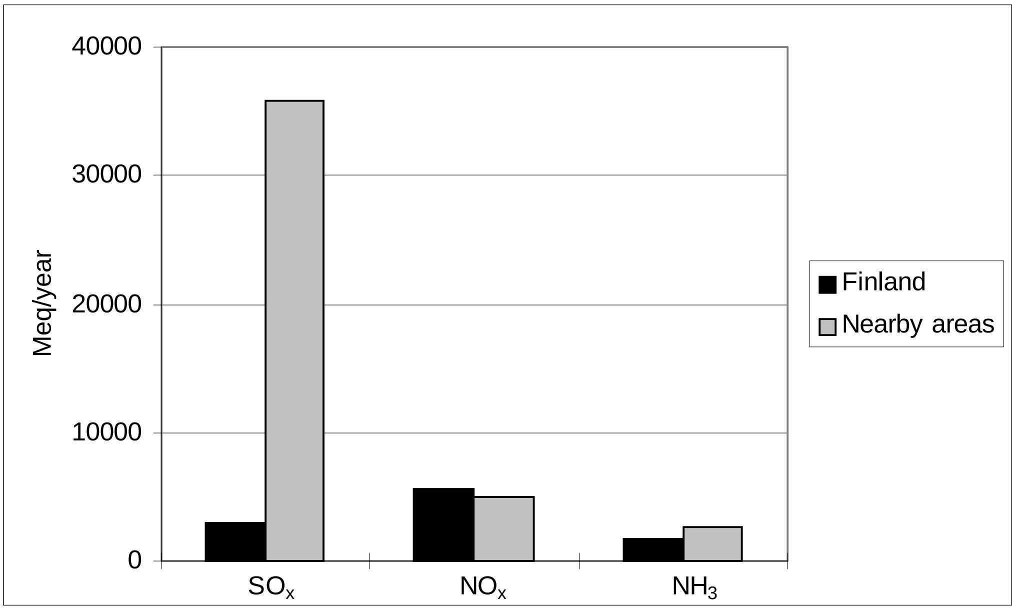

Fig. 6. Acidifying emissions in Finland and the nearby areas in the beginning of the 1990's. The emissions are expressed in units (acid equivalents[1]) corresponding to the potential acidifying impact of the pollutants.

The NH_3 emissions in the nearby Russian areas (the Murmansk, the Karelia and the St. Petersburg and Leningrad regions) and Estonia were estimated using the same method as for the Finnish emissions. The special features of livestock waste management could be incorporated in the model only partly as details of the practices were not always known, or because data on how the practices affected the emissions was not available.

The potential and costs of controlling the emissions of SO_2, NO_x and NH_3 have been estimated for the years 2000 - 2005. The basis of the emission projections and abatement possibilities and associated costs is presented in paper III. The potential for NH_3 emission abatement has been estimated using the approach presented in chapter 2 (see eq. 2).

The efficiencies of the NH_3 abatement measures were derived from data presented at workshops, UN ECE working group meetings and literature (ApSimon 1994; UN ECE 1996; Ammoniakförluster från jordbruket. 1994; etc.). The applicability of the measures was estimated from general data on the special features in agriculture (agricultural practices, farms size etc.) in the areas. For Finland the current usage of the abatement measures and expert judgement on the applicability measures to the rest of the farms was also used in the estimation.

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[1] The acid equivalent is a rough commensurate unit for the description of the acidifying impact of SO_2, NO_x and NH_3. One acid equivalent corresponds to 16 g sulphur and 14 g of nitrogen.

The costs of the abatement measures for NH_3 emission reduction in Finland were based largely on Finnish data (Grönroos 1993). Other sources (ApSimon 1994; UN ECE 1996; Ammoniakförluster från jordbruket. 1994; etc.) were used only for abatement measures, for which Finnish data was lacking. Grönroos (1993) had estimated costs of NH_3 emission abatement measures for typical farms in Finland. The data were converted to costs per animal. Costs of labour were added where necessary as these were omitted by Grönroos (1993).

The costs of NH_3 emission abatement in the Russian areas and Estonia were estimated using the Finnish data with the exception of labour costs, for which national data was used. The efficiency and applicability estimates of the measures in the Russian areas and Estonia are much more uncertain than the Finnish estimates, as the reliability of input data is lower and the agricultural practices are not known as well as for Finland.

The cost-effectiveness of the emission reducing measures was calculated as if the measures would be applied separately. The emission reduction potential was calculated over the whole chain and double counting of the reductions of parallel measures was avoided by subtracting the reduction achieved with the more cost-effective measure from the less cost-effective but otherwise more effective measure. The cost-effectiveness calculations may overestimate the total reduction potential, as the reduction achieved by measures applied at the end of the waste treatment chain are decreased by measures at the beginning of the chain.

The sequential dependence of the removal efficiencies of the abatement measures can be taken into consideration by looking at the effectiveness of combinations of abatement measures (Klaassen 1991 and 1994) or by using iterative processes, in which the options already implemented are fixed and all remaining options are assessed independently (Cowell & ApSimon 1996). Even these approaches have their shortcomings. The removal efficiencies of the combinations are smaller or equal to the efficiencies of the separate measures, and selected combinations may not produce the most cost-effective solution for abatement. The applicability of the combinations is also more difficult to estimate, especially in situations, were some measures are already in use. The iterative approach produces a cost-curve with a fixed order of abatement steps. If the materialised strategy differs in some respect (some measure is not acceptable or otherwise not implemented), the calculations would need to be repeated.

The estimated cost-effectiveness of the abatement measures for NH_3 emissions in Finland, Estonia and the Russian areas is given in Fig. 6 in paper III.

Cost-effective reduction of acidifying deposition in Finland

The optimisation model considered the cost-effective reduction of acidifying deposition in Finland by controlling the SO_2, NO_x and NH_3 emissions in Finland, Estonia and nearby Russian areas. The optimisation was done for different acidification reduction targets which were defined as percentages of the maximum possible decrease in the acidifying load due to all measures considered in the study.

Optimal reduction of the acidifying deposition in Finland would mean that more than two thirds of the reduction costs should be directed to the nearby areas in all cases studied. The reduction targets of 20 - 40 per cent would be achieved cost-effectively with measures aimed at SO_2 and NH_3 emissions only. Most of the reduction costs would be caused by SO_2 emission control, but the reduction percentage of possible reduction by the measures considered would be of the same order of magnitude or even greater for NH_3 emissions than for SO_2 emissions (see Table 3).

An acidification reduction target of 20 per cent would mean that NH_3 emission abatement should be directed mostly to the nearby areas. This can be explained by the fact that no abatement measures are assumed to be implemented in the nearby areas in the reference case, whereas in Finland some measures are already in use. Reduction targets of 40 - 60 per cent would mean significant NH_3 emission reductions both in Finland and the nearby areas with emphasis on reduction of the domestic emissions. In order to achieve higher reduction targets, most of the feasible NH_3 emission reduction measures would need to be implemented both in Finland and the nearby areas.

Even if the share of the NH_3 emissions of the total acidifying emissions in the areas (see Fig. 6) is small, the abatement of the emissions seems to be cost-effective and the implementation of NH_3 emission reduction measures means that the use of the more costly measures to reduce SO_2 and NO_x emissions could be avoided in controlling acidifying deposition in Finland.

Table 3. Annual reductions as percentage of the maximum reduction potential in Finland and the nearby areas with measures considered in the study (modified from table 4 in paper III).

Acidification reduction target*)	Emission area	Annual reduction per cent of MFR**)		
		SO_2	NO_x	NH_3
- 20 %	Finland	21	0	11
	Nearby areas	27	0	46
- 40 %	Finland	47	0	56
	Nearby areas	37	0	46
- 60 %	Finland	60	43	88
	Nearby areas	68	8	64
- 80 %	Finland	89	62	88
	Nearby areas	80	29	91

* Percentage of the maximum decrease in the acidifying load if all measures considered in the study are implemented.

** MFR = maximum feasible reduction with measures considered in the study.

4 GREENHOUSE GAS EMISSIONS AND MITIGATION OPTIONS

4.1 GLOBAL ANTHROPOGENIC GREENHOUSE GAS EMISSIONS AND MITIGATION OPTIONS

Inventories of the national anthropogenic greenhouse gas emissions and removals by sinks are important sources of information in the assessment of the anthropogenic enhancement of the greenhouse effect and the mitigation options. The parties of the Framework Convention on Climate Change (FCCC) are required to periodically inventory their greenhouse gas emissions not controlled by the Montreal Protocol. Use of comparable methodologies is required in the preparation of the inventories and the use of the IPCC guidelines (1995) is recommended. The inventories contain information on both current emissions and projections of future emissions as well as plans to mitigate the emissions.

The national inventories serve many purposes. They are used as information sources in global estimates on the magnitude of the problem and as material in the negotiations on emission reduction. In developing and implementing national environmental and climate policies the inventories are of vital importance as they give information on the most significant emission sources and mitigation options.

The emission sources and sinks for the most important greenhouse gases and mitigation options to reduce the greenhouse gas emissions are presented in the following chapters.

4.1.1 Emission sources and sinks

Carbon dioxide (CO_2)

Anthropogenic CO_2 emissions come mainly from fossil fuel combustion and to a lesser extent from cement production. Land use change in the tropical regions is also an important source of atmospheric CO_2. Biomass burning and decay processes also emit CO_2 into the atmosphere but this is not accounted for in the emission inventories when biomass is regrown at approximately the same rate as it is harvested. Growing biomass binds about the same amount of CO_2 from the atmosphere as is released when it is burned or decaying.

The removal of CO_2 from the atmosphere is a result of numerous processes which operate on different time-scales. The fastest removal process is CO_2 uptake in the surface layer of the oceans and vegetation. Other processes which remove CO_2

from the atmosphere operate on longer time scales (e.g. the transfer to soils and deep oceans). The time scales of the removal processes vary from a few years to centuries. The removal of CO_2 excess from the atmosphere must be usually described with more complicated models than a model with a single atmospheric lifetime. Nevertheless, if the CO_2 emissions were ceased, it is estimated that most of the excess CO_2 would be removed from the atmosphere in one hundred years (IPCC 1996a).

The CO_2 concentrations in the atmosphere have increased from about 280 ppmv in pre-industrial times to 358 ppmv in 1994. If the global CO_2 emissions were maintained at the current level the atmospheric concentrations would increase steadily and approach a concentration level twice the pre-industrial (about 550 ppmv) by 2100 (IPCC 1996a).

Methane (CH_4)

CH_4 emissions are largely caused by bacteria induced decay of organic material in anaerobic conditions. Natural wetlands are the main source for CH_4 emissions from decaying organic material; the decay process is also an important anthropogenic CH_4 source in the digestive processes and manure of domestic animals, rice cultivation, landfills and wastewater treatment. Other important anthropogenic CH_4 sources are fossil fuel production (coal mines and natural gas production), and combustion, especially small scale burning of biomass.

The human activities are estimated to be responsible for 60 - 80 per cent of the total CH_4 emissions. The uncertainties are largely due to the varying nature of the sources and the close relations to natural processes.

CH_4 is removed from the atmosphere mainly through oxidation by the hydroxyl (OH) radical and its lifetime is estimated to be between 9 - 15 years. The CH_4 concentration in the atmosphere, 1 720 ppbv in 1994, is about 145 % higher than the pre-industrial concentration of 700 ppbv. The CH_4 concentrations in the atmosphere are expected to increase even if the growth in the concentrations has varied much during the last decades (IPCC 1996a).

Nitrous Oxide (N_2O)

Global N_2O sources are poorly quantified. The natural emissions are estimated to be twice as large as the anthropogenic emissions. Agriculture (especially nitrogen fertilisation) and industrial processes (production of adipic and nitric acids) are the most important anthropogenic emission sources. Some emission friendly energy technologies like fluidized bed combustion and catalytic converters in cars also produce significant amounts of N_2O and will become more important emission sources in the near future (IPCC 1996a).

N_2O is a long lived gas in the atmosphere with a life time of approximately 120 years. N_2O is removed from the atmosphere mainly by photolysis in the stratosphere. The photolysis reaction produces nitric oxide which participates in the catalytic cycles that destroy stratospheric O_3. The N_2O concentrations in the atmosphere have been increasing slowly (current concentration of about 312 ppbv and pre-industrial concentration about 275 ppbv) and this trend is expected to continue (IPCC 1996a; Wayne 1991).

CFCs and other halogenated compounds

Halocarbons containing fluorine, chlorine and bromine are significant greenhouse gases on a per-molecule basis. Halocarbons containing chlorine and bromine are also involved in the O_3 depleting processes in the stratosphere.

The most important halocarbons in this context are the CFCs (chlorofluorocarbons), HCFCs (hydrochlorofluorocarbons) and HFCs (hydrofluorocarbons). Methyl chloride (CH_3Cl), methyl bromide (CH_3Br), carbon tetrachloride (CCl_4), 1,1,1-trichloroethane (CH_3CCl_3) and halons are also greenhouse gases and O_3 depleting substances, and PFCs (perfluorocarbons) and sulphur hexafluoride (SF_6) greenhouse gases with similar characteristics and environmental impacts but these gases are not addressed in more detail in this thesis.

CFCs are man-made substances that are used in a variety of industrial and consumer applications (see paper VI). They are stable chemical substances with long atmospheric life times. They are removed from the atmosphere through photolytic reactions in the stratosphere and the chlorine that is released in the reactions acts as a catalyst in reactions that destroy O_3. O_3 is also a greenhouse gas and the destruction of O_3 cools the climate.

HCFCs and HFCs are mainly developed as substitutes for CFCs. Their lifetimes are on average shorter than those of the CFCs as they are removed from the atmosphere in addition to the photolytic reactions in the stratosphere through reactions with OH radicals in the troposphere. Hence the impact of the HCFCs on stratospheric O_3 depletion is lesser than that of the CFCs as not all HCFCs reach the stratosphere. HFCs do not contain chlorine and therefore do not destroy stratospheric O_3 (see Table 4).

Table 4. Lifetime, global warming potential (both direct and net impact) and ozone depletion potential of some halogenated hydrocarbons and other halogen compounds (IPCC 1996a).

Substance	Atmospheric lifetime (years)	GWP*	NGWP**	ODP***
CFC-11 (CCl_3F)	50	3 800	540 - 2 100	1.0
CFC-12 (CCl_2F_2)	102	8 100	6 200 - 7 100	1.0
CFC-113 (CCl_2FCClF_2)	85	4 800	2 600 - 3 600	0.8
HCFC-22 ($CHClF_2$)	12	1 500	1 300 - 1 400	0.055
HCFC-123 (CF_3CHCl_2)	1.4	90	20 - 50	0.020
HCFC-124 (CF_3CHClF)	5.9	470	390 - 430	0.022
HCFC-141b (CCl_2FCH_3)	9.4	600	170 - 370	0.110
HCFC-142b ($CClF_2CH_3$)	19.5	1 800	1 600 - 1 700	0.065
Carbon tetrachloride (CCl_4)	42	1 400	-2 400…-650	1.1
1,1,1-trichloroethane (CH_3CCl_3)	5.4	100	-320…130	0.1
Halon 1301 (CF_3Br)	65	5 400	-85 000…-14 000	10
HFC-23 (CHF_3)	264	11 700		
HFC-125	32.6	2 800		
HFC-134a (CF_3CH_2F)	14.6	1 300		
HFC-143a (CF_3CH_3)	48.3	3 800		
HFC-152a (CHF_2CH_3)	1.5	140		
HFC-227ea (C_3HF_7)	36.5	2 900		
Sulphur hexafluoride (SF_6)	3 200	23 900		
Perfluoromethane (CF_4)	50 000	6 500		
Perfluoroethane (C_2F_6)	10 000	9 200		
Perfluorohexane (C_6F_{14})	3 200	7 400		

* GWP = Global Warming Potential, potential direct global warming impact compared with that of CO_2 on a time scale of 100 years.

** NGWP = Net Global Warming Potential, potential net global warming impact that includes the cooling effect of O_3 depletion.

*** ODP = Ozone Depletion Potential, impact on O_3 depletion compared with that of CFC-11. The ozone depletion potential depends on the chlorine concentration in the atmosphere and the values in the table are estimated for concentrations of the 1990's (about 3 ppbv chlorine in the atmosphere).

The O_3 depleting substances are controlled by the Montreal Protocol and its subsequent amendments and adjustments (hereafter called only the Montreal Protocol). The objective of the Montreal protocol is to phase out the O_3 depleting substances, and the production and consumption of the most important O_3 depleting substances are already prohibited in the industrialised countries with the exception of some essential uses (WMO 1994). The most important CFC substitutes, the HCFCs (hydrochlorofluorocarbons) will be phased out gradually by 2030. HFCs (and also PFCs and SF_6) are not controlled by the Montreal protocol but subject to the FCCC.

The effect of the Montreal Protocol can already be seen: the growth rates of many of the CFCs and other O_3 depleting substances in the atmosphere have fallen. The global warming impact of HFCs is currently small but expected to grow (IPCC 1996a).

4.1.2 Mitigation options and the timing of the reduction measures

The greenhouse gas emissions come mainly from sources that are connected with the livelihood, well-being and prosperity of humans. The energy sector (supply and consumption of energy) and land-use change (activities associated with agriculture and forestry) are the most important sources of the emissions. Industrial emissions are of lesser importance with one exception; almost all CFC and other halocarbon emissions are associated with industrial production or applications.

The second assessment report by IPCC (1996b) presents a range of measures to mitigate global warming. Reduction of greenhouse gas emissions in the energy supply sector can be achieved by measures like

- more efficient conversion of fossil fuels
- switching to low-carbon fossil fuels
- decarbonization of flue gases and fuels and CO_2 storage
- increasing the use of nuclear energy and/or renewable sources of energy.

Energy demand and consumption can be lowered by improving the efficiency of energy use in industry, transportation and consumer products. Enhancement of carbon sinks can be achieved with extensive forestation programmes. CH_4 emissions from landfills can be reduced with landfill gas recovery or alternative waste treatment methods. N_2O emissions from fertilization without subsequent production losses could be reduced with improved fertilizer efficiency. CFC and other halocarbon emissions are controlled by substituting the compounds with other less harmful compounds or by new production technologies where the compounds are no longer needed.

The above mentioned mitigation measures make up only a small part of the options available for the reduction of the greenhouse gas emissions. The growing population and energy demand in the world diminishes, however, the effect of the measures. The environmental sustainability of some of the measures is also questionable and may hinder their implementation. Greenhouse gas emission reduction and enhancement of the sinks also have vast economic consequences.

The implementation of greenhouse gas emission control measures, which are economic and have also other environmental benefits, will therefore be favoured.

In the future the absolute value of the radiative forcing is estimated to increase. Most of the increase will be due to increasing CO_2 concentrations in the atmosphere but the expected increase in the radiative forcing of the non-CO_2 greenhouse gases is also important. The predicted changes in the radiative forcing components resulting from the IS92a scenario for 1990 to 2100 are given in Fig. 7. The effect of the negative forcing caused by stratospheric O_3 depletion and aerosols is also shown in the figure (IPCC 1996a).

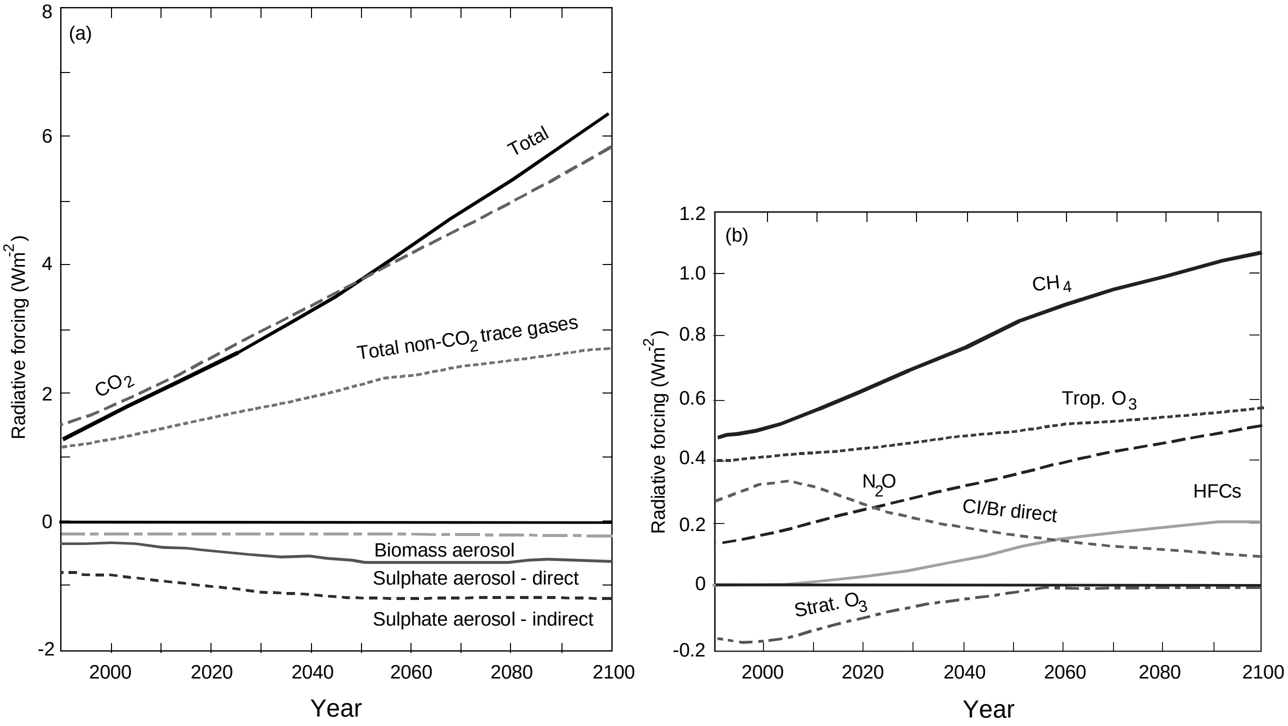

Fig. 7. a) Radiative forcing components resulting from the IS92a emission scenario for 1990 to 2100. The non-CO_2 trace gas radiative forcing components are illustrated in more detail in figure b) (IPCC 1996a).

The atmospheric life times of the important greenhouse gases are long and stabilisation of the concentrations at today's level would involve significant reductions in anthropogenic emissions compared with current emissions: e.g. CO_2 and N_2O emissions would need to be reduced more than 50 per cent and CH_4 emissions about 8 per cent (IPCC 1996a).

The timing of the emission reductions is also important. The longer the emission reductions are postponed, the larger annual reductions will be needed in the future in order to stabilise the atmospheric concentrations at fixed levels within a given time frame. The effect of the timing of the reductions on atmospheric concentrations is illustrated by estimates made by IPCC (1996a) on possibilities to stabilise the CO_2 concentrations at different target levels (Fig. 8).

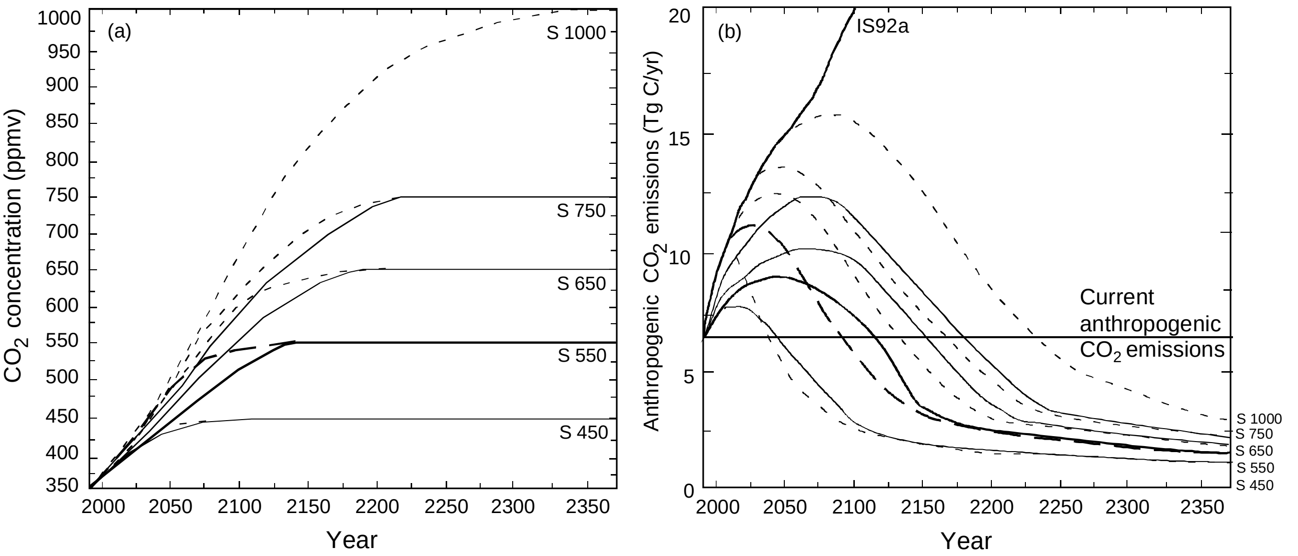

Fig. 8. a) CO_2 concentration profiles and b) corresponding CO_2 emission profiles. In the solid curves the emission reductions are implemented earlier than in the dashed curves. The adjournment of the reduction measures means that larger emission reductions are needed in the future in order to reach the same level of stabilisation in the atmospheric concentrations (IPCC 1996a).

4.2 NON-CO_2 GREENHOUSE GAS EMISSIONS IN FINLAND

The research on climate change in Finland was prompted much by the multidisciplinary Finnish Research Programme on Climate Change (SILMU) that was carried out during six years 1990 - 1995. The goals of the SILMU programme were

1) to increase the knowledge of climate change, its causes and consequences,
2) to strengthen the research on climate change in Finland,
3) to increase the participation of Finnish researchers in international research programmes and

4) to prepare and disseminate information for policy makers on adaptation and mitigation (Roos 1996).

The Technical Research Centre of Finland (VTT) participated actively in the SILMU programme and especially in the research related to human dimensions of climate change. Research on national anthropogenic greenhouse gas emissions and assessments of response strategies to reduce the emissions were performed. Much of the research was focused on studies of CO_2 emissions and control potential of these emissions from the energy sector (Korhonen et al. 1993a and b; Savolainen & Sinisalo 1994; and others).

The objective of the studies on non-CO_2 greenhouse gas emissions was to estimate their importance to the overall greenhouse impact caused by the Finnish emissions and to provide data for the Finnish greenhouse gas inventory required by the FCCC. Scenarios for future emissions and control possibilities were also prioritised in the studies (Pipatti 1992b; Pipatti 1994b; papers IV and VI).

The greenhouse impact of the Finnish greenhouse gas emissions was estimated by calculating the radiative forcing caused by the emissions with the REFUGE model developed at VTT (Korhonen et al. 1993a; Savolainen & Sinisalo 1994; see also papers IV and VI). A rough estimate on the impact on chlorine loading in the stratosphere by the Finnish CFC emissions was also made (paper VI).

4.2.1 Methane and nitrous oxide emissions in Finland in 1990

Estimated anthropogenic CH_4 and N_2O emissions in Finland in 1990 are given in paper IV.

The Finnish anthropogenic CH_4 emissions in 1990 were estimated to be approximately 250 Gg CH_4 (paper IV). The most important emission sources were landfills (about 100 Gg CH_4) and animal husbandry (about 90 Gg CH_4). Wastewater treatment was estimated to emit some 30 Gg CH_4/year and energy production and consumption some 20 Gg CH_4/year. The CH_4 emissions from wastewater treatment included the emissions from sludge treatment and disposal. The uncertainty range of the emission estimate was estimated to be considerable, 160 - 440 Gg CH_4/year. The variable and complex nature of the sources and also inadequacies in statistical information and other input data contribute to the uncertainties.

The N_2O emissions in Finland were estimated to be about 20 Gg N_2O in 1990 (paper IV). Most of the N_2O emissions were estimated to come from cultivated land and fertilizer use (about 12 Gg N_2O/year). Manufacture of nitric acid (about 3 Gg N_2O/year) and the energy sector (about 4 Gg N_2O/year) were other important sources. The uncertainty range of the Finnish N_2O emissions was estimated to about 10 - 30 Gg N_2O/year.

The CH_4 and N_2O emissions presented in paper IV were estimated using the methodology developed for the IPCC by IEA/OECD expert groups (OECD 1991) complemented with Finnish research data and the results of the ”Methane and nitrous oxide workshop” held in Amersfoort in 1993 (van Amstel 1993). The development of the IPCC emission inventory methodology is an ongoing process and since the writing of paper IV, IPCC Guidelines (1995) and Revised IPCC 1996 Guidelines (1997) have been published. In recent updates of the Finnish greenhouse gas emission inventories the improvements in the methodologies have been taken into consideration (Pipatti 1997; Finland’s second report under the FCCC 1997).

In the following chapters the Finnish CH_4 and N_2O emission inventories and estimation methods used and input data, as well as the improved IPCC methodologies and the impact they have on the emission inventories, are discussed briefly. The estimated Finnish CH_4 and N_2O emission inventories are compiled in Tables 5 and 6. The estimates presented in paper IV are complemented with the results of the recent estimates (Pipatti 1997; Finland’s second report under the FCCC 1997).

Table 5. Estimates of anthropogenic methane emissions (Gg CH_4) in Finland in 1990 and 1995 (paper IV; Finland’s second report under the FCCC 1997; Pipatti 1997).

	1990 (paper IV)	1990 *	1995 *
All Energy	17	15	16
- Stationary sources	11	11	13
- Transportation	5	3	3
Industrial processes	NE	4	4
Agriculture	94	101	88
- Enteric fermentation	83	90	78
- Manure Management	11	11	10
Waste**	134	126	133
- Landfills	100	116	123
- Landfill gas recovery	-	-	3
- Wastewater treatment	34	10	10
TOTAL	245	246	241
International bunkers	NE	1	1

* Finland’s second report under the FCCC 1997; Pipatti 1997

** In paper IV the CH_4 emissions from sludge disposal are reported under wastewater treatment, whereas these emissions are included in the emission estimates from landfills in the recent estimates.

Table 6. Estimates of anthropogenic nitrous oxide emissions (Gg N_2O) in Finland in 1990 and 1995 (paper IV; Finland's second report under the FCCC 1997; Pipatti 1997).

	1990 (paper IV)	1990 *	1995 *
All Energy	4	5	6
- Stationary sources	2	3	4
- Transportation	2	2	2
Industrial processes	3	3	3
Agriculture	12	10	9
- nitrogen load	6	6	5
- cultivated land**	6	NE	NE
- cultivated peatsoils**		4	4
N deposition***	2		
TOTAL	21	18	18
International bunkers	NE	1	1

* Finland's second report under the FCCC 1997; Pipatti 1997

** In the recent inventories N_2O emissions from cultivated land are assumed to be background emissions and are not included in the emission inventories with the exception of the emissions from cultivated peatsoils.

*** In the recent inventories the emissions from energy, industrial processes and agriculture include the emissions caused by N-deposition from NO_x and NH_3 emissions from these sources. In the inventory of paper IV these emissions were estimated separately and division by emission sources was not made.

Due to rounding errors given totals are not always equal to the sums of the given numbers. The uncertainties in the estimates are considerable and the numbers should be given with maximum two meaningful digits. However, to show the differences in the estimates this manner of presentation was chosen.. NE = Not estimated.

CH_4 and N_2O emissions from energy production and use

CH_4 and N_2O emissions from energy production presented in paper IV were calculated by Boström (et al. 1992; 1994). The calculations were based on a data base on Finnish burning equipment and emission factors specified by fuel and burning equipment type.

CH_4 and N_2O emissions from transportation were calculated using both fuel consumption and traffic performance related emission factors. Emission factors given in the literature showed a wide range and the best estimate values were chosen with weight given to recent measurements and studies, as well as expert opinions.

The CH_4 emissions from the energy sector are relatively small and represent only some 6 to 7 percent of the total estimated anthropogenic CH_4 emissions in Finland. CH_4 is released to the atmosphere in combustion mainly as a result of incomplete burning. Approximately half of the CH_4 emissions from energy production comes from small scale burning of wood, even though the share of energy produced by small scale burning is only about 15 percent. Transportation causes less than a third of the CH_4 emissions of the energy sector. The role of fugitive emission from natural gas distribution is also minor (paper IV; Grönfors 1996; Pipatti 1997).

N_2O emissions from the energy sector are, contrary to CH_4 emissions, significant in Finland; about one fifth of the total anthropogenic N_2O emissions come from energy production and consumption. Most combustion processes produce only small amounts of N_2O. The fluidized bed combustion technique is an exception and the N_2O emissions are important. The fuel and combustion conditions like temperature and air coefficient influence the emissions from fluidized bed combustion decisively (Kilpinen 1995). Also NO_x reduction techniques like urea addition can increase the N_2O emissions from energy production, but these emissions have not been included in the inventory as quantitative data on the emissions are lacking.

Catalytic converters in cars increase the amount of N_2O emitted compared to cars without them and the ageing of the catalysts increase the emissions even more (de Soete 1993). In 1990 only 5 per cent of personal cars in Finland were equipped with catalytic converters. N_2O emissions from road transport are becoming more important as the share of cars with catalytic converters is increasing.

The recent inventories on greenhouse gas emissions from the energy sector have been calculated with the ‘ILMARI’ model of Statistics Finland (Grönfors 1996; Finland’s second report under the FCCC 1997). The calculation methods in the emission inventories are similar, and most of the emission factors are the same as in Boström’s (et al. 1992; 1994) calculations. The emission data for the road transportation sector have been calculated with the LIISA95-model of VTT Communities and Infrastructure (Mäkelä et al. 1996). The results of the LIISA95 model agree well with the estimates given in paper IV.

The emission sources in the energy sector are covered well in the inventories, but the reliability of the emission factors is only moderate.

CH_4 and N_2O emissions from industrial processes

CH_4 emissions are produced in a variety of industrial processes, but the importance of the industrial emissions in the total inventories is estimated to be small. The Finnish industrial CH_4 emissions were not estimated in paper IV.

IPCC Guidelines (1995) give CH_4 emission factors for coke, sinter, pig iron, carbon black, ethylene, dichloroethylene, styrene and methanol production. In Finland only CH_4 emissions from the iron industry (coke, sinter and pig iron production) are considered to be notable. The production of coke, sinter and pig iron has been fairly constant during the time period 1990 to 1995 and the yearly CH_4 emissions estimated with the IPCC methodology are approximately 4 Gg CH_4 for the whole period. The emission estimate is very uncertain. The emissions from the other production processes mentioned are estimated to be insignificant (less than 1 Gg CH_4/year).

N_2O emissions from the production of nitric acid and adipic acid can be significant. In Finland only nitric acid is produced. In the inventories (paper IV; Finland's second report under the FCCC 1997; Pipatti 1997) the given values for N_2O emissions from nitric acid production in Finland represent the mean value obtained using the emission factor range (2 - 9 g N_2O/kg HNO_3) given by de Soete (1993). This range is given as default value also in the IPCC Guidelines (1995).

Emission factors for N_2O emissions from nitric acid production are also given in the Revised IPCC 1996 Guidelines (1997), in CORINAIR (McInnes 1996) and by Oonk (1996) (see Table 7). Finnish nitric acid plants are all medium pressure plants and the emission factor range given in the Revised IPCC 1996 Guidelines (1997) suggests that the Finnish emissions could be somewhat higher than currently estimated. Higher emissions are supported also by Oonk's (1996) studies. The actual emissions are, however, plant specific and, in order to improve the reliability and accuracy of the inventory, measurements and more detailed analyses at plant level would need to be carried out.

Table 7. Estimates of Finnish N_2O emissions from nitric acid production in 1990 using various sets of emission factors given in literature.

Reference	Emission factor g N_2O/kg HNO_3	Estimated range of Finnish emissions in 1990 Gg N_2O/year
de Soete 1993/IPCC Guidelines 1995	2 - 9	1.1 - 5.0
Revised IPCC 1996 Guidelines:		
- modern, integrated process	< 2	< 1.1
- low pressure process	4 - 5	2.2 - 2.7
- medium pressure process	6 - 7.5	3.3 - 4.1
CORINAIR 1996:		
- generated in the process	11	6.1
- default value	0.8	0.4
- 1990 inventory range	1 - 79	0.5 - 43.5
Oonk 1996	8 - 12.5	4.4 - 6.9

CH_4 emissions from animal husbandry

The CH_4 emissions from agriculture mainly derive from the digestive processes and manure of livestock. In Finland the digestive processes cause most of the emissions (83 to 90 Gg CH_4 in 1990) and treatment and storage of manure less (11 Gg CH_4 in 1990). Totally these emissions make up about 40 % of the anthropogenic CH_4 emissions in Finland in 1990.

In paper IV CH_4 emissions from livestock digestion and manure have been estimated using the detailed (Tier 2) IPCC methodologies (OECD 1991) complemented with results of Gibbs & Leng (1993). The methodologies require input data on characteristics of the animal species, feeding and keeping specified in more detail in paper IV. Much of this data can be found in agricultural statistics, other data has been estimated by interviewing agricultural experts. Due to the type of the input data, it will always contain some uncertainties which are reflected in the emission estimates.

The methodology given in IPCC Guidelines (1995) used in the recent inventories is basically the same as used in paper IV. The emission estimate for 1990 is higher than the estimate in paper IV due to data reviewed on animal weights and weight gain. Also fewer animal categories have been used in the calculations, which also affects the results (Pipatti 1997).

The emission factors for enteric fermentation and manure management for the main animal categories derived by applying Finnish input data to the IPCC methodology and the corresponding default emission factors for Western Europe (cold climate) in the IPCC Guidelines (1995) are given in Table 8.

The emission factors are very similar with the exception of emission factors for manure management of dairy cows and other cattle. The much lower Finnish emission factors for manure management of cattle can be explained by differences in cattle stock (Finnish cattle are small), feeding of cattle (Finnish cattle receive mostly a roughage based diet, high energy corn-based diets enhance the CH_4 emissions from manure) and manure management (solid manure treatment is still common in Finland for cattle, CH_4 emissions from liquid treatment are tenfold compared with solid manure treatment in cold climate and even more so in warmer climates) (IPCC guidelines 1995; Gibbs & Leng 1993).

Table 8. Comparison between emission factors derived by Pipatti (1997) and corresponding default emission factors given in IPCC Guidelines (1995) for CH_4 emissions from enteric fermentation and manure management.

Animal category	Emission factor kg/animal/year			
	Pipatti (1997)		IPCC Guidelines (1995)*	
	Enteric fermentation	Manure	Enteric fermentation	Manure
Dairy cattle	96	5	100	14
Heifers	60	4	48**	6
Mother cows	62	5	48**	6
Bull, > 1 year	55	4	48**	6
Calves < 1 year	38	3	48**	6
Pigs	1.5	4	1.5	3***

* Default values for emission factors in Western Europe with cold climate.

** Emission factor for the category other cattle.

*** Probably a calculation error in the IPCC Guidelines, should be 4.

CH_4 and N_2O emissions from agricultural soils

Soils can act both as sources and sinks of the important greenhouse gases: CO_2, CH_4 and N_2O. In agricultural soils the mass balances of these gases are affected by the management system and fertilizer use. Climate and soil type are also important parameters when estimating the strength of the greenhouse gas sources and sinks. The methods for the estimation of the emissions or the sink strengths from agricultural soils are, however, still largely under development.

Soil microbes can oxidise CH_4 into CO_2 and H_2O, and this process is especially effective in forest soils. In cultivated soils CH_4 oxidation is decreased and nitrogen fertilisation inhibits it further. Cultivated soils can even emit CH_4 locally. IPCC (OCED 1991; IPCC Guidelines 1995; Revised IPCC 1996 Guidelines 1997) do not provide methodology for the estimation of CH_4 emissions or its uptake in agricultural soils.

In the Finnish Research Programme on Climate Change (SILMU) organic agricultural soils (peatsoils) were estimated to emit about 0.8 Gg CH_4/year (Kuusisto et al. 1996). The CH_4 emissions from agricultural soils have, however, been omitted from the inventories presented in paper IV and the recent inventories (Pipatti 1997; Finland’s second report under the FCCC 1997).

N_2O is formed in soils through microbial processes: nitrification and denitrification (Fig. 9). The processes are controlled by a number of soil characteristics, nitrogen availability, temperature and moisture being the most significant among them. In agricultural soils the formation of N_2O is enhanced by increased nitrogen availability. Nitrogen fertilisation is presumed to result in additional N_2O emissions. The N_2O emissions may also be enhanced in unfertilised cultivated soils as a result of enhanced mineralisation of organic matter.

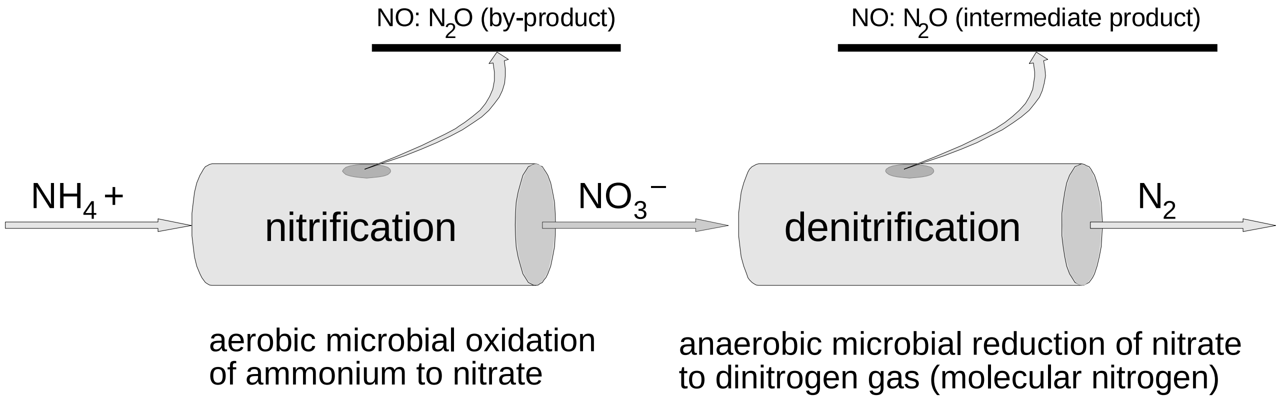

Fig. 9. N_2O formation in soils through the microbial processes of nitrification and denitrification (adapted from Firestone & Davidson 1989).

The Finnish N_2O emissions from agricultural soils in 1990 have been estimated to be approximately 10 - 12 Gg N_2O depending on how the emissions from unfertilised cultivated land are taken into consideration. Agricultural soils are estimated to be the most important source of N_2O emissions in Finland. The uncertainties associated with the emissions are, however, significant.

The methodologies for estimates on N_2O emissions from agricultural soils have undergone many changes during the development of the IPCC Guidelines. Methodologies are provided for enhanced nitrogen input in the soils through fertilisation (mineral and organic nitrogen input and biological nitrogen fixation through cultivation of legumes) and deposition of airborne nitrogen compounds. The N_2O emissions from unfertilised cultivated soils are considered as background emissions in most cases as their distinction from the natural emissions is difficult.

In the draft version of the IPCC Guidelines (OECD 1991) the N_2O emissions were calculated using emission factors and quantity data for different commercial fertiliser types. IPCC Guidelines (1995) recommended the use of averaged general emission factors independent of fertiliser type instead. The use of emission factors relating to fertiliser types was not considered justified as existing information on emission factors by fertilizer type showed wide and overlapping ranges. Use of three year averages for activity data was also recommended.

The Revised IPCC 1996 Guidelines (1997) has extended the methodology to include N_2O emissions from cultivation of high organic content soils. Also methodologies to account for atmospheric deposition of NO_x and NH_3 and leaching and runoff of fertiliser nitrogen have been added. In the 1990's the Finnish agricultural NH_3 emissions have been estimated to increase the N_2O emissions by less than 0.5 Gg NH_3/year. The corresponding impact of leaching and runoff of fertiliser nitrogen has not been estimated.

The estimation methodology for Finnish N_2O emissions from agricultural soils in paper IV is similar to the methodology given in IPCC guidelines (1995), but the emissions factors used were determined from Finnish research data (Jaakkola 1985; Renlund 1991). The emission estimate includes emissions also from unfertilised cultivated land.

In the recent estimates the default emission factors given in IPCC Guidelines (1995) have been used in the calculations. The emissions from unfertilised cultivated land have been omitted from the inventory with the exception of emissions from cultivated peatsoils. The emissions from cultivated peatsoils are based on estimates given in the Finnish Research Programme on Climate Change

(Kuusisto et al. 1996). The estimate (approximately 4 Gg N_2O/year) is comparable with the value that would be obtained with the default emission factor of the Revised IPCC 1996 Guidelines (1997).

N_2O emissions from nitrogen deposition

Nitrogen deposition caused by NO_x and NH_3 emissions from various sources increase the nitrogen load of the soil and can contribute to the N_2O emissions. In paper IV the emissions from nitrogen deposition were estimated assuming one per cent of the nitrogen deposited in Finland to be released as N_2O. The emission factor was chosen in accordance with Mosier (1993) and Robertson (1991). No differentiation on basis of the source of the emissions was made. The total emissions caused by nitrogen deposition were relatively large in 1990, approximately 1.9 Gg N_2O, which is about 10 per cent of the total anthropogenic N_2O emissions in Finland that year.

In the recent inventories the emissions caused by nitrogen deposition were calculated from the NO_x and NH_3 emissions from energy production, transportation, industrial processes and agriculture in Finland, and the emissions were allocated to the emission source in question (see Table 9). As the nitrogen deposition and the amount of nitrogen emitted to the atmosphere in 1990 is of the same order of magnitude the total N_2O emissions from N deposition were about the same.

Table 9. N_2O emissions caused by NO_x and NH_3 emissions in Finland in 1990 (Pipatti 1997).

Emission source	N_2O emissions in 1990 Gg N_2O/year
Energy production	0.45
Transportation	0.86
Industry	0.12
Agriculture	0.43
TOTAL	**1.85**

CH_4 emissions from waste management

Solid waste disposal on land (landfills and dumps) and wastewater treatment cause significant CH_4 emissions as organic matter decomposes under oxygen-free conditions. The emissions from waste are estimated to cause more than half of the anthropogenic CH_4 emissions in Finland (about 130 Gg CH_4 in 1990). Most of the CH_4 emissions come from landfills (about 120 Gg in 1990), the emissions from wastewater treatment are smaller (about 10 Gg in 1990) .

In paper IV CH_4 emissions from land disposal of municipal solid waste (MSW) and from municipal and industrial wastewater treatment were estimated. The emissions from land disposal of MSW were estimated using the mass balance approach developed by Bingemer & Crutzen (1987) and used as the IPCC default methodology (OECD 1991; IPCC Guidelines 1995; Revised IPCC 1996 Guidelines 1997). As the conditions at Finnish landfills are not optimal for CH_4 generation, an emission factor lower than the IPCC default value was used in the estimate.

In paper IV CH_4 emissions from wastewater treatment were estimated using a methodology given by Thorneloe (1993). The CH_4 emissions were estimated for the whole treatment chain, wastewater and sludge treatment as well as the disposal of the sludge.

In recent inventories the estimate of CH_4 emissions from landfills has been complemented with the emissions from solid waste disposal of industrial waste and construction and demolition waste. In accordance with the IPCC Guidelines (1995), the CH_4 emissions from sludge disposal in landfills are also reported in the landfill sector and not the wastewater treatment sector as in paper IV.

In the recent inventories emissions from solid waste disposal on land have been estimated using the first order kinetic decay model (see paper IV for descriptions). The degradation coefficient values used in the calculations were 0.02 per year for construction and demolition waste (wood waste), 0.03 per year for MSW and industrial solid waste and 0.1 per year for community and industrial sludges. The first order dynamic model also requires data on historical solid waste disposal on land. As the data in this field is scarce, the input values were estimated proportional to population, GNP, industrial production etc.

Landfill gas recovery is practised on a minor scale in Finland (in 1995 the impact of recovery was estimated to be about 3 Gg CH_4). In the forthcoming years the importance of landfill gas recovery is estimated to increase substantially.

The emissions from wastewater treatment have been estimated similarly as in paper IV with the exception of the emissions from sludge disposal in landfills. CH_4 emissions generated during anaerobic treatment are recovered and used for energy production. This was not taken into account in the estimate in paper IV but has been taken into consideration in the recent inventories. The emissions from municipal wastewater treatment were estimated to be almost negligible in the recent estimates (less than 1 Gg CH_4/year).

Waste incineration can also cause emissions of greenhouse gases (CO_2, N_2O and CH_4). These emissions are of smaller significance than the CH_4 emissions from landfills and are reported in the energy sector.

The emission estimates calculated with the mass balance approach and the kinetic decay model are not comparable. The mass balance model gives an estimate of the potential CH_4 emissions of solid waste disposed on land without consideration of the timing of the emissions. The kinetic decay model takes the timing of the emissions into consideration and gives a more realistic picture of the actual emissions during the period under consideration. The different approaches are illustrated in Fig. 10 and the results of calculations of the Finnish emissions in 1990 are given in Table 10.

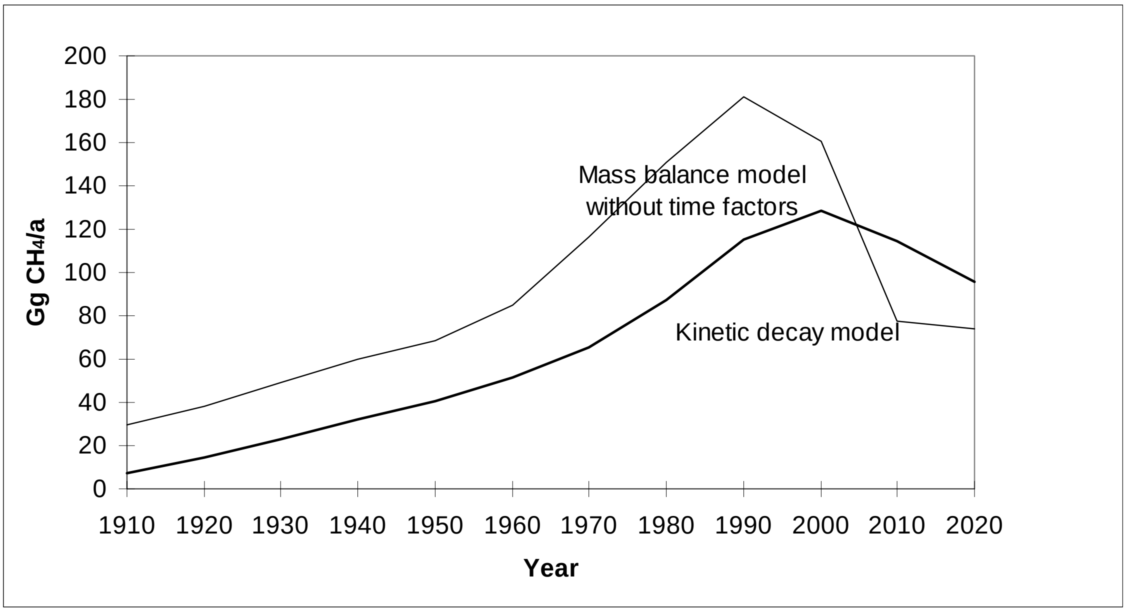

Fig. 10. Illustration of differences in values of estimated methane emissions from landfills in Finland using the first order kinetic decay model and the mass balance model.

Table 10. Recent emission inventory of CH_4 emissions (Gg/year) from solid waste disposal on land in Finland in 1990 estimated with the first order kinetic decay model and the mass balance approach (Pipatti 1997; Finland's second report under the FCCC 1997). For comparison the emission estimate for 1990 given in paper IV is also presented.

	1990 (paper IV)	1990* Mass balance model	1990* Kinetic decay model
Landfills	**100**	**181**	**115**
- MSW	100	105	71
- Industrial solid waste	NE	27	15
- Construction and demolition waste	NE	22	8
- Community sludge	NE	6	4
- Industrial sludge	NE	21	18
Wastewater treatment	**34****	10	10
- municipal	7**	< 1	< 1
- industrial	27**	10	10
Total	**134**	**191**	**126**

* Finland's second report under the FCCC 1997; Pipatti 1997

** In paper IV the estimated emissions from wastewater treatment include emissions from sludge disposal at landfills.

Both the mass balance model and the kinetic model have advantages depending on how the results are used. The mass balance model gives an estimate of the total potential CH_4 emissions caused by landfill disposal of a certain amount of waste, and the decay model an estimate on how these emissions are realised in time. Changes in the amount of landfilled waste are reflected immediately in the results given by the mass balance model, whereas the kinetic decay model responds corresponding to reality more slowly to the changes.

The mass balance model is well suited for national and global inventories and system studies on the potential of alternative mitigation options. The kinetic decay model gives a more realistic estimate of current and future emissions, and is better suited for estimates on the impacts on radiative forcing and progress of global warming. In site-specific analyses on the emissions and mitigation options the kinetic decay model is undisputedly advantageous.

The uncertainties in the estimates on CH_4 emissions from waste are large, regardless of the model used. The data on composition and amount of waste landfilled is still often based on rough estimates and, when looking at past values, the lack of data is even greater. Statistics on both municipal and industrial waste management are currently improving, and future emissions will at least to some extent be based on more reliable data.

Other anthropogenic CH_4 and N_2O emission sources

Artificial lakes, which are built as water reservoirs for power plants, can release significant amounts of CH_4 as the organic matter flooded by the water decomposes. Measurements at the Lokka reservoir in northern Finland gave emissions in the range of 20 - 120 g CH_4/m^2 during the growing season (Kuusisto et al. 1996). As the current reservoir area in Finland is about 630 km^2 the corresponding emission range would be 13 - 75 Gg CH_4/year. The emissions have not been included in the CH_4 emission inventories, even if their importance is recognised. The emission estimate is uncertain as it is based on a limited number of measurements, and more research on the emissions is needed.

All N_2O emission sources and their strength are not well known. The atmospheric N_2O concentrations have increased more rapidly than the difference between the known emission sources and sinks would indicate. De Soete (1993) and Kleffmann et al. (1994) suggest that N_2O could be formed from NO_2 in the flue gas plumes of power plants. The formation would be due to heterogeneous reactions catalysed by acid surfaces. The new source for N_2O could be an important contributor to the emissions in countries like Finland, where the role of energy production is substantial. The studies are, however, too preliminary and uncertain for quantitative estimates of the emissions.

Dentener & Crutzen (1994) have also indicated that N_2O could be formed from NH_3 in the atmosphere by oxidation in conditions, where the hydroxyl concentrations are high and sulphate concentrations small. This would enhance the importance of agriculture as a N_2O source. The importance of the finding to Finnish emission inventories is considered to be small, as conditions required by the process are met mainly in tropical regions. The associated uncertainties are also large.

Also other anthropogenic activities like logging of forests and bog ditching can enhance N_2O emissions. Quantitative estimates are, however, very uncertain and the distinction of the emissions from natural emissions difficult.

Natural CH_4 and N_2O emissions in Finland

This thesis is concerned with the anthropogenic emissions, but to give a general view of the total Finnish CH_4 and N_2O emissions, the natural emissions are addressed briefly. Natural CH_4 emissions are significant in Finland and estimated to be more than three times larger than the anthropogenic emissions. The natural CH_4 emissions in Finland come from the wetlands (bogs and mires), which occupy large land areas mostly in eastern and northern Finland. Surface waters may also be significant CH_4 sources, but a quantitative estimate of the source strength cannot be made with current information on the emissions.

Globally natural soils and waters are estimated to produce the bulk part of the N_2O input to the atmosphere. In Finland these natural N_2O emissions have been estimated to be small. The forest soils are usually nitrogen deficient and the microbial activity low due to the cold climate (Kuusisto et al. 1996; Martikainen et al. 1993).

4.2.2 Historical CH_4 and N_2O emissions

The greenhouse gases are long-lived in the atmosphere, and in the assessment of the current and future anthropogenic warming impact also historical emission data is needed. CH_4 has an atmospheric lifetime of only about ten years so that estimates of only some past decades would be needed. However, in order to get comparable time series of the warming impact caused by the different greenhouse gas emissions in Finland, CH_4 emissions have also been estimated from the beginning of the century (see estimation methods in paper IV).

The CH_4 emissions from agriculture were important already in the beginning of the nineteenth century. Small scale burning was an important source then. CH_4 emissions from landfills have increased steadily with growth in population, welfare and urbanisation. Emissions associated with industry and transportation have become notable after the 1960’s. Total anthropogenic CH_4 emissions in Finland have doubled during the period (see Fig. 2 in paper IV).

The N_2O emissions from agriculture have grown with increased use of commercial fertilisers. Emissions from industry, energy production and transportation have started to become important after the second half of the century and increased much since. The current emissions are much higher than the emissions at the beginning of the century (see Fig. 3 in paper IV).

The historical CH_4 and N_2O emissions are very uncertain. Detailed and accurate activity data is not available, and many generalisations have been made in the estimates.

4.2.3 Scenarios for future CH_4 and N_2O emissions

The base and the reduction scenarios

The development of the CH_4 and N_2O emissions in the near future was estimated in two scenarios. In the base scenario the emissions were estimated assuming expected changes in the volume and structure of the emission producing activities. Policies and measures, which reduce the emissions were considered if the decisions or plans on their implementation had already been made. In the reduction scenario the reduction potential compared with the base scenario was estimated. The reduction scenario in paper IV was preliminary and rough.

In paper IV an overall reduction of 50 per cent was assumed for both CH_4 and N_2O emissions in 2010 compared with the base scenario with one exception. The CH_4 emissions from the transportation sector were assumed to be the same both in the base and the reduction scenarios as the emissions will be reduced substantially already by the increased use of catalytic converters in cars.

The possibilities to reduce the anthropogenic CH_4 emissions in Finland were estimated to be promising and a reduction of approximately 50 per cent compared with the base scenario achievable. The N_2O emissions, on the other hand, are estimated to increase in the coming years. Abatement techniques for the N_2O emissions are not known well and the emissions are increasing as both expected volume and structural changes increase the emissions (see paper IV).

Potential and cost-effectiveness of CH_4 and N_2O emission reduction in Finland

The recent study on the potential and cost-effectiveness of reducing the Finnish CH_4 and N_2O emissions confirms that the possibilities to reduce the CH_4 are good in Finland, whereas the possibilities to reduce the N_2O emission are still very uncertain (Pipatti 1997).

Finnish CH_4 emissions could be reduced by 30 per cent with measures considered in the study. The emission reduction is almost entirely due to measures in the waste sector. Landfill gas recovery is an efficient and cost-effective way to reduce the current emissions from the landfill. If the recovered gas can be utilised in energy production, the landfill gas recovery can even be a profitable CH_4 abatement measure. Alternative waste treatment techniques like waste incineration and biological treatment would reduce the future emissions efficiently even if their ability to reduce the current emissions is small.

In the other sectors the possibilities to reduce the CH_4 emissions are usually of less importance or not known. The emission reduction potential of CH_4 emissions from manure treatment was estimated to be small and the abatement costs to be high. The reduction options and potential for CH_4 emissions from enteric fermentation in Finland are not known.

The estimated reduction and cost-effectiveness of the implementation of the reduction measures considered in the recent study are given in Fig. 11. It is assumed that the recovered gas from the landfills can be utilised for energy and hence considerable emission reductions can be achieved with negative or negligible costs.

There is little data available on N_2O emission reduction measures. Agricultural emissions can be reduced by reduced fertilisation, but at the same time the agricultural production is lowered. Reducing over-fertilisation and timing the fertilisation more accurately has also been put forward as means to reduce the N_2O emission from agriculture, but quantitative data on efficiencies and applicability in Finland is not available. Information on N_2O abatement from agricultural soils is available in studies, which have been done in the Netherlands (Kroetze 1994; de Jager et al. 1996), but the results cannot be applied directly as the conditions in Finland differ significantly from those in the Netherlands.

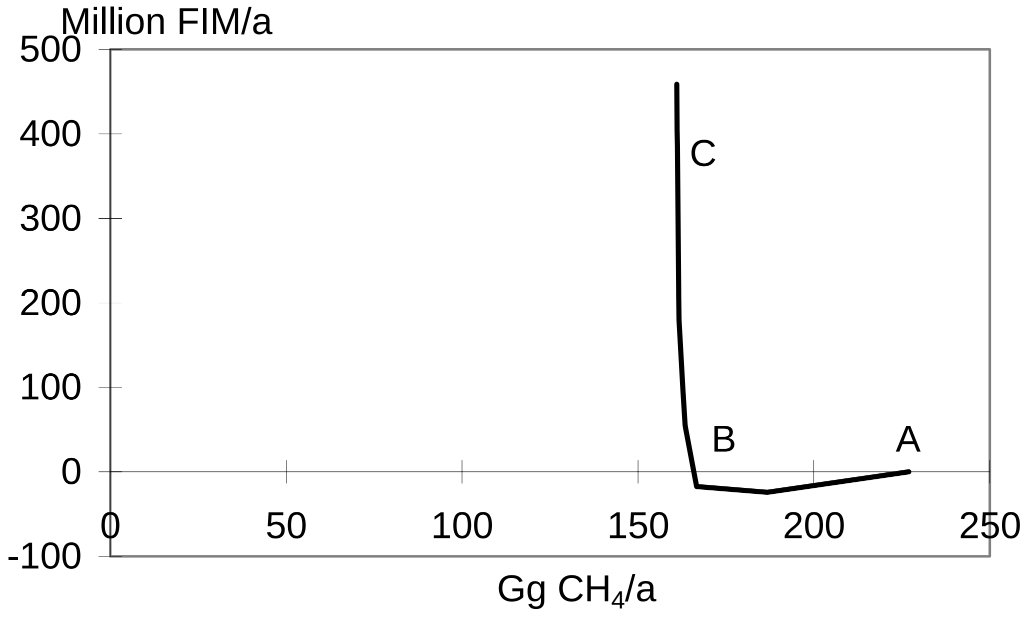

Fig. 11. Cost effectiveness of reduction measures for methane emission reduction in Finland (Pipatti 1997). Present emission (A) can be reduced with slightly negative costs B (landfill gas recovery and use for energy). Further reductions appear to be very costly (C).

Measures to reduce N_2O emissions from nitric acid production and fluidized bed combustion are available, but plant scale data on efficiencies and applicability is lacking. The abatement techniques are, however, promising (de Jager et al. 1996; Marban et al. 1996). Even if the techniques could reduce the emissions from these sources by 80 to 90 per cent, they would reduce the total estimated N_2O emissions in Finland in 2010 only by 20 to 30 per cent, which is approximately equal to the expected growth in the Finnish N_2O emissions.

Greenhouse impact of CH_4 emission mitigation in the waste sector

In paper IV and the recent study by the disputant (Pipatti 1997) the reduction potential of the Finnish CH_4 and N_2O emissions was determined without considering the impact of the abatement measures on emissions of other greenhouse gases. A more integrated approach is presented in paper V, where the greenhouse impact of alternative waste management strategies is assessed.

In paper V emissions of the most important greenhouse gases (CO_2, CH_4 and N_2O) in eight alternative municipal solid waste (MSW) treatment chains are presented. The comparison was made between alternative waste treatment chains as the individual techniques are not fully parallel. The comparison was based on the treatment of one Mg municipal solid waste (dry matter) of average composition in Finland at the end of the 1980's.

The organic fraction in municipal solid waste consists mostly of biomass from different sources converted to various products. When biomass is regrown at approximately the same rate as it is harvested no net CO_2 flux into the atmosphere is formed. This is assumed in the estimate, and CO_2 emissions from treatment of biomass based waste are therefore not considered. CO_2 emissions originating from carbon in fossil waste (plastics) and CH_4 and N_2O emissions are estimated in the usual way in accordance with the IPCC methodology. The CH_4 emissions from landfills are estimated with the mass balance methodology.

In addition to the greenhouse gas emissions, energy production and long-term carbon storage in landfills in the alternative treatment chains are estimated. The energy use of waste is assumed to replace energy produced by fossil fuels and thus reduce emissions from fossil fuel combustion (emission savings). All organic matter will not decompose in the landfills, and landfills will form a sink for the part that is not decomposed. Carbon originating from renewable sources (food and garden waste, paper, cardboard and wood waste) will thus be removed from the carbon cycle and reduce the CO_2 concentration in the atmosphere. This is also accounted for in the estimate.

The results of the study are given in table 11 and Fig. 2 in paper V. The emissions of the different greenhouse gases and the impact of energy production and long-term carbon storage in landfills are expressed in CO_2-equivalents derived from GWP-values given by the IPCC. The GWP-values used in paper V have been updated since the writing of paper V by the IPCC (1996a) and the new values (GWP for CH_4 = 21 and for N_2O = 310, 100 year time horizon) are used to calculate the values in Table 11. The new GWP-value for CH_4 is more than 15 per cent lower than the old value, and the effect on the estimated greenhouse impact is significant. The results of the comparison are, however, roughly the same.

Disposal of MSW in landfills without landfill gas recovery causes the largest greenhouse gas emissions and the largest net greenhouse impact of the alternatives. The CH_4 emissions can be lowered substantially by landfill gas recovery. Landfill gas recovery efficiency depends on the method used and the time at which the recovery is started, and also on how the loss through the landfill cover is avoided. The efficiencies of the collecting systems vary usually between 50 - 90 per cent and with optimal coverage of the landfill efficiencies of almost 100 per cent can be achieved. The CH_4 generation is at its best years after the landfilling took place, and gas collection systems are therefore installed in the landfills years after the landfilling began or when the landfills are closed. This reduces the overall efficiency of the recovery. Oonk and Boom (1995) have presented efficiencies of 24 - 60 % of the total gas production at landfills in their studies. In paper V the landfill gas recovery efficiency was assumed to be 40 % of the total potential CH_4 production.

The recovered landfill gas is burned in a flare or used for energy production. The greater the share of the recovered landfill gas that can be utilised in energy production, the more is the net greenhouse impact lowered.

The direct greenhouse gas emissions in alternatives (4 and 5), where biowaste is treated separately by composting or in biogas utilities and the rest of the waste is landfilled, are comparable with those of the alternative where all the waste is deposited in the landfill and the landfill gas recovered. The net greenhouse impact of alternatives with separate biowaste treatment is, however, higher than in the alternative where the waste is landfilled and the gas recovered (with or without energy production).

Table 11. Estimates of greenhouse gas emissions and net greenhouse impact from alternative waste treatment chains. Emissions (kg), energy produced (MJ) and emission savings (kg) are estimated for 1 Mg (dry matter) MSW of average composition in Finland. The CH_4 *and* N_2O *emissions are converted to* CO_2*-equivalents using global warming potential factors (GWP) of 21 and 310, respectively, corresponding to an integration period of 100 years (Pipatti et al. 1996).*

	Waste treatment chain	**Emissions**					**Emission savings**	**Carbon stored in the landfill**	**Net impact**[2]
		CO_2	CH_4	N_2O	**Total CO_2-eq.**	Energy produced	CO_2-eq.	CO_2-eq.	CO_2-eq.
1	Landfilling		60		**1260**			697	563
2	Landfilling + gas recovery + flaring		36		**756**			697	59
3	Landfilling + gas recovery + energy production		36		**756**	1200	93	697	-34
4	Separation and composting of biowaste + landfilling		37		**777**			433	344
5	Separation and anaerobic treatment of biowaste + landfilling		37		**777**	800	62	433	282
6	Separation and burning of combustible waste + landfilling	150	28	0.04	**751**	9 000	701	331	-281
7	Separation and anaerobic treatment of biowaste + separation and burning of combustible waste + landfilling	150	6	0.04	**289**	9 550	744	67	-522
8	Mass incineration	150	0.08	0.09	**179**	16 000	1246		-1067

Due to rounding errors given totals are not always equal to the sums of the given numbers. The uncertainties in the estimates are considerable and the numbers should be given with one or two meaningful digits. However, to show the differences in the estimates this manner of presentation was chosen..

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[2] The net impact is equal to emissions minus carbon sinks and savings in fossil energy use due to energy recovery from waste treatment.

All MSW or the combustible fraction of MSW can be burned. The greenhouse gas emissions of mass incineration are clearly the smallest of all the alternative treatment chains, and if the energy produced in the combustion can be utilised effectively, the net greenhouse impact is negative. The greenhouse gas emissions from burning of the combustible fraction of MSW are also low compared with alternatives that do not contain combustion but the emissions depend on how effectively the separation of the different waste fractions can be done.

The uncertainties in the estimate on the greenhouse gas emissions and the net greenhouse impact of alternative waste treatment chains are considerable, and the results are therefore only indicative. Regardless of the uncertainties, the analysis shows that options to reduce the CH_4 emissions from waste management are good and that energy use of waste in energy production plays an important role in reducing the net greenhouse impact of the waste sector.

4.2.4 Finnish halocarbon emissions

Estimates for some halocarbon (CFC, HCFC and HFC) emissions in Finland are presented in paper IV.

The halocarbons in question have not been manufactured in Finland, and the emission estimates are based on the consumption of the chemicals in Finland. Consumption figures for the years 1986 to 1990 were obtained from the Ministry of Environment based on information obtained from the importers of the chemicals. Earlier CFC consumption was estimated to have begun in 1960 and follows a similar development path as CFC-11 and CFC-12 production in the developed world (Hoffman 1990). The HCFC consumption was estimated to have grown linearly from 1960 to 1996. HFC consumption in 1990 and before was estimated to be negligible (see paper VI).

The future consumption of the CFCs and HCFCs was estimated to follow the agreed and target phase out schedules in the Montreal Protocol and in the Principal Decision of the Finnish Government of Deduction of CFC Compounds and other Substances Depleting the Ozone Layer (1992). HFC consumption was estimated to be equal to the decrease in HCFC consumption after 1996, when the HCFC restrictions enter into force.

The CFC emissions were estimated to be equal to the yearly consumption in applications (use in aerosols, open-cell foams and as solvents) where the chemicals are released to the atmosphere within a short time frame after consumption. For other applications the time-dependence of the emissions was considered with data on the time-lags obtained from international (closed-cell foams) and national (refrigerants) studies.

The future CFC emissions were estimated in two scenarios. In the base scenario the emissions were estimated in accordance with the consumption pattern described above, and the effect of enhanced recovery on the emissions was estimated in the recovery scenario. The CFC-11 emissions from different kinds of closed-cell foams could be lowered mostly by enhanced recovery.

HCFC and HFC emissions were estimated to be equal to the consumption with the exception that in the future HCFC used in industrial and commercial refrigerators was assumed to be recovered completely (see paper VI).

The Finnish CFC and HCFC emissions in 1990 were compared with corresponding global emission estimates given by IPCC (1992). On a per capita basis the Finnish CFC emissions were estimated to be about twice and the HCFC about one and a half times greater than the global emissions.

4.3 IMPACTS OF THE FINNISH NON-CO_2 GREENHOUSE GAS EMISSIONS

4.3.1 Impacts on global warming

In papers (IV and VI) the global warming impact of the Finnish non-CO_2 greenhouse gas emissions has been estimated by calculating the radiative forcing caused by the emissions and by comparing the greenhouse impacts to that of CO_2 emissions by using GWP (Global Warming Potential) weights. The GWP is defined as the ratio of the time integral of the radiative forcing of a unit emission of the considered gas to the time integral of the radiative forcing of the same unit emission of CO_2. The integration times used are typically 20, 100 or 500 years, depending on the time horizon of the study. The meaning of radiative forcing is defined more clearly in the paper VI.

Since the writing of papers IV and VI, IPCC (1996a) has improved the calculation methodology for radiative forcing and most of the improvements have been included in the REFUGE model of VTT. The GWP values have also been updated by the IPCC (1996a) accordingly. As many of the changes have been significant, the global warming impact of the Finnish non-CO_2 emissions is here presented using the new values, and the most important changes to the estimates given in papers IV and VI are discussed.

In the calculation of the radiative forcing caused by the CH_4 emissions the indirect effects (tropospheric O_3 formation and increase in stratospheric water vapour due to CH_4 build-up) are now taken into consideration, and hence the estimated radiative forcing by mass unit CH_4 is significantly higher than in the previous estimates. The changes in the calculation of the radiative forcing caused by N_2O emissions have undergone smaller changes.

The radiative forcing due to the estimated Finnish CH_4 and N_2O emissions is given in Fig. 12 (for comparison, see also Fig. 4 in paper IV). The radiative forcing values have been calculated up to the year 2100 using the updated emission estimates in the recent study by the disputant (Pipatti 1997). The emissions from 2020 onwards have been estimated to be constant. Emissions since 1900 have been taken into consideration, whereas in paper IV emissions since the 1800’s were included. The radiative forcing caused by the N_2O emissions does not include the impact caused by emissions from cultivated peatlands due to lack of historical data. Hence the overall level of the N_2O radiative forcing is lower than the level in Fig 4b in paper IV.

The radiative forcing in 1990 due to Finnish CH_4 emissions is about 0.6 mW/m^2 according to the recent estimates. In the base scenario the radiative forcing stays relatively stable during the next century, and in the reduction scenario it is lowered by approximately 20 % already before the middle of the century.

The radiative forcing in 1990 caused by the Finnish N_2O emissions is much lower, less than 0.25 mW/m^2. In the base scenario the radiative forcing is more than tripled to approximately 0.8 mW/m^2 by the year 2100, and even in the reduction scenario the radiative forcing is more than doubled.

The current IPCC methodology for calculating the radiative forcing due to CFCs and HCFCs includes the impact of stratospheric O_3 loss caused by the emissions, which lowers the radiative forcing. These improvements have, however, not been included in the REFUGE model. According to the estimates given in paper VI, the radiative forcing in 1990 caused by the CFC and HCFC emissions in Finland was between 0.5 - 0.6 mW/m^2. More than half of this was caused by emissions of CFC-12. The impact of the HCFC emissions on the radiative forcing was small, about ten per cent of the forcing of the CFCs (see Fig. 4 in paper VI).

The forcing of the Finnish CFCs and HCFCs emissions is estimated to peak at a slightly higher value than 0.6 mW/m^2 after the turn of the century and decline to about one third of the peak value by 2100. If the impact on stratospheric O_3 loss is taken into account, the radiative forcing values will be lower.

The HFC emissions do not destroy O_3 and therefore the estimate given in paper VI is still valid. The radiative forcing due to the HFCs is estimated to rise to almost 0.2 mW/m^2 by 2100, which means that the HFC emissions in Finland could become more important contributors to the radiative forcing in the future.

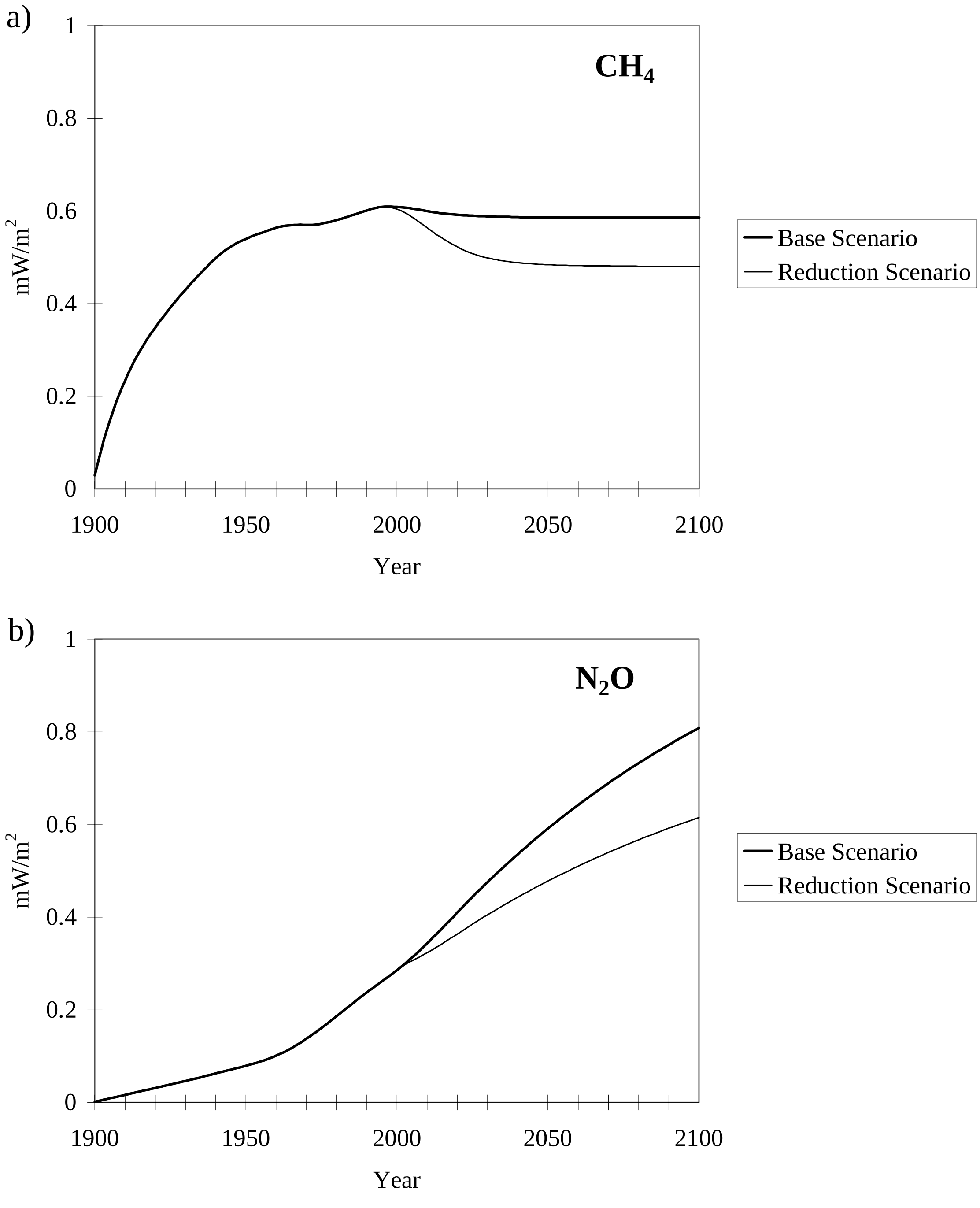

Fig. 12. Radiative forcing due to estimated Finnish a) CH_4 and b) N_2O emissions in the updated base and reduction scenarios (Pipatti 1997). Emissions from 1900 to 2100 are considered. N_2O emissions from cultivated peatsoils are not included in the radiative forcing calculations due to lack of historical data on the emissions.

The greenhouse impact of the Finnish non-CO_2 emissions estimated by using GWP factors is given in table 12.

Table 12. Estimated greenhouse impact of Finnish anthropogenic greenhouse gas emissions in 1990 and 2010. The greenhouse impact of the non-CO_2 emissions have been calculated using GWP-values (100 year time horizon) given by IPCC (1996a). The values include considerable uncertainty (see Chapter 4.4).

Greenhouse gas	Emissions * (Gg)		GWP factor (100 years)	GWP-weighted impact (Gg CO_2-eq.)	
	1990	2010		1990	2010
CO_2	**53**	**55 - 70**	1	**53**	**55 - 70**
CH_4	246	191	21	5	4
N_2O	18	23 - 24	310	6	7
CFCs	2	0.2	1320 - 6650**	6	0.3
HCFCs	0.3	0.3	270 - 1650**	0.4	0.4
HFCs	0	0.9	1300	0	1
Non-CO_2 total				**17**	**13 - 14**

* The CO_2, CH_4 and N_2O emission estimates are taken from Finland's second report under the FCCC 1997. The CO_2 emissions include only emissions from fossil fuels and peat. The CFC, HCFC and HFC emission estimates are the same as in the base scenario in paper VI.
** Mean NGWP values (see table 4).

Calculated in this way the estimated relative impact of Finnish non-CO_2 emissions in 1990 is about 30 per cent of the impact of fossil CO_2 emissions. The CH_4, N_2O and CFC emissions contribute to the greenhouse impact at almost equal force, and the meaning of the other gases is negligible. In 2010 the estimated impact of the non-CO_2 gases is smaller, about 20 per cent of the impact of fossil CO_2 emissions. The decline in the impact is mainly due to the phase out of the CFCs. The impact of the CH_4 emissions is also lowered by approximately one fifth. N_2O emissions are estimated to become the most important non-CO_2 greenhouse gas in Finland in the beginning of the next century. The significance of the HFC is also expected to increase.

The greenhouse impact estimates using both radiative forcing and GWP calculations contain much uncertainty. The uncertainties derive mainly from the uncertainties in the emission estimates, but also the modelling of the atmospheric processes that lead to global warming, contain many uncertainties due to the complex nature of the phenomena.

4.3.2 Impacts on ozone depletion

CFCs and the other stable halocarbons are removed from the atmosphere mainly through photolytic reactions in the stratosphere. These reactions release chlorine, which participates in catalytic chain reactions that destroy O_3 in the stratosphere. Bromine, which is released from e.g. halons in the stratosphere, is even more effective in destroying O_3, but is not considered here. The connection between increasing CFC concentrations in the atmosphere and stratospheric O_3 depletion was discovered by Rowland & Molina (1974). The scientific work on O_3 depletion processes, environmental and health effects and technology and economic implications of mitigation approaches has been active since and led to the signing of the Montreal Protocol, which aims to reduce and finally to phase out the production and consumption of the CFCs and other similar O_3 depleting substances globally.

The O_3 depletion has been most severe in regions near the Antarctic but in the recent years the O_3 depletion has also been significant in the Northern hemisphere. The phase out of the CFC emissions and other O_3 depleting substances has been efficient and the rates of increase in atmospheric concentrations for the major CFC substances have slowed markedly (IPCC 1996a). Even so, the removal of the CFCs from the atmosphere is slow and O_3 depletion will continue to pose threats to humans and the environment still in the next century.

In paper VI the Finnish CFC and HCFC emissions were estimated for global warming studies and only a rough estimate on the impact of the emissions on O_3 depletion was made. The O_3 depletion impact of the Finnish emissions and for comparison also that from global emissions (IPCC-scenario IS92d) was estimated by calculating the amount of chlorine that could be released into the stratosphere. The time frame of the study extended to the year 2100.

The results of the estimate show that the CFCs will be important sources of chlorine in the stratosphere also in the next century. The chlorine loading from Finnish emissions peaks at the turn of the century, whereas the peak from the global emissions is some ten years later. The importance of the HCFCs emissions to the chlorine loading is much smaller than that of the CFCs during the whole period. The share of chlorine loading that is caused by the HCFCs is larger for Finnish emissions than for the global emissions. The differences in the chlorine load from Finnish and global emissions could be explained by differences in the use of the individual substances and phase out time tables.

Stratospheric O_3 formation and depletion processes are complex and depend on many variables. The above estimate gives only a rough comparison of the impact and timing of the Finnish and global CFC and HCFC emissions on O_3 depletion. Also other greenhouse gases (CO_2, N_2O and CH_4) affect the O_3 depletion processes but the impact is not considered in this thesis.

4.4 UNCERTAINTIES IN THE NON-CO$_2$ EMISSION ESTIMATES

Most of the CH$_4$ and N$_2$O emissions come from natural sources: wetlands, soils and water systems. The anthropogenic CH$_4$ and N$_2$O emission sources are also linked closely to natural processes, and the estimation of the strength of the sources is difficult. In the Revised IPCC 1996 Guidelines (1997) the uncertainties of the national CH$_4$ emissions are estimated to be 20 to 100 per cent for individual sources (though the overall error could be 30 per cent). The uncertainties in the N$_2$O emissions are estimated to be larger, up to factor 2 for emissions from agricultural soils. Compared with the estimated uncertainties in CO$_2$ emissions from fossil fuels of 10 per cent for countries with good energy statistics and emission factor data, the uncertainties in the CH$_4$ and N$_2$O emission inventories are very large.

The uncertainty ranges for individual sources of the Finnish CH$_4$ and N$_2$O emissions in paper IV were in most cases determined by calculating the emissions with different emission factors given in literature. The applicability of the emission factors to Finnish conditions was considered by comparing the underlying information to Finnish research and expert evaluations. The uncertainty range for CH$_4$ emissions from enteric fermentation was determined by analysing the sensitivity of the estimation methodology to the input data.

The activity data for most emission categories was estimated to be reliable and not considered in the determination of the uncertainty range. Activity data on waste forms an exception to this, but even here the uncertainty estimate was based only on uncertainties in the emission factors.

The overall uncertainty range was determined simply as the sum of the uncertainties in the individual source categories. If the uncertainties of the different sources compensate each other, the overall uncertainty will be lowered. The uncertainty of the emission estimates for CH$_4$ and N$_2$O in Finland is in any case considerable, and the uncertainty is reflected to the analyses on mitigation options and costs as well as the impact estimates. Despite the uncertainty of the results, the order of magnitude in the estimates is adequate to give an understanding of the importance of the emissions to global warming and the order of priority of the emission reduction measures.

The uncertainties of the CFC emission scenarios are discussed in paper VI and the uncertainties of the impact estimates in the previous chapters.

5 DISCUSSION

5.1 GENERAL DISCUSSION

In this thesis estimates for Finnish anthropogenic NH_3 and the most important non-CO_2 greenhouse gas emissions are presented. The estimates include historical, current and future emissions as well as assessments of the potential to control the emissions on a national level. The estimates have been used as material in national emission inventories and environmental impact calculations, and also as background material for environmental decision-making. The emission and control potential and cost estimates presented in this thesis are considered to be of moderate confidence level and reflect well the current scientific understanding.

Many of the important anthropogenic emission sources of NH_3, CH_4 and N_2O are closely linked to natural processes, and the distinction of the anthropogenic and natural emissions is not always clear. Agriculture is an important source for all three pollutants. NH_3 is emitted to the atmosphere mainly through evaporative processes in livestock manure during the whole waste treatment chain. Enhanced microbial processes in agricultural soils due to an increasing nitrogen load cause the bulk part of the agricultural N_2O emissions. The agricultural CH_4 emissions derive mainly from digestive processes in domestic animals, anaerobic microbial breakdown of organic matter in livestock waste is a smaller but also an important source of agricultural CH_4. Similar microbial processes take place in landfills and waste water treatment, which are also significant sources of CH_4 emissions.

The NH_3, N_2O and CH_4 emissions from agriculture and waste treatment are depending on many factors: animal characteristics and feed, livestock and other waste treatment methods, soils properties, temperature and other climatic factors, pH, waste composition etc. Although the impact of the individual factors on the emissions are known fairly well, the interactions of all the important factors is often complicated and not known in all cases. The interactions of the factors to emissions are especially poorly known in the case N_2O emissions from agricultural soils. The used estimation method is therefore very rough, taking into account only the nitrogen input to the soil and soil mineralisation in cultivation of organic soils.

The methodologies used in the calculation of the NH_3 and CH_4 emissions from agricultural sources and landfills are more complicated and require specified input data. The quantification of some of the data is difficult already for individual farms and landfills, and to derive good mean values on national level is even more difficult. Finnish statistics and research data as well as expert judgements have been used in derivation of the input data, and on average the data used in the calculations is considered to be of moderate confidence level.

The close linkage to the natural processes and the varying conditions of the emission sources mean that the uncertainties in these emission estimates are significant. Better understanding of the processes and conditions which influence the emissions and improved statistics on the input data needed in the calculations, will improve the emission estimates in time. The uncertainties will, however, still be higher than for estimates on industrial and other technology linked emissions in general.

In the future the distinction between natural and anthropogenic emissions will be even more complicated. The emissions derive mainly from microbial processes, which are enhanced by human activities. Microbial activities are by rule more intense in elevated temperatures. Global warming will also enhance the emissions from natural sources.

Energy production and use also cause emissions of CH_4 and N_2O. These emissions have been estimated with energy system models that are developed to produce the national estimates of other air pollutants (CO_2, SO_2 and NO_x etc.) in Finland. The models include a very detailed description of the energy system, fuels used and technologies applied, and cover the energy sector well. The emission factors for CH_4 and N_2O emissions are not, however, of the same accuracy as those for the other mentioned pollutants. Better knowledge of the processes, which cause the emissions and more plant scale measurements, are needed to improve the inventories. The same line of thought applies for the N_2O emissions from the industrial sources.

CFCs and the other halocarbons addressed in this thesis are used mainly in technical applications like refrigeration, as foam-blowing agents, industrial solvents and cleaning agents. The Finnish CFC emission estimates are based on the consumption of the substances in the various applications taking into account production losses, emissions during filling, maintenance and repair of equipment and the mean lifetime of the substances in the products and equipment. The assumptions used in the calculations cause uncertainties in the timing of the emissions. In the total emission estimates most of the uncertainties are due to uncertainties in the historical data on consumption of the substances in Finland. None of the studied halocarbons are manufactured in Finland, and the consumption amounts are based on import figures.

The environmental impact analyses require long time series of emission data for pollutants that persist long in the atmosphere or have other long-lasting or accumulative environmental impacts. Also the timing of the emissions is of importance to the environmental impacts studied. Both past and future emissions are known with less accuracy than current emissions. The estimates on the past emissions are based on statistics and other official sources when data has been available. Otherwise they have been estimated proportional to population, industrial production, urbanisation ratio and other known characteristic parametres.

The estimates on the future emissions should not be viewed as forecasts but as alternative scenarios under various defined presumptions of changes in the volume and structure of the emission sources. The future emissions are by rule viewed in two scenarios: the base and the reduction scenarios. The base scenarios reflect the expected volume and structural changes of the emission sources including the impact of existing environmental policies and plans. Official projections have been used when available in the definition of the scenarios. In the reduction scenarios the possibilities to further reduce the emissions by new reduction measures are assessed.

The estimates on mitigation potential and costs presented in this thesis are calculated using mean values of emissions, control potential and costs on a national level, and do therefore not apply to site-specific emission reduction projects.

Decision-making also needs data on what the impact of the control measures will be on other emissions and other environmental detriments. The study on the greenhouse impact of alternative waste treatment chains shows the importance of more holistic analyses even if it deals with the mitigation of only one environmental problem. The study shows that the greenhouse impact of waste management can be lowered substantially through energy use of waste. Combining the results of the study with studies on other environmental impacts of waste management will provide decision-making on future waste management strategies with useful knowledge.

The environmental impacts of the air pollutants addressed in this study vary. NH_3 has an impact on acidification and eutrophication, all the other gases are greenhouse gases and some of them also have an impact on ozone depletion. The studies, which are the basis of this thesis, have dealt mainly with acidification and global warming. The impacts have been calculated with models developed at VTT for national purposes, and they are not as detailed and sophisticated as regional and global impact models. Regardless of this, the impact assessment models provide tools with which the impacts of the different pollutants can be assessed with adequate accuracy.

5.2 ISSUES FOR FURTHER STUDIES

The NH_3 emissions have been estimated using methodologies developed originally by Buijsman et al. (1985 and 1986). The newest estimation model takes well into account the emissions in the different stages of waste treatment chain and the abatement measures already in use. The estimated evaporation of ammonia in the different stages as well as the effectiveness of the reduction measures are still largely based on experimental data from central Europe (Buijsman et al. 1986; ApSimon 1994; UN ECE 1996 etc.).

The Finnish climate, soil characteristics and agricultural practices differ much from those in central Europe and more measurements corresponding to the special conditions in Finnish agriculture would be needed to validate the estimated emissions and emission reduction potentials. More experimental data on the impact of the long storage period of livestock manure in Finnish climate conditions on the emissions would be an especially valuable input. Also measurements on the effectiveness of different kinds coverings and drying agents in reducing the emissions from storage of dry manure are needed.

The inventories on CH_4 and N_2O have been estimated in accordance with the IPCC methodologies (OECD 1991; IPCC Guidelines 1995; Revised IPCC 1996 Guidelines 1997) with some minor deviations. Even though the IPCC methodologies aggregate the current scientific understanding of the emissions in a commendable way they are still tentative and under development. One important issue for improvement in guidelines in view of the Finnish CH_4 and N_2O emission estimates would better and more consistent methodologies to account for the influence of climate on the emissions.

The CFC and other halocarbon emissions have been estimated with methodologies derived from international and national literature. The estimation methodologies are similar to those given in the Revised IPCC 1996 Guidelines (1997) for emissions related to the consumption of halocarbons. Only estimates of the potential emissions of HFCs in Finland have been estimated. In view of the growing importance of the HFC emissions also the actual emissions should be estimated. The HFC emission scenarios should also be updated to better correspond to current prospects of growth in the emission producing sectors.

Even if the estimates on the potential to control the emissions are rough, they are estimated to be adequate background material for setting preliminary targets for mitigation of the emissions. Before the establishment of emission reduction strategies in the sectors concerned the impact of the reduction measures on other environmental emissions should be estimated, however.

In the energy sector the measures to reduce the CO_2 emissions are the most important in the mitigation of global warming. In order to find the most efficient and cost-effective reduction measures the impacts on the CH_4 and N_2O emissions should, however, be included in the analyses on mitigation and taken into account in the decision-making. The knowledge on the N_2O emissions from the new combustion technologies and the possibilities to control them needs, however, to be improved. Especially measured data from existing plants are needed.

In agriculture the greenhouse gas and acidifying emissions, and also emissions to surface and ground waters, are interdependent and integrated environmental analyses on the impacts of emission reduction are even more important. Similar approaches as used in the study on the impact of waste management alternatives on the greenhouse gas emissions could be used to evaluate the possibilities of greenhouse gas emission reduction in the energy sector and in agriculture, and the results should be combined with research on the other environmental impacts.

6 CONCLUSIONS

The main source of NH_3 emissions is livestock manure. Since 1990 the emissions in Finland have decreased as emission reducing measures have been implemented increasingly on a voluntary basis, and also because the cattle population has been declining. In Finland the NH_3 emissions are small compared to the total acidifying emissions. The impact of the NH_3 emissions to acidifying deposition in Finland is more important though, as a larger part of the NH_3 emissions than of the other acidifying emissions is deposited near the emission sources.

The study on economic reduction of acidifying deposition in Finland by decreasing emissions in Finland, Estonia and Russia concluded that many of the reduction measures for ammonia emissions are cost-effective in mitigating acidification and that by reducing the NH_3 emissions some of the more costly measures needed to reduce SO_2 and NO_x emissions could be avoided.

Finnish CH_4 emissions come mainly from landfills and agricultural sources (enteric fermentation and livestock manure). Other CH_4 sources in Finland are wastewater treatment, energy production and use and industry but their significance is minor.

The potential to reduce the CH_4 emissions is estimated to be good. In the recent study it is estimated that the CH_4 emissions could be reduced by approximately 30 per cent with measures mainly aimed at waste treatment. These measures are also largely cost-effective. Landfill gas recovery offers an option to reduce the emissions significantly at negligible cost if the energy produced can be utilised in electricity and/or heat production. The potential to reduce the emissions from enteric fermentation in Finland are not known. If measures to reduce these emissions prove efficient and economically promising in future studies, the total reduction in the Finnish CH_4 will be higher and in the long run the halving of the emission level of 1990 seems achievable.

Although the N_2O emissions in Finland are considerably smaller than the CH_4 emissions the greenhouse impact of the N_2O emissions if of similar magnitude as that of the CH_4 emissions. The most important Finnish N_2O emission sources are use of nitrogen fertilisers, nitric acid production and energy production and use. The importance of the N_2O emissions is estimated to increase as emissions from energy production and transportation are assessed to grow with increased use of fluidized bed combustion in energy production and catalytic converters in cars in the near future. The otherwise environmentally friendly technologies produce significantly more N_2O than the corresponding conventional technologies.

Measures for N_2O emission control are not known very well and many of the measures are still at an experimental stage. Promising measures to reduce the N_2O emissions from nitric acid production and fluidized bed combustion have been put forward but plant scale applications of the measures are still lacking. If the measures can be realised and implemented on plant scale, emission reductions of the same order of magnitude as the estimated growth in the N_2O emissions is anticipated.

The CFCs and other considered halocarbons are already partly phased out. The halocarbons that destroy stratospheric O_3 are subject to regulations under the Montreal protocol, and in Finland most of the consumption ceased in 1996. The O_3 depleting substances have been partly substituted with substances that are effective greenhouse gases, the most important of which are the HFCs. The emission estimates and impact analyses suggest that the HFCs could be of importance in the next century if the emissions were allowed to grow unrestricted.

The importance of the Finnish non-CO_2 greenhouse gas emissions to anthropogenic greenhouse impact caused by Finnish emissions is significant. Calculated with GWP-values (time horizon 100 years) the greenhouse impact of the anthropogenic non-CO_2 greenhouse gas emissions is about 30 per cent of that caused by the CO_2 emissions in Finland. In the future the impact caused by the CO_2 emissions will grow in importance compared with the non-CO_2 greenhouse gases. The growing emissions of N_2O and HFCs and their importance to the global warming should, however, not be left without notice as their removal from the atmosphere is very slow.

Acidification and global warming, as well as ozone depletion are complicated environmental problems. This thesis pursues to enlighten the role of NH_3, CH_4, N_2O, CFCs and some other halocarbon emissions to problems from a Finnish perspective. The knowledge on both the emissions and impacts is still in many aspects uncertain. In the future research efforts are needed to enlarge and complete our understanding on the subject. Regional and global assessments are vital in estimating the extent of the problems and establishing international environmental policies to mitigate them. As the conditions and characteristics of the emission sources vary from country to country, studies like the ones presented in this thesis are of importance in the decision-making on national scale.

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