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International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

Interim Report **IR-05-055**

The GAINS Model for Greenhouse Gases – Version 1.0: Nitrous Oxide (N_2O)

Wilfried Winiwarter

Approved by

Markus Amann
Program Leader
Transboundary Air Pollution Program
(amann@iiasa.ac.at)

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Abstract

Many of the traditional air pollutants and greenhouse gases have common sources, offering a cost-effective potential for simultaneous improvements of traditional air pollution problems and climate change. A methodology has been developed to extend the RAINS integrated assessment model to explore synergies and trade-offs between the control of greenhouse gases and air pollution. With this extension, the GAINS (**G**HG-**A**ir pollution **IN**teraction and **S**ynergies) model will allow the assessment of emission control costs for the six greenhouse gases covered under the Kyoto Protocol (CO_2, CH_4, N_2O and the three F-gases) together with the emissions of air pollutants SO_2, NO_x, VOC, NH_3 and PM. This report describes the first implementation (Version 1.0) of the model extension model to incorporate N_2O emissions.

GAINS Version 1.0 assesses the options for reducing N_2O emissions from the various source categories. It quantifies for 43 countries/regions in Europe country-specific application potentials of the various options in the different sectors of the economy, and estimates the societal resource costs of these measures. Mitigation potentials are estimated in relation to an exogenous baseline projection that is considered to reflect current planning.

In Europe, emissions from soils are generally considered the most important source of N_2O, followed by industrial process emissions. Formation of nitrous oxide in soil is triggered by the availability of nitrogen. A number of emissions controls directed at other pollutants (e.g., NO_x or CH_4) have positive or negative impacts on N_2O emissions. Some of the earlier projections of N_2O emissions have not taken full account of these interactions. Recent information on technological changes (e.g., for some technological processes) indicates a significant decline in N_2O emissions in the past years, especially from adipic and nitric acid production.

Catalytic reduction of N_2O from industrial processes (adipic and nitric acid production), optimizing sewage treatment, modifications in fluidized bed combustion, and reduction of fertilizer application in agriculture can reduce N_2O at moderate costs. Current legislation in EU countries addresses only some of these measures, which leaves an additional potential for further mitigation. However, the remaining mitigation potential is associated with high or even excessive costs. N_2O emissions from non-agricultural soils induced from the atmospheric deposition of NO_x and NH_3, though of clearly anthropogenic origin, have not been counted as anthropogenic emissions by the Intergovernmental Panel on Climate Change (IPCC) methodology. However, the inclusion of such emissions to obtain full coverage of man-made N_2O flows would not strongly alter N_2O emissions from European countries.

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About the author

Wilfried Winiwarter works in the Transboundary Air Pollution program of the International Institute for Applied Systems Analysis (IIASA). He is also affiliated with Vienna-based ARC systems research, a subsidiary of the Austrian Research Centres in Seibersdorf. His main scientific interests cover the emissions of air pollutants and trace constituents and their chemical transformations in the atmosphere.

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1 Introduction

1.1 Interactions between air pollution control and greenhouse gas mitigation

Recent scientific insights open new opportunities for an integrated assessment that could potentially lead to a more systematic and cost-effective approach for managing traditional air pollutants simultaneously with greenhouse gases. These include:

- Many of the traditional air pollutants and greenhouse gases (GHG) have common sources, offering a cost-effective potential for simultaneous improvements for both air pollution problems and climate change. For instance, climate change measures that aim at reduced fossil fuel combustion will have ancillary benefits for regional air pollutants (Syri *et al.*, 2001). In contrast, some ammonia abatement measures can lead to increased nitrous oxide (N_2O) emissions. Structural measures in agriculture could reduce both regional air pollution and climate change. Methane (CH_4) is both an ozone (O_3) precursor and a greenhouse gas. Hence, CH_4 abatement will have synergistic effects and some cheap abatement measures may be highly cost effective.
- Some air pollutants (e.g., tropospheric ozone and aerosols) are also important greenhouse gases and exert radiative forcing. As summarized by the Intergovernmental Panel on Climate Change (IPCC), changes in tropospheric ozone were found to have the third-largest positive radiative forcing after carbon dioxide (CO_2) and CH_4 (Houghton *et al.*, 2001), while sulphate aerosols exert negative forcing. Furthermore, understanding is growing on the role of carbonaceous aerosols, suggesting warming effects for black carbon and cooling effects for organic carbon.
- Other air pollutants such as ozone, nitrogen oxides (NO_x), carbon monoxide (CO) and volatile organic compounds (VOC) act as indirect greenhouse gases influencing (e.g., via their impact on OH radicals) the lifetime of direct greenhouse gases (e.g., CH_4 and hydrofluorocarbons). Global circulation models have only begun to incorporate atmospheric chemistry and account fully for the important roles of conventional air pollutants.

It is clear that interactions between air pollutants and radiative forcing can be multiple and can act in opposite directions. For instance, increases in NO_x emissions decrease (via OH radicals) the lifetime of CH_4 in the atmosphere and thereby cause reduced radiative forcing. At the same time, NO_x emissions produce tropospheric ozone and increase radiative forcing. A further pathway leads to increased nitrogen deposition that may cause, via the fertilisation effect, enhanced growth of vegetation. This in turn offers an increased sink for carbon – although the net effect cannot yet be fully quantified.

Time is an important factor in the context of mitigation. While the climate change benefits (i.e., temperature stabilization) take effect on the long-term, reduced air pollution will also yield benefits for human health and vegetation in the short and medium terms.

1.2 GAINS: The RAINS extension to include greenhouse gases

The Regional Air Pollution INformation and Simulation (RAINS) model has been developed at the International Institute for Applied Systems Analysis (IIASA) as a tool for the integrated assessment of emission control strategies for reducing the impacts of air pollution. The present version of RAINS addresses health impacts of fine particulate matter and ozone, vegetation damage from ground-level ozone as well as acidification and eutrophication. To explore synergies between these environmental effects, RAINS includes emission controls for sulphur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOC), ammonia (NH_3) and fine particulate matter (PM).

Considering the new insights into the linkages between air pollution and greenhouse gases, work has begun to extend the multi-pollutant/multi-effect approach that RAINS presently uses for the analysis of air pollution to include emissions of greenhouse gases (GHG). This could potentially offer a practical tool for designing national and regional strategies that respond to global and long-term climate objectives (expressed in terms of greenhouse gas emissions) while maximizing the local and short- to medium-term environmental benefits of air pollution. The emphasis of the envisaged tool is on identifying synergistic effects between the control of air pollution and the emissions of greenhouse gases. The new tool is termed ‘GAINS’: **G**HG-**A**ir pollution **IN**teractions and **S**ynergies. It is not proposed at this stage to extend the GAINS model towards modelling of the climate system.

1.3 Objective of this report

The objective of this report is to describe a first version of the GAINS model (Version 1.0) related to emission control options for N_2O and associated costs. Other reports have been prepared for the other five Kyoto greenhouse gases (CO_2, CH_4, HFCs PFCs, SF_6) and are available on the Internet (http://www.iiasa.ac.at/rains/gains/index.html).

The emission assessment presented in this report is based on the Intergovernmental Panel on Climate Change (IPCC) guidelines proposed by Houghton *et al.* (1997). Part of the approach, especially for those sources where sufficient information was available, has already been reported previously (Klaassen *et al.*, 2004). This paper includes all sources, specifically emissions from soils. While the available information on N_2O emissions from soils is still very scarce, a number of studies are expecting completion in the near future. The approach presented here allows a first evaluation with GAINS 1.0, but remains open to future improvements of the algorithm.

This report has the following structure: Section 2 describes the general GAINS methodology and its specific application for N_2O. In Section 3, the methodology to derive emissions of N_2O is explained in detail. Section 4 reports the available options to control emissions of N_2O, and the effects of control options included in GAINS which indirectly have (side-) effects on N_2O. The interactions between N_2O emissions and other relevant emissions are discussed in Section 5. Initial results are compared with findings from other studies in Section 6, and conclusions are drawn in Section 7.

2 Methodology

2.1 Introduction

A methodology has been developed to assess, for any exogenously supplied projection of future economic activities, the resulting emissions of greenhouse gases and conventional air pollutants, the technical potential for emission controls and the costs of such measures, as well as the interactions between the emission controls of various pollutants. This new methodology revises the existing mathematical formulation of the RAINS model to take account of the interactions between emission control options of multiple pollutants and their effects on multiple environmental endpoints (see Klaassen *et al.*, 2004).

This report addresses the implementation of nitrous oxide (N_2O) and its interactions into GAINS. Accompanying reports have been prepared for methane (Höglund-Isaksson and Mechler, 2005), for the F-gases (Tohka, 2005), and for carbon dioxide (Klaassen *et al*., 2005). This section of the N_2O report first describes the basic model concept of the RAINS model for air pollution. Subsequently, the method to calculate emissions of N_2O is described, followed by the costing methodology.

2.2 The RAINS methodology for air pollution

The Regional Air Pollution Information and Simulation (RAINS) model developed by the International Institute for Applied Systems Analysis (IIASA) combines information on economic and energy development, emission control potentials and costs, atmospheric dispersion characteristics and environmental sensitivities towards air pollution (Schöpp *et al.*, 1999). The model addresses threats to human health posed by fine particulates and ground-level ozone as well as risk of ecosystems damage from acidification, excess nitrogen deposition (eutrophication) and exposure to elevated ambient levels of ozone.

These air pollution related problems are considered in a multi-pollutant context (see Figure 2.1) that quantify the contributions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), non-methane volatile organic compounds (VOC), and primary emissions of fine (PM2.5) and coarse (PM10-PM2.5) particles. A detailed description of the RAINS model, on-line access to certain model parts, as well as all input data to the model, can be found on the Internet (http://www.iiasa.ac.at/rains).

The RAINS model framework makes it possible to estimate, for any given energy and agricultural scenario, the costs and environmental effects of user-specified emission control policies. Furthermore, a non-linear optimisation model has been developed to identify the cost-minimal combination of emission controls meeting user-supplied air quality targets. This optimisation mode takes into account regional differences in emission control costs and atmospheric dispersion characteristics. The optimisation capability of RAINS enables the development of multi-pollutant, multi-effect pollution control strategies.

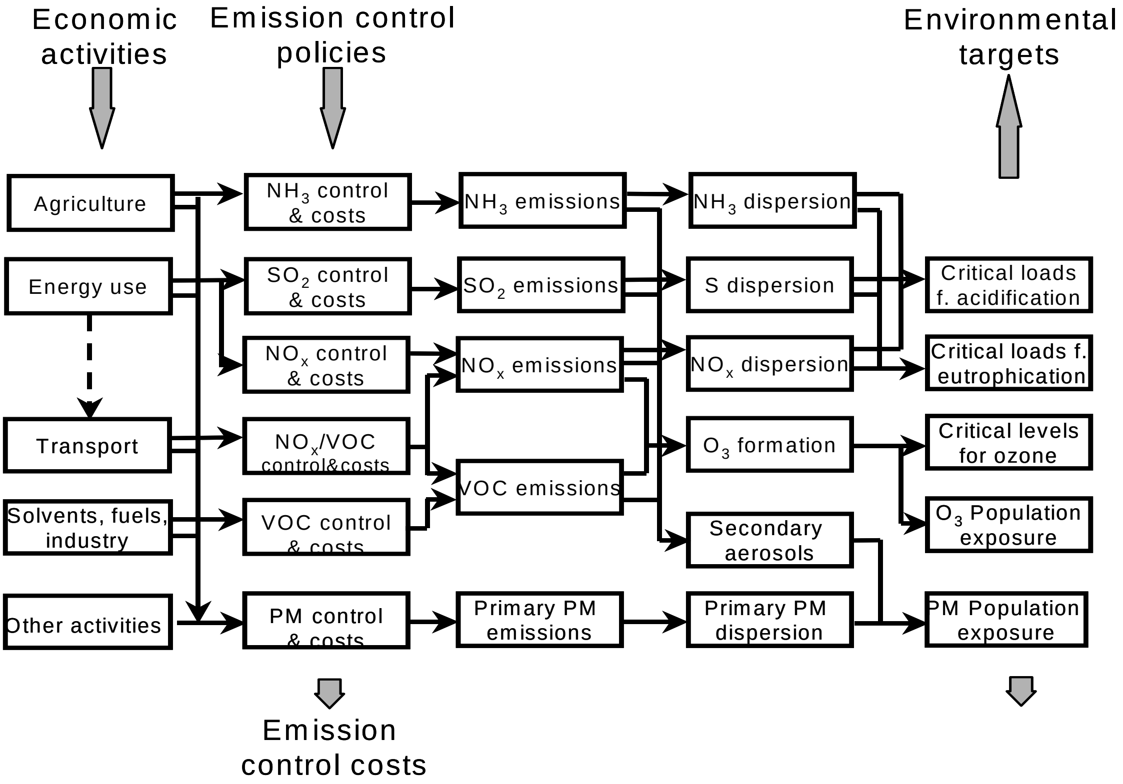

Figure 2.1: Flow of information in the RAINS model.

In particular, the optimisation can be used to search for cost-minimal balances of controls of the six pollutants (SO_2, NO_x, VOC, NH_3, primary PM2.5, primary PM10-2.5 (= coarse PM)) over the various economic sectors in all European countries that simultaneously achieve:

- user-specified targets for human health impacts (e.g., expressed in terms of reduced life expectancy),
- ecosystems protection (e.g., expressed in terms of excess acid and nitrogen deposition), and
- maximum allowed violations of World Health Organisation (WHO) guideline values for ground-level ozone.

The RAINS model covers the time horizon from 1990 to 2030, with time steps of five years. Geographically, the model covers 47 countries and regions in Europe. Five of them represent sea regions, the European part of Russia is divided into four regions, and 38 are individual countries. Overall, the model extends over Europe from Ireland to the European part of Russia (West of the Ural) and Turkey. In a north to south perspective, the model covers all countries from Norway down to Malta and Cyprus.

2.3 Emission calculation

2.3.1 Methodology for N_2O

The methodology adopted for the estimation of current and future greenhouse gas emissions and the available potential for emission controls follows the standard RAINS methodology. Emissions of each pollutant p are calculated as the product of the activity levels, the “uncontrolled” emission factor in absence of any emission control measures, the efficiency of emission control measures and the application rate of such measures:

$$E_{i,p} = \sum_{j,a,t} E_{i,j,a,t,p} = \sum_{j,a,t} A_{i,j,a} ef_{i,j,a,p} \left(1 - eff_{t,p}\right) X_{i,j,a,t} \qquad \text{Equation 2.1}$$

where

i,j,a,t,p	Subscript to denote country, sector, activity, abatement technology, and pollutant, respectively
$E_{i,p}$	Emissions of the specific pollutant p in country i,
A_j	Activity in a given sector j,
ef	“Uncontrolled” emission factor,
eff	Reduction efficiency
X	Actual implementation rate of the considered abatement.

If no emission controls are applied, the reduction efficiency equals zero ($eff = 0$) and the implementation rate is one ($X = 1$). In that case, the emission calculation is reduced to a simple multiplication of the activity rate by the “uncontrolled” emission factor.

For N_2O, the fate of emissions abatement is often connected with action taken to control other pollutants. For example, it frequently happens that after control (e.g., of NO_x emissions), N_2O emissions become higher than in the unabated case. To reflect this effect, negative reduction efficiencies would need to be used for N_2O. To avoid computational complications associated with negative reduction efficiencies, a “controlled” emission factor is used instead that describes the emission factor of a process after installation of abatement technology.

The “controlled” emission factor can then be easily derived from the “uncontrolled” emission factor and the reduction efficiency, if not available from measurements directly:

$$efc = ef\,(1 - eff) \qquad \text{Equation 2.2}$$

where

efc	“Controlled” emission factor.

An additional advantage of this approach is that emission factors of controlled processes are more directly accessible from emission measurements than reduction efficiencies. The factor is closer to the original measurement, so uncertainty and sensitivity can be determined much more easily.

For the calculation of baseline emission estimates, the "uncontrolled" emission factor is assumed to be constant over time with potential changes in activity levels as a result of exogenous and autonomous developments. For example, an increased production of nitric acid will thus result in a higher activity level and consequently in more emissions.

In GAINS, emission control scenarios start from the "controlled" emission factors of the base year, and modify them following the implementation of abatement measures assumed in the particular scenario.

2.3.2 Specific considerations for emissions from microbial processes

While the calculation procedure of N_2O from microbial processes in soils follows the same structure as in RAINS, the way activities have been selected and emission factors derived requires additional attention. The underlying processes are complex and influenced by very different anthropogenic activities. Separation of these processes is often difficult or ambiguous. Since microbial processes are assumed to be responsible for the major part of N_2O emissions, a conceptual model has been developed to capture include the main pathways of nitrogen (N) compounds leading to N_2O formation (Figure 2.2).

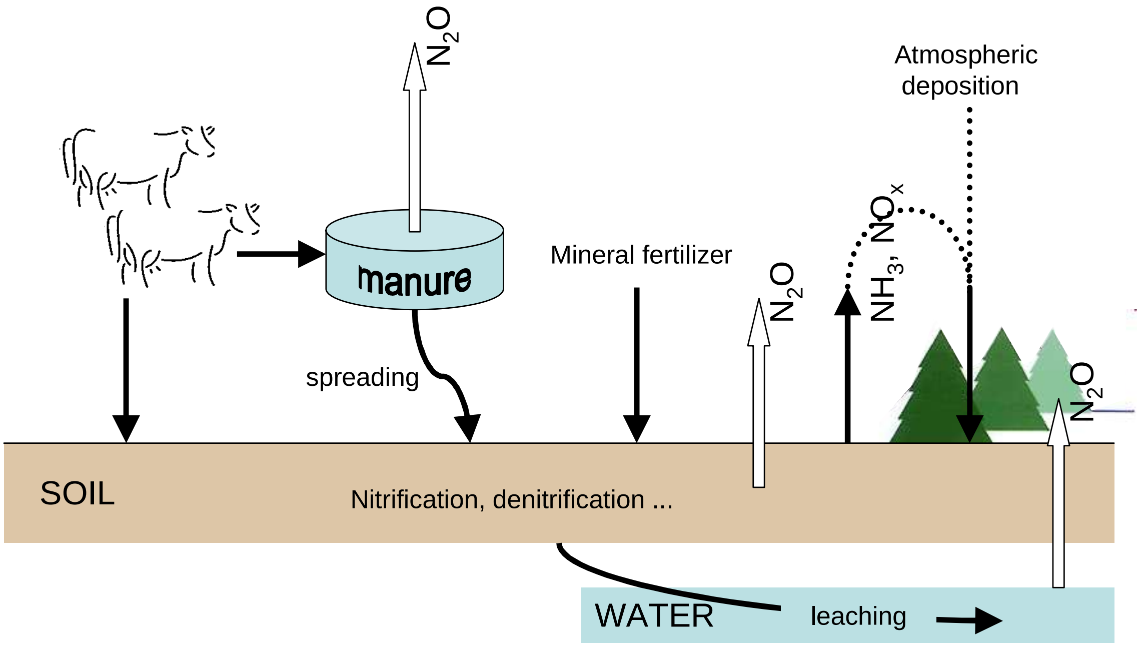

Figure 2.2: A conceptual model of N_2O emissions from agriculture and soils.

Potential sources of nitrogen derive from animal manure (direct deposition on pastures or spreading on fields after storage), mineral fertilizers, and atmospheric deposition of air pollutants (nitrates or ammonia). Molecular nitrogen, the main constituent of the atmosphere, is chemically inert and will hardly contribute, except for conversion by symbiotic bacteria in the roots of leguminous plants. Adding plant material (crop residues) to soils will also return nitrogen that conceptually had already been removed from soil. GAINS Version 1.0 does not consider other potential inputs of nitrogen to soils. These include sewage sludge that might be spread on fields, which the model treats together with sewage treatment plants (Section 3.2.7). Land use changes that will alter the composition of soil primarily affect the carbon content, so that the change of the nitrogen content (and related N_2O emissions) is considered negligible.

The fate of nitrogen in soil depends on its chemical form. Organic nitrogen is mineralized, ammonia (NH_3) undergoes nitrification to form nitrate, which itself is removed by denitrification. These are all microbial processes, and nitrification and denitrification produce N_2O as a side product. Ammonia can be stored in soil, while nitrates are washed out quickly. This makes it easier for plants to assimilate NH_3. Hence, inhibition of nitrification will keep a high availability of nitrogen for plants and prevent N_2O formation. Evaporation of nitrogen compounds and leaching will also remove nitrogen from the system, but (with the exception of molecular nitrogen, the main product of denitrification) it will remain active for subsequent conversion to N_2O (which is termed indirect emissions in the IPCC-guidelines). Assimilation of nitrogen by plants and conversion to organic nitrogen is certainly the most efficient removal pathway from the soil system.

Consequently, the fraction of nitrogen released in the form of N_2O depends on a large number of variables. These include soil properties (temperature, humidity, density, pore size, sand content, clay content, carbon content, nitrogen content, etc.), the chemical form and pathway of nitrogen input into soil, and the further fate of compounds (i.e., leaching). For simplification, the current IPCC emission reporting guidelines (Houghton *et al.*, 1997) recommend a uniform emission factor related to the nitrogen input only. The uncertainty of emission calculations based on this approach was estimated at two orders of magnitude (Houghton *et al.*, 1997). As soil emissions are considered to contribute half of N_2O emissions within the EU (Behrend *et al.*, 2004) and globally (Bouwman, 1995), or about four percent of total greenhouse gas emissions, an improved quantification has become a target for research.

The emission factors endorsed by the IPCC rely on relatively old results. For instance, Bouwman (1994) derived an emission factor for soils, between 0.25 percent and 2.25 percent of nitrogen input into soils, from 43 experiments performed globally. The original literature focuses on fertilizer induced N_2O emissions, and enhanced effects due to crop residues or atmospheric deposition (indirect effects) are only seen qualitatively. In the IPCC approach, this factor of 1.25 percent is applied to all nitrogen input, where just the evaporation of NH_3 has to be subtracted. The evaporated NH_3 is then considered specifically for calculating indirect N_2O emissions with a slightly different emission factor.

The IPCC also considers leaching of nitrate into groundwater as another source of indirect N_2O emissions. Here microbial processes are also responsible for the conversion of N leached into N_2O, – according to Houghton *et al.* (1997) 2.5 percent. A more recent literature survey (Nevison, 2000) indicates that this emission factor is probably significantly lower and the treatment of indirect emissions from groundwater will have to be adapted in the near future.

The availability of organic carbon as an energy source is an important factor that influences the activity of soil microbes in N_2O production. The current IPCC methodology recognizes this as the only soil related parameter. Emissions from agriculturally used carbon-rich soils (histosols) are assessed according to the agricultural area concerned, independent of nitrogen input.

For GAINS, the IPCC emission factor is used as a default option, in absence of more detailed information. However, as discussed above, improved approaches are either already available or are expected to become available in the near future.

To allow for future improvements, GAINS is constructed in a modular way so that new information can replace the default methodologies where and when available. For instance, instead of using the amount of nitrogen input as the only model parameterisation, emission factors per land area could be assigned to a number of land use classes. Such “effective emission factors”, can then be derived from:

- the default IPCC emission factor (if no better information is available),
- a simple empirical relationship between N_2O emissions and driving parameters, or
- a process-orientated model describing in detail the activities in soil (optimum solution).

2.3.3 Converting land-use information for application in GAINS emission factors

For its emissions and cost calculations, GAINS applies a spatial resolution of individual countries (or a limited number of sub-national regions for the largest countries) so that it holds average emission factors for these spatial units. In practice, however, many of the factors determining N_2O emissions show high variability at the small scale that can be captured by high resolution data.

Sub-national information can be used to assess total emissions for a specific source in a country. For deriving data that are representative for aggregates such as entire countries, it is crucial that for non-linear mechanisms or model systems parameters cannot be simply averaged. In such cases, calculations must be carried out at the highest level of resolution, and only then can the results be aggregated into national data. With this approach, internationally uniform emission factors for individual land use categories will result in different country-specific average emission factors, reflecting different composition of land use classes in the various countries. Such a calculation needs to be performed outside the GAINS model, and GAINS will then consider these country-specific emission factors.

In many cases, underlying information is only available at different geographical resolutions or projections. Such datasets need to be matched by intersecting the respective geographical grids using a geographical information system and applying a weighted average procedure to bring information mostly from the finer to the coarser grid. For the GAINS Version 1.0 assessment, three datasets with two different resolutions have been merged. Land use information from the European CORINE activity has been converted into the EMEP 50 x 50 km^2 grid system (Slooteweg, 2004). Deposition data is available for the same EMEP grid system (Tarasson, 2003). Soil data was taken from the ISRIC 0.5° x 0.5° global database (Batjes, 2003) and have been converted to the EMEP grid system. Cell sizes and respective positions of the grid systems in relation to the national boundaries are shown in Figure 2.3.

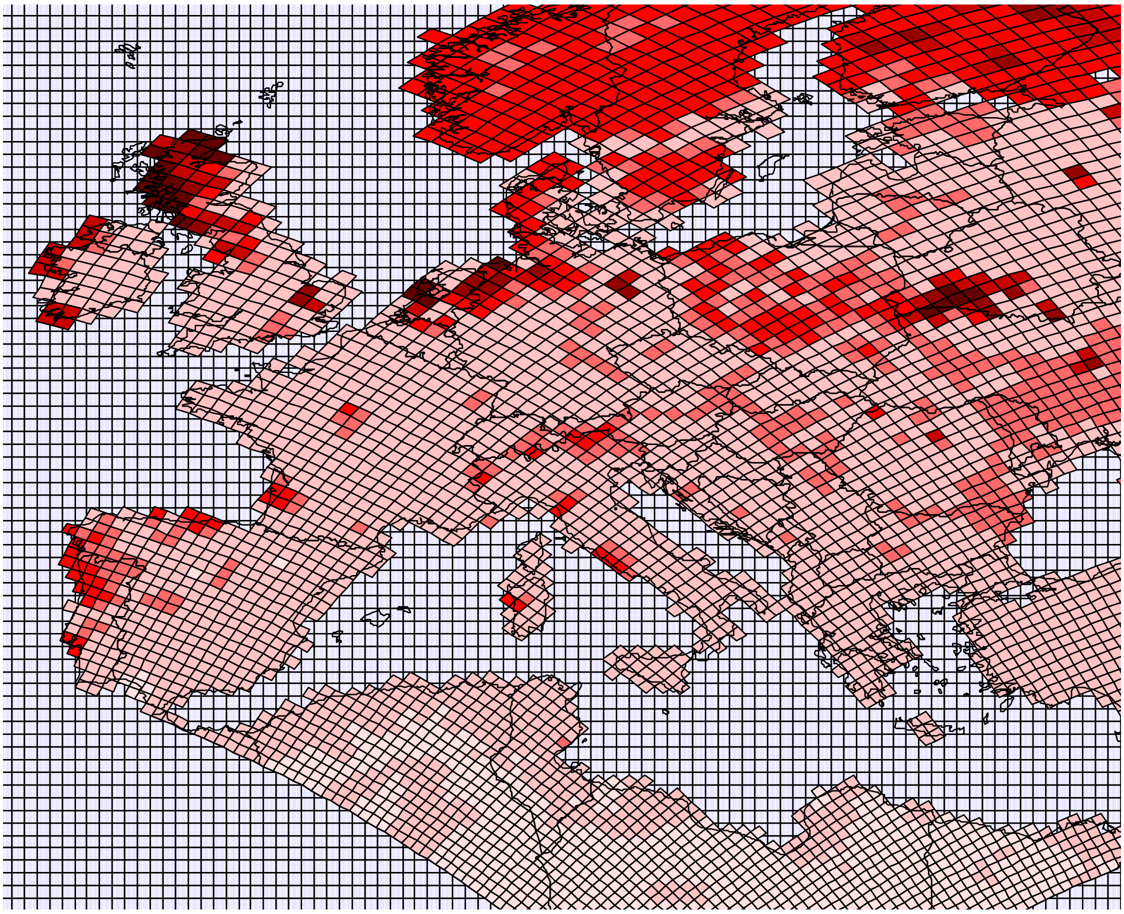

Figure 2.3: Excerpt of a thematic map of Europe. In this example, organic carbon concentrations in soil (a driving parameter of soil microbial activity) are overlaid on the EMEP grid system. ISRIC grid cells are shown where no information on soil properties is available (e.g., for sea areas) and outside the EMEP domain.

2.4 Cost calculation

In principle, GAINS applies the same concepts of cost calculation as the RAINS model to allow consistent evaluation of emission control costs for greenhouse gases and air pollutants. The methodology is described in full details in Klaassen *et al.* (2005). The cost evaluation in the RAINS/GAINS model attempts to quantify the values to society of the resources diverted to reduce emissions in Europe (Klimont *et al.*, 2002). In practice, these values are approximated by estimating costs at the production level rather than at the level of consumer prices. Therefore, any mark-ups charged over production costs by manufacturers or dealers do not represent actual resource use and are ignored. Any taxes added to production costs are similarly ignored as subsidies since they are transfers and not resource costs.

A central assumption in the RAINS/GAINS cost calculation is the existence of a free market for (abatement) equipment throughout Europe that is accessible to all countries at the same conditions. Thus, the capital investments for a certain technology can be specified as being independent of the country. The calculation routine takes into account several country-specific parameters that characterise the situation in a given region. For instance, these parameters may include average operating hours, fuel prices, capacity/vehicles utilization rates and emission factors. The expenditures for emission controls are differentiated into:

- investments,
- fixed operating costs,
- variable operating costs, and
- transaction costs.

From these elements RAINS/GAINS calculates annual costs per unit of activity level. Subsequently, these costs are expressed per metric ton of pollutant abated. Some of the parameters are considered common to all countries. These include technology-specific data, such as removal efficiencies, unit investment costs, fixed operating and maintenance costs. Parameters used for calculating variable cost components such as the extra demand for labour, energy, and materials are also considered common to all countries.

Country-specific parameters characterise the type of capacity operated in a given country and its operation regime. They include the average size of installations in a given sector, operating hours, annual fuel consumption and mileage for vehicles. In addition, the prices for labour, electricity, fuel and other materials as well as cost of waste disposal also belong to this category. Transaction costs are country-specific since they describe costs of diverse activities such as training or even information distribution required for implementation of an abatement option. All costs in RAINS/GAINS are expressed in constant € (in prices of the year 2000).

As emission abatement of N_2O occurs in many cases as a side-effect of emission control measures directed at other pollutants, care needs to be taken to avoid double-counting of the costs since costs of these measures are accounted for in other GAINS modules. For the few measures that are directly related to N_2O emissions, cost calculation has been simplified by representing total costs through variable operating costs only, for which data have been taken from the literature (Section 4). Due to a lack of solid information on which calculations could be based upon, GAINS Version 1.0 does not distinguish differences in emission control costs (per ton of N_2O) across countries. However, it considers differences in the applicability of specific abatement measures.

3 Nitrous Oxide (N_2O)

Nitrous oxide (N_2O) is a very stable compound in the atmosphere. With a mean lifetime of 120 years (Seinfeld and Pandis, 1998), emissions will have an effect on the global concentrations in the atmosphere for many decades. As N_2O is able to strongly absorb infrared light, it also exerts a considerable effect on the earth’s radiation budget. On a scale of 100 years, its global warming potential (GWP) is considered 296 times that of the same mass of carbon dioxide (Houghton *et al.,* 2001). Consequently, fairly small concentrations of this gas are sufficient to make it an important greenhouse gas. At current estimates, it contributes about seven percent of the greenhouse gas emissions in terms of the GWP, which is somewhat less than half of that of methane. As a result, among the gases considered by the Kyoto Protocol, N_2O is ranked third in importance behind carbon dioxide (CO_2) and methane (CH_4).

Atmospheric concentrations of N_2O have increased since pre-industrial times from a high natural background. The observed increase of only 15 percent is the smallest of all the Kyoto gases. N_2O is to a large extent a by-product of biological processes that occur in soils over large areas of land (see Section 2). For these two reasons, anthropogenic emissions of N_2O only lead to small concentration increments over the natural background, which are difficult to track by measurements. The soil processes themselves are poorly understood and associated with high uncertainty. On a national scale, soil N_2O was clearly identified as the largest single contribution to overall uncertainty of the greenhouse gas inventory (Winiwarter and Rypdal, 2001).

3.1 Emission source categories

Greenhouse gas emissions are released from a large variety of sources with significant technical and economic differences. Conventional emission inventory systems, such as the inventory of the United Nations Framework Convention on Climate Change (UNFCCC), distinguish several hundreds of different processes causing various types of emissions.

In the ideal case, the assessment of the potential and costs for reducing emissions should be carried out at a very detailed process level. In reality, however, the objective to assess abatement costs for a large number of countries, as well as the focus on emission levels in 10 to 20 years from now, restricts the level of detail that can be meaningfully maintained. While technical details can be best reflected for individual (reference) processes, the accuracy of estimates on an aggregated national level for future years will be seriously hampered by a general lack of reliable projections of many of the process-related parameters, such as future activity rates or autonomous technological progress.

For an integrated assessment model focusing on the continental or global scale, it is imperative to aim at a reasonable balance between the level of technical detail and the availability of meaningful data describing future development, and to restrict the system to a manageable number of source categories and abatement options. For the GAINS greenhouse gas module, an attempt was made to aggregate the emission producing processes into a reasonable number of groups with similar technical and economic properties. Considering the intended purposes of integrated assessment, the major criteria for aggregation were:

- The importance of the emission source. It was decided to target source categories with a contribution of at least 0.5 percent to the total anthropogenic emissions in a particular country.
- The possibility of defining uniform activity rates and emission factors.
- The possibility of constructing plausible forecasts of future activity levels. Since the emphasis of the cost estimates in the GAINS model is on future years, it is crucial that reasonable projections of the activity rates can be constructed or derived.
- The availability and applicability of “similar” control technologies.
- The availability of relevant data. Successful implementation of the module will only be possible if the required data are available.

It is important to carefully define appropriate activity units. They must be detailed enough to provide meaningful surrogate indicators for the actual operation of a variety of different technical processes, and aggregated enough to allow a meaningful projection of their future development with a reasonable set of general assumptions.

The literature provides global and national estimates of nitrous oxide (N_2O) emissions by source category. As a contribution to the Global Emissions Inventory Activity (GEIA) project, a compilation of world-wide emission sources has been performed (Bouwman, 1995). Based on this experience, Houghton *et al.* (1997) have published guidelines to assess national emission estimates for N_2O. For the European Union (EU), national estimates have been compiled from national submissions of the Member States to the UNFCCC (Behrend *et al.*, 2004, Figure 3.1). This overview provides a first indication of the most important contributors to N_2O emissions in Europe. According to this estimate the dominant source is agriculture, in particular emissions from soils. Other important sources are transport and industrial processes.

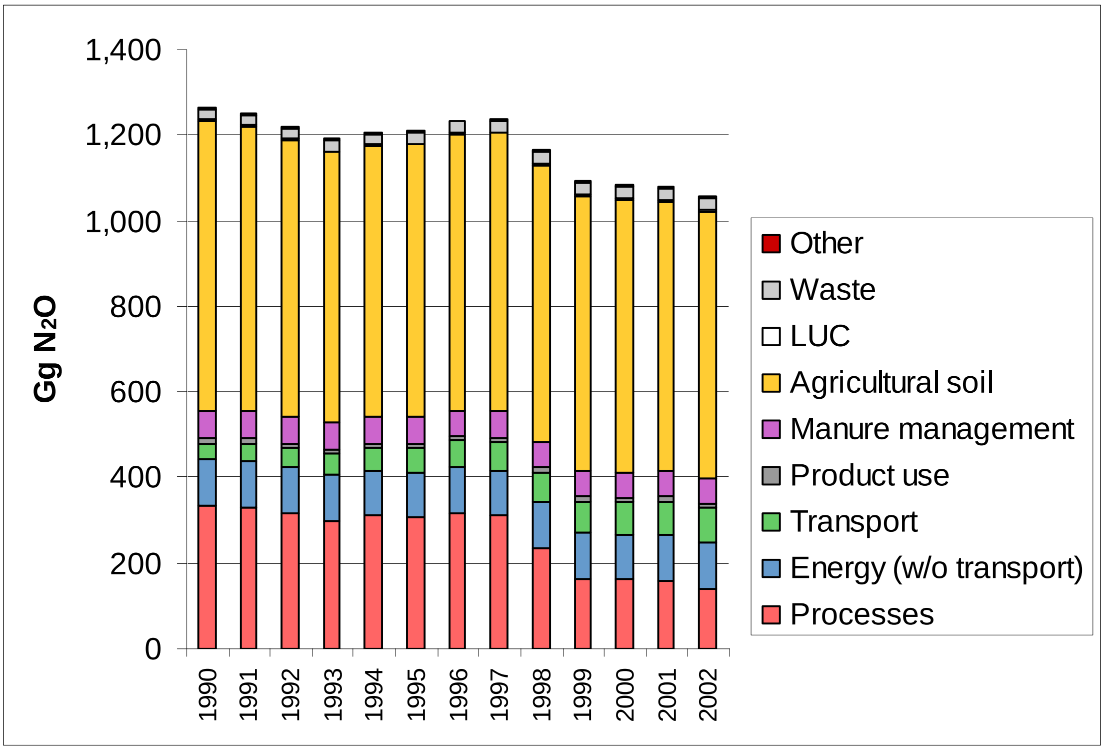

Figure 3.1: Nitrous oxide (N_2O) emissions from the EU-15 in the year 2000 (Behrend *et al.*, 2004) [Gg/yr or kt/yr].

For GAINS Version 1.0, it has been decided to distinguish the following eight source categories for N_2O:

- Industrial processes
- Combustion in industry and power plants
- Transport
- N_2O use
- Agricultural soils
- Animal manure
- Sewage treatment plants
- Other soil emissions

Table 3.1 lists the associations of the GAINS sectors with the categories of the UNFCCC emission inventory.

The following section (Section 3.2) will describe the GAINS implementation for N_2O for each of these source sectors. It will discuss side-impacts of emission control measures directed at other pollutants on N_2O emissions, but will not go into detail on their cost calculations, since these are included in other modules of the RAINS/GAINS modelling system. N_2O-specific mitigation options will be covered in Section 4.

Table 3.1: Assignment of GAINS source sectors to UNFCCC sectors

GAINS sector	*UNFCCC*	*GAINS sector*	*UNFCCC*
AGR_BEEF	4B_manure	PP_NEW	1A1_energy
AGR_COWS	4B_manure	PP_NEW1	1A1_energy
AGR_OTANI	4B_manure	PP_NEW2	1A1_energy
AGR_PIG	4B_manure	PP_NEW3	1A1_energy
AGR_POULT	4B_manure	PR_ADIP	2B_processes
ARABLE_SUBB	4D_soils	PR_NIAC	2B_processes
ARABLE_TEMP	4D_soils	TRA_OT	1A3_transport
CON_COMB	1A1_energy	TRA_OTS	1A3_transport
DOM	1A4_other	TRA_OTS_L	1A3_transport
FOREST	Forest_indir	TRA_OTS_M	1A3_transport
GRASSLAND	4D_soils	TRA_OT_AGR	1A3_transport
HISTOSOL	4D_soils	TRA_OT_AIR	1A3_transport
IN_BO	1A2_industry	TRA_OT_CNS	1A3_transport
IN_BO1	1A2_industry	TRA_OT_INW	1A3_transport
IN_BO2	1A2_industry	TRA_OT_LB	1A3_transport
IN_BO3	1A2_industry	TRA_OT_LD2	1A3_transport
IN_OC	1A2_industry	TRA_OT_LF2	1A3_transport
IN_OC1	1A2_industry	TRA_OT_RAI	1A3_transport
IN_OC2	1A2_industry	TRA_RD	1A3_transport
IN_OC3	1A2_industry	TRA_RDXLD4	1A3_transport
N_2O_USE	3D_solvents	TRA_RD_HD	1A3_transport
PP_EX_OTH	1A1_energy	TRA_RD_LD2	1A3_transport
PP_EX_OTH1	1A1_energy	TRA_RD_LD4	1A3_transport
PP_EX_OTH2	1A1_energy	TRA_RD_LF2	1A3_transport
PP_EX_OTH3	1A1_energy	TRA_RD_M4	1A3_transport
PP_EX_WB	1A1_energy	WASTE_SEW	6B_Waste

3.2 Activity data and emission factors

3.2.1 Industrial processes

Nitrous oxide is formed in processes that involve nitric acid, especially when nitric acid is used as an oxidant. This is the case for the production of adipic acid, a chemical used for Nylon® production. Emissions from this process are large, typically 0.3 ton per ton product (de Soete, 1993). Only few installations in four EU-15 countries (Germany, France, Italy and UK) make up for a significant part of total EU-15 N_2O emissions. Adipic acid production, albeit at a smaller scale, is also performed in Europe outside the EU-15. According to the EDGAR database (Olivier, personal information), Poland produced adipic acid up to the early 1990s, and some production continues in Romania and the former Soviet Union.

According to the Russian and the Ukrainian national communications to UNFCCC (http://unfccc.int/resource/natcom/nctable.html), there are only two plants in the area of the former Soviet Union, which are located in the Ukraine. Since the quantity of emissions cannot be determined from these national reports, data from EPA (2001) were used, even if this report erroneously attributed adipic acid production in the former Soviet Union to Russia. For GAINS Version 1.0, the official Romanian figure has been subtracted from the number given by EPA for Eastern Europe, assuming that the remaining production takes place in the Ukraine. The second significant source is the production of nitric acid.

Production statistics and projections are part of the RAINS databases, and the emission factor given in Table 3.2 is applied for GAINS. It is possible to control N_2O emissions from adipic acid and from nitric acid production with specific technology. The associated efficiencies, costs and application potentials are further described in Section 4.

Table 3.2: Calculation of nitrous oxide (N_2O) emissions from industrial processes in GAINS. The emission factor marked with "ANY" will be applied to all sectors/activities/technologies other than the combinations specifically mentioned (including technologies aimed at reducing NO_x or other pollutants).

GAINS sectors	PR_ADIP PR_NIAC	Adipic acid production (NEW) Industry - Process emissions - Nitric acid plants		
Activity rate	Production			
Unit	Mt product			
Data sources	Nitric acid production is taken from the RAINS-Europe database. Adipic acid production is derived from the national communications to the UNFCCC (only applicable for DE, FR, IT, UK, RO, and UA; no production in other European countries).			
Emission factors	Sector	Activity	Abatement technology	Emission factor [kt N_2O/Mt product]
	Adipic acid production	Production	No control	300.0
	Nitric acid plants	Production	ANY	5.7
Data sources	de Soete (1993)			

3.2.2 Combustion in industry and power plants

Certain emissions of N_2O emerge from combustion in industry and power plants. Emissions from conventional boilers are rather low, but they can increase if nitrogen oxide (NO_x) control technologies are applied. Specific options are available to reduce N_2O emissions in these cases. Fluidised bed combustion (FBC) operates at different combustion conditions, especially at lower temperature and longer residence time of combustion gases, which inhibits NO_x formation. Selective non-catalytic reduction of NO_x (SNCR) with ammonia (NH_3) or urea as reducing agent converts NO_x in the plume. Both options favour the formation of N_2O.

De Soete (1993) reports a dataset of measured energy-related emission factors (50-140 mg N_2O/MJ) for a coal fired FBC power plant, showing distinct temperature dependence (lower N_2O at higher temperatures). Even considering the common practice of adding calcium oxide (CaO) to reduce sulphur dioxide (SO_2) emissions, which at the same time destroys part of N_2O, emissions are clearly higher due to FBC. In conventional boilers, increased N_2O emissions have been systematically observed after SNCR, but only occasionally for selective catalytic reduction SCR (de Soete, 1993).

For SNCR, 50 ppm N_2O in flue gas (20-70 for temperatures at high NO_x reduction efficiency) has been reported after 200 ppm nitrogen oxide (NO) for an installation applying urea injection. With NH_3 as a reducing agent, only about one third of the N_2O concentration is generated at the same NO concentration (de Soete, 1993). Using an unabated emission factor of 0.1 t NO_x (as NO_2)/TJ for heavy fuel oil and neglecting the molecular weight differences of NO_2 and N_2O, an N_2O emission factor of 25 kg/TJ for urea injection (or about 8 kg/TJ for NH_3 injection) is estimated. Emission factors and emission control measures employed for GAINS Version 1.0 are presented in Table 3.3.

Table 3.3: Calculation of combustion emissions of nitrous oxide (N_2O) in GAINS. The emission factor marked with "ANY" will be applied to all sectors/activities/technologies other than the combinations specifically mentioned. Priority decreases from top to bottom, i.e., the fluidized bed emission factor is used as soon as this technology is implemented.

GAINS sectors	CON_COMB	Fuel production and conversion: Combustion		
	DOM	Combustion in residential/commercial sector		
	IN_BO	Industry: Combustion in boilers		
	IN_OC	Industry: Other combustion		
	PP	Power plants: Combustion		
Activity rate	Fuel consumption			
Unit	PJ			
Data sources	RAINS databases			
Emission factors	Sector	Activity	Abatement technology	Emission factor (kt N_2O / PJ)
	Industry	Heavy fuel oil, industrial boilers and other combustion	Combustion modification + Selective non-catalytic reduction (SNCR) oil &gas	0.008
	ANY	ANY	Fluidised bed*	0.08
	ANY	Brown coal/lignite	ANY	0.0014
	ANY	Hard coal	ANY	0.0014
	ANY	Derived coal	ANY	0.0014
	ANY	Heavy fuel oil	ANY	0.0006
	ANY	Medium distillates (diesel, light fuel oil)	ANY	0.0006
	ANY	Gasoline	ANY	0.0006
	ANY	Liquefied petroleum gas	ANY	0.0006
	ANY	Natural gas (incl. other gases)	ANY	0.0001
	ANY	Other solid fuels	ANY	0.004
Data sources	de Soete (1993), Houghton *et al.* (1997)			

*) Activity data on combustion in different boiler types are part of the RAINS databases.

3.2.3 Transport

A detailed description of a large number of different studies on traffic emissions, including own measurements, is presented by Jimenez *et al.* (2000). Emission factors in GAINS Version 1.0 are derived from N_2O to carbon dioxide (CO_2) ratios presented by Jimenez *et al.* (2000) and have been recalculated for fuel use. Following the RAINS/GAINS concept, “uncontrolled” emission factors are determined for pre-EURO standard vehicles, and specific reduction efficiencies have been specified for each class of EURO emission standards (Table 3.4).

Earlier assessments of N_2O emissions from dynamometer and field studies (e.g., de Soete, 1993) had suggested higher emissions from catalyst cars, but lower emissions from non-catalyst cars. These data provided the basis for the emission factors recommended in the guidelines of the Intergovernmental Panel on Climate Change (IPCC) (Houghton *et al.*, 1997), but were not confirmed by the more recent review of Jimenez *et al.* (2000). To reconcile results of earlier studies, it is assumed that advancements in three-way catalysts have led to changes in N_2O emissions between the early generation and the new generation of catalysts.

Jimenez *et al.* (2000) report a very similar distinction made by the United States EPA, which produces emission factors similar to his own measurements, if the ratio between unabated (non-catalyst) and catalyst-equipped cars is correctly considered. For future generations of vehicle emission control, it is assumed as a first approximation that future regulatory packages for gasoline cars will maintain the N_2O emission factor that is currently associated with the EURO-IV standards. For heavy duty diesel vehicles, following the findings presented in RICARDO (2003), it is assumed that exhaust $DeNO_x$ equipment (SCR supported by urea as reducing agent) as required by the EURO-IV standards will lead to higher N_2O emissions.

Table 3.4: Calculation of nitrous oxide (N_2O) traffic emissions in GAINS. Emission factor marked with “ANY” will be applied to all sectors/activities/technologies other than the combinations specifically mentioned.

GAINS sectors	TRA_RD	Road transport		
	TRA_OT	Other transport		
Activity rate	Fuel consumption			
Unit	PJ			
Data sources	RAINS databases			
Emission factors	Sector	Fuel use	Abatement technology	Emission factor (kt N_2O / PJ)
	Road transport	Diesel	ANY	0.0018
	Light duty vehicles	Diesel	EURO-IV	0.0052
	Heavy duty vehicles	Diesel	EURO-IV and later	0.0031
	Road transport	Gasoline	ANY	0.0031
	Light duty vehicles, 4-stroke (excl. GDI)	Gasoline	EURO-I	0.0136
	Light duty vehicles, 4-stroke (excl. GDI)	Gasoline	EURO-II and later	0.0055
	Other transport	Medium distillates (diesel, light fuel oil)	ANY	0.0018
	Other transport	Gasoline	ANY	0.0031
Data sources	Jimenez *et al.* (2000), Houghton *et al.* (1997), RICARDO (2003)			

3.2.4 Nitrous oxide (N_2O) use

The specific properties of N_2O are taken advantage of in medicine as an anaesthetic gas, in the food industry as an unreactive propellant, and in specific combustion engine applications providing additional oxygen to the combustion process. At least for the first two applications, virtually all of the N_2O used will eventually be emitted to the atmosphere. In both cases, N_2O enters the human body where it remains only for a short time and is not metabolised.

The IPCC guidelines on national greenhouse gas (GHG) emission inventories (Houghton *et al.*, 1997) do not suggest a specific methodology to assess N_2O use. Only few national submissions to UNFCCC include this source explicitly.

- Belgium: The national inventory report (VMM *et al.*, 2004) refers to a study by ECONOTEC reporting the consumption of 10.3 kg N_2O per hospital bed in Wallonie. At five hospital beds per 1000 inhabitants (OECD, 2000), this yields an emission factor of 50 g N_2O per inhabitant and year.

- Netherlands: Emissions from N_2O use have been gathered in a study by Spakman *et al.* (2002) from sales figures. Scaled to inhabitants, emissions are estimated for anaesthetic purposes 31 g N_2O per person per year, and for aerosol cans (whipped cream) 7 g N_2O per person per year.

- Germany: The figures in the national inventory report (Strogies *et al.*, 2004) refer to production figures that were available in the German Democratic Republic before

1990 and have been scaled to all of Germany by inhabitant. The emission factor is 76 g N_2O per person and year.

- Austria: Figures used for the national inventory have been taken from a survey of major gas distributors in Austria (M. Wieser, Federal Environment Agency, personal communication). The supplied numbers were 50 g N_2O per inhabitant and year as anaesthetic, and 50 g in aerosol cans.

Due to lack of reliable country-specific information, GAINS 1.0 applies the German emission factor per person and year (see Table 3.5) to all countries. The UK and Italy did not submit data for this sector to UNFCCC (2002), which does not mean that there are no emissions from these sources in these countries. Furthermore, the collective report for the EU- 15 (Behrend *et al.*, 2004) does not provide own estimates, but merely sums up country submissions. It reports 11 kt N_2O for the entire EU-15, which is less than twice the amount of Germany alone (6.2 kt). A different path has been taken by France, where the French figure relies on an EU market assessment on N_2O for medical applications (S. Beguier, CITEPA, personal communication). This can be converted into an emission factor of 5 g/person.

Following this study, the total EU consumption would amount to 1,800 t/year, which is less than 50 percent higher than the known production capacity of the former German Democratic Republic. Should this market assessment apply to the past situation, it is in conflict with information provided by the Swiss engineering company SOCSIL. This company reports having installed globally more than 100 N_2O production units, at standard sizes between 25 and 300 kg/hr (www.socsil.ch). Assuming half of the production is sold in the EU, an average production of 75 kg/hr during 8,000 hours per installation and year suggests a total annual production of 30 kt. Though this estimate depends strongly on the assumptions taken, it is consistent with the German emission factor, but not with the French one.

In recent years, application practices of N_2O as an anaesthetic have changed. The numbers reported above all originate from the early or mid 1990s. Since then, health (specifically the potential exposure of hospital personnel) and environmental issues have emerged and have led to an apparent reduction in N_2O consumption. This trend is documented by environmental statements published by German hospitals (e.g., http://www.klinikum-kuhlbach.de/pub/bin/umwelterklaerung_1.pdf). Typical emission factors of such "good practice" will be approximately 11 g N_2O per inhabitant per year.

The recent national assessment from the Netherlands (Spakman *et al.*, 2002) also reports a decrease in N_2O sales to hospitals since 1995 from 31 g N_2O to 18 g N_2O in the year 2000 per inhabitant per year. Assuming a constant load from aerosol cans of 7 g N_2O as reported for the Netherlands, this indicates an overall emission reduction of 34 percent. Based on these different sources discussed above, we suggest an unabated emission factor of 76 g N_2O per inhabitant, with a reduction potential of 34 per cent due to modern medicine (see Section 4.4).

Table 3.5: Calculation of emissions due to direct use of nitrous oxide (N_2O) in GAINS.

GAINS sectors	N_2O_USE	Use of N_2O		
Activity rate	Population			
Unit	Million inhabitants [Mperson]			
Data sources	RAINS databases			
Emission factors	Sector	Activity	Abatement technology	Emission factor [kg N_2O/person]
	Use of N_2O	Population	No control	0.076
Data sources	Strogies *et al.* (2004)			

3.2.5 Agricultural soils

Microbial processes in soil and manure (nitrification and denitrification processes) are considered the dominant sources of N_2O emissions world-wide and in Europe. These soil processes require partly aerobic conditions (nitrification), and partly anaerobic conditions (denitrification). For the complete chain of processes, these conditions need to occur in close vicinity to each other. Soil conditions, temperature and water availability all play an important role in the process. One key parameter is the availability of nitrogen in soils, which is the sole parameter considered in the IPCC approach (Houghton *et al.*, 1997).

The concepts outlined in Section 2.3.2 relate emissions to freely available nitrogen, rather than total nitrogen in soil. Consequently, one may expect to find a saturation point, with low emissions and low sensitivity to the application of nitrogen as long as plants are able to quickly assimilate nitrogen, and high sensitivity above this saturation point. Additionally, the potential of soils to store nitrogen over several years has been proven, for example in connection with effects of nitrogen deposition to natural soils (Posch *et al.*, 2003). Such memory capabilities of soils possibly modify any clear input versus emission relationship, and a threshold value of N_2O formation as suggested by a “saturation point” model will not be found.

These considerations point to the necessity of process-oriented soil models. Attempts to include such aspects into soil models have been made with the Denitrification-Decomposition (DNDC) model family (Li *et al.*, 1992). However, the performance of this DNDC model to simulate emissions from agriculture is not yet fully established, with current discrepancies between model results and measurements of a factor of 10 (Werner *et al.*, 2004; Neufeldt *et al.*, 2004). Present model results are strongly driven by the soil carbon content in a way which is not reflected by measurements.

It is not clear at the moment whether a more accurate representation of the soil water availability (as, e.g., in the Erosion Productivity Impact Calculator (EPIC) model, Williams *et al.*, 1989) or an improved version of the DNDC model would produce better results. In principle, a parameterisation of a soil model would be the ideal approach for including soil information into GAINS. However, a lack of reliable models led to the decision to implement the much simpler IPCC approach for describing soil N_2O emissions into GAINS Version 1.0.

The IPCC methodology distinguishes direct and indirect N_2O emissions from soils. Direct emissions are caused by nitrogen input to the soil, and indirect emissions are related to subsequent processes after evaporation and re-deposition, or after leaching. The concept and its physical background have been described in Section 2.3.2.

GAINS Version 1.0 uses the default loss fractions suggested in Houghton *et al.* (1997), i.e., 20 percent for manure, 10 percent for inorganic fertilizer evaporation, and 30 percent for leaching losses. Furthermore, GAINS uses IPCC default emission factors of 1.25 percent for direct emissions, 1 percent for emissions from evaporative losses and 2.5 percent for emissions from leaching. With these assumptions, an overall emission factor that includes direct and indirect emissions of 1.95 percent of the total N input, or 0.031 g N_2O per g N-input, can be computed. Deviation from this default overall emission factor due to country-specific conditions can easily be implemented by using country-specific correction factors when available.

GAINS Version 1.0 distinguishes three pathways of nitrogen input into soils to establish the relevant activity rates for the emission calculation:

- Nitrogen input from mineral fertilizer application. Consumption statistics are taken from the RAINS database.
- Nitrogen input from farm animals. Animal numbers and total nitrogen excretion rates per animal are available in the RAINS databases. Note that both indoor and outdoor excretion eventually leads to input of nitrogen to soils.
- Nitrogen from crop residues. The calculation is based on national data on crop yields (FAOSTAT, 2003) and on generic assumptions about a nitrogen content in residues of 0.5 percent and 30 percent of crop mass left on the field. Nitrogen uptake by leguminous plants is treated in the same way using higher nitrogen content (1.5 percent) and a share of 50 percent of crop mass left on the field.

Figure 3.2 presents the way how nitrogen input is linked with the various source categories. Data on mineral fertilizer application (FAO, 2002) and manure allow differentiation between grassland and arable land. Crop residues are only attributed to arable land. The overall emission factor is representative for a situation without any emission controls. Specific options targeted at the reducing of N_2O emissions are discussed in Section 4.

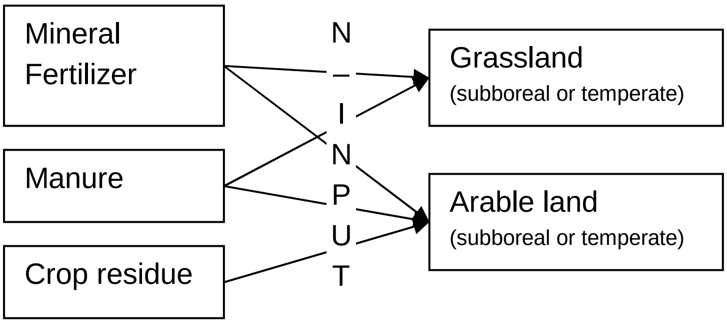

Figure 3.2: Distribution of nitrogen supply to different land classes.

N_2O emissions from manure application are possibly influenced by measures to reduce NH_3 emissions to the atmosphere. Brink *et al.* (2001) point out that deep injection of manure could possibly double N_2O emissions from soils. However, other authors such as Vabitsch *et al.* (2004) suggest that this additional potential is essentially related to the additional nitrogen in soil, which could instead replace mineral fertilization and thus reduce N_2O emissions.

GAINS Version 1.0 considers a reduction of nitrogen input as one N_2O-specific abatement option, and therefore quantifies additional emissions caused by manure injection. Following the analysis of Brink *et al.* (2001), GAINS Version 1.0 associates the "low ammonia application, high efficiency" (LNA-high) measure of the RAINS NH_3 module with double N_2O emissions. For the less efficient options, i.e., "low ammonia application, low efficiency" (LNA-low) and "covered outdoor storage of manure and low nitrogen application" (CS_LNA), a 50 percent increase in N_2O emissions is assumed.

The IPCC guidelines draw special attention to N_2O emissions from organic soils (histosols). These soils are characterized by important anoxic (oxygen-deficient) zones, which together with the availability of carbon lead to excessive activity of microbes. Under crop, these soils allow for a prolific N_2O production. The emission factor of organic soils used in GAINS Version 1.0 was taken from the recent compilation by Penman *et al.* (2000), which suggested revisions compared to previous publications.

Table 3.6 presents the parameter values used for the GAINS Version 1.0 calculations. GAINS uses for each sector an emission factor related to land area parameter and another emission factor related to nitrogen input. In GAINS Version 1.0, area-related emission factors are only used for histosols. The land area of histosols in each country was estimated from the soil organic carbon content.

Table 3.6: Emission factors for agricultural emissions in GAINS.

GAINS sectors	ARABLE	Agricultural land (NEW)		
	GRASSLAND	Grassland (NEW)		
	HISTOSOL	Histosols (NEW)		
Activity rate	Area		N-input	
UNIT	Million hectares		kt N	
Data sources	RAINS databases, FAO (2002), IFA (2004), FAOSTAT (2004)			
Emission factors	Source category	Activity	Abatement technology	Emission factor kt N_2O/kt N-input
	Arable land / grassland*	N-input	No control	0.031
	Arable land / grassland*	N-input	Deep injection	0.061
	Histosol	N-input	No control	0
				kt N_2O/Mio ha
	Arable land / grassland*	Area	No control	0
	Histosol	Area	No control	12.6
Data sources	Houghton *et al.* (1997), Penman *et al.* (2000)			

*) GAINS allows separate emission factors for arable land (both in the temperate and sub-boreal climate zone) and grassland. This feature is currently not used.

3.2.6 Animal manure

The revised IPCC guidelines (Houghton *et al.*, 1997) assume emissions from manure storage “not to occur before spreading”. This would make a specific treatment unnecessary, as the GAINS model covers soil emissions after spreading in its soil emission category (Section 3.2.5). New research and results of measurements inside animal housing (Berges and Crutzen, 1996; Hassouna *et al.*, 2004) call for a reconsideration of this approach. The IPCC Good Practice Guidelines (Penman *et al.*, 2000) call for treating animal manure emissions “separate from emissions resulting from manure spread on soil”. The same processes (microbial nitrification and denitrification) are responsible for N_2O formation during manure storage.

Recent findings suggest that the nitrogen that has not been converted during manure storage may once more undergo these processes when applied to soil. Removal of nitrogen to the atmosphere during storage ideally should be subtracted when calculating nitrogen input to soil in order to remain at a consistent nitrogen balance. For simplification, this has been neglected for GAINS Version 1.0 as the difference is not considered very large. Consequently, nitrogen input from manure to soils, as described in Section 3.2.5, remains unaffected by any calculation of N_2O emissions from manure in animal housing or storage.

According to Penman *et al.* (2000), the emission behaviour strongly differs by storage process. For solid storage of manure, an emission coefficient of N_2O-N of two percent is appropriate. All other storage methods, specifically those where manure remains in liquid form, do not show relevant emissions of N_2O. The only exception is poultry manure, which exhibits higher emissions if not treated by anaerobic digestion. Country-specific information on different storage processes is directly available in the RAINS NH_3 module (Table 3.7).

Nitrous oxide emissions from animal manure emissions are related to the amount of manure excreted in stables. Using all required data from the RAINS NH_3 database, the amount of nitrogen excreted by animal and year is calculated for each country, and multiplied by the fraction of indoor excretion. Any emissions due to excretion on pasture/range/paddock are included in soil emissions (see Section 3.2.5), as are emissions from spreading of manure. There is an issue of potential double counting as this approach neglects losses of nitrogen during manure handling, but these are believed to be quite small.

Table 3.7: Calculation of nitrous oxide (N_2O) emissions from animal manure in GAINS. The emission factor marked with "ANY" will be applied to all sectors/activities/technologies other than the combinations specifically mentioned.

GAINS sectors	AGR_COWS	Agriculture: Livestock - dairy cattle		
	AGR_BEEF	Agriculture: Livestock - other cattle		
	AGR_PIG	Agriculture: Livestock - pigs		
	AGR_POULT	Agriculture: Livestock - poultry		
	AGR_OTANI	Agriculture: Livestock - other animals		
Activity rate	Animal numbers			
Unit	M animals			
add'l operation	conversion to N excreted, scaled by in-house excretion fraction			
Data sources	RAINS databases			
Emission factors	Sector	Activity	Abatement technology	Emission factor (kt N_2O/kt N excreted)
	All above	ANY	Manure digesting	0.0016
	poultry	ANY	ANY	0.008
	All above	Solid storage of manure	ANY	0.031
	All above	ANY	ANY	0.0016
Data sources	Penman *et al.* (2000)			

3.2.7 Sewage treatment plants

The contribution of sewage treatment plants to total N_2O emissions is fairly small (Figure 3.1). The main reason to include this sector in GAINS is the existence of N_2O-specific mitigation measures from this source (Hendriks *et al.*, 1998). Due to the low overall importance of N_2O emissions from sewage treatment plants, GAINS estimates uncontrolled emissions on a per-capita basis. Total emissions were taken from the official EU database submitted to UNFCCC (Behrend *et al.*, 2004), which presents a number that is three times as high (converted to an emission factor by population in Table 3.8) as that given in Hendriks *et al.* (1998).

Table 3.8: Calculation of nitrous oxide (N_2O) emissions from sewage treatment plants in GAINS.

GAINS sectors	WASTE_SEW	Sewage treatment		
Activity rate	Population			
Unit	Million inhabitants [Mperson]			
Data sources	RAINS databases			
Emission factors	Sector	Activity	Abatement technology	Emission factor (kt N_2O/Mperson)
	Sewage treatment	Population	No Control	0.051
Data sources	Behrend *et al.* (2004)			

It is also useful for sewage treatment plants to consider the pathway of nitrogen, as the underlying processes are nitrification and denitrification. Using the recommended daily allowances of to the United States Food and Drug Administration (FDA) as a basis (http://www.fda.gov), humans need to replace 0.8 g protein per kg body mass per day due to losses from excretion. This is about 50 g protein or (at 16% N-content) 8 g N per day, 3 kg/yr.

Following the FDA's assumption that the human diet in developed countries is in large surplus and will yield approximately twice this amount, the uptake (and at the same time excretion) remains at 6 kg per person. This is still considerably lower than typical animal consumptions because animal metabolic rates are usually optimized. This would suggest emission factors derived from the sector emissions reported by Behrend *et al.* (2004) are somewhat below one percent of excreted nitrogen (compared to the IPCC default value of 1.25 percent). There is no indication that this emission factor is extremely high, rather that the emission factor presented by Hendriks *et al.* (1998) is at the very low end of the possible range.

As nitrogen removal is the major objective of a sewage treatment plant, it can be safely assumed that nitrogen content downstream of the plant will have considerably decreased and will not contribute strongly to N_2O formation. Untreated sewage may also undergo nitrification and denitrification, but this is not considered explicitly in the GAINS model.

3.2.8 Other soil emissions

Official emission reporting within UNFCCC is limited to emissions to the atmosphere resulting from anthropogenic activities. For this reason, only agricultural soil emissions have previously been included in the inventories. Nevertheless, there is a considerable amount of anthropogenic influence on other soils. Nitrogen input to forests is provided by fertilisation (during reforestation after clear cutting) and by air pollution. Both ammonia and oxidised nitrogen (NO_x, nitric acid) are contributing to wet and dry deposition. These nitrogen compounds are clearly of anthropogenic origin, although it is difficult to hold a single country responsible for the deposition at a given site due to long-range transport in the atmosphere.

In addition to forest soils, GAINS Version 1.0 considers different types of scrubland even if the assumption that their behaviour is equivalent to that of a forest soil has not yet been proven. Emissions of N_2O from soils are attributed to the country where re-emission takes place, irrespective from where original emissions may have occurred. There is a disadvantage that improvements performed in one country are not immediately reflected in this country's emissions inventory. However, this particular approach does allow one to identify the magnitude and the trend of these emissions.

An estimate of NO_x and NH_3 deposition for all of Europe is available from EMEP model calculations (Tarrason *et al*., 2003). These calculations yield annual deposition of more than 20 kg/ha for many grids in the more densely populated area of Europe. The magnitude indicates that the source should not be neglected in relation to agricultural activities. It seems useful to assume that N_2O emissions are caused by nitrogen available in soil. Consequently, the simplest concept is to apply IPCC default emission factors for agricultural soils to the atmospheric nitrogen input. However, this simple approach is loaded with some uncertainties, as pointed out by Borken *et al. (*2002, 2004), who insist that a statistically significant relationship between emissions and input can not be established.

For forest soils, mechanistic soil models have delivered excellent agreement with measurements, even when temporal trends and the freeze-thaw cycles are taken into account (Butterbach-Bahl *et al.*, 2001). Thus it might be useful to apply a parameterisation of that model (PnET-N-DNDC, one of the DNDC type models) to assess the European temporal and spatial distribution of N_2O emissions from forest soils. Data on the model sensitivity exist from Stange *et al.* (2000). While these sensitivity figures are not the latest state of art, they are a published source of information and can be used until better information becomes available.

This sensitivity analysis by Stange *et al.* (2000) indicates strongest sensitivity on forest soil pH, clay content and forest type (coniferous versus deciduous trees). Through interpolation of the available data points, “correction factors” can be derived to correct the default emission factor of 1.25 percent N emitted as N_2O-N (0.0196 kg N_2O emitted per kg N-input) (Table 3.9). Correction factors have been calculated for the smallest spatial resolution available, and *cf[all]* has then been averaged for each country. National emissions are calculated in GAINS as 1.25 percent of N-deposition (per area) times forest area, corrected by *cf[all]*. The exact procedure of emission calculation is as follows:

1. Determine area-based total nitrogen deposition (oxidized plus reduced nitrogen, EMEP model results from 2000) and apply it to forest and scrubland area to arrive at an amount deposited.
2. Calculate the overall correction factor per 50 km grid cell.
3. Determine scrubland emissions per grid cell, correcting the IPCC default emission by the correction factor.
4. Add up for country totals, divide by country total of N-deposition on forests to arrive at an average country specific emission factor per country, which can be multiplied by the N-deposition to yield emissions.

While step 4 may seem cumbersome, it allows us to adapt for changed nitrogen input if other data than the 2000 deposition model results become available. This step transfers the gathered information into the emission factor approach used elsewhere in GAINS. However, a direct coupling of GAINS measures in terms of NO_x or NH_3 reductions and their consequences in terms of deposition and subsequently N_2O emissions is not intended at this time.

Table 3.9: Calculation algorithm for correction factors for nitrous oxide (N_2O) emissions from forests in GAINS.

GAINS sectors	FOREST		Forests and natural vegetation	
Activity rate	Atmospheric deposition (NO_x and NHx)			
Unit	kt N			
Data sources	Tarasson *et al.*, 2003			
Emission factors	Sector	Activity	Abatement technology	Emission factor (kt N_2O/kt N-input)
	Forest	AREA	No control	0.0196
Correction factors	Type		Equation	
	Soil pH ($CaCl_2$)		cf[pH]=pH*1.6-4.4	
	Fraction of deciduous forest		cf[tree]= 0.75 + 0.0045 * %deciduous	
	Soil texture as a parameterisation of clay content in soils		cf[tex]=%clay*0.05	
	Overall correction factor		cf[all]=cf[pH]*cf[tree]*cf[tex]	
Data sources	Stange *et al.* (2000)			

This four-step procedure possibly overestimates the variability of the correction factors. For GAINS Version 1.0, sensitivities have been determined separately for each variable. However, correlation may occur between these variables, and one parameter may affect more than one variable. In this case, the influence of this parameter would be applied twice. A correction of this problem can only be performed at a later stage.

4 Emission control options and costs

4.1 Concept relating to other GAINS modules

A number of measures have been identified that are available to change emissions of nitrous oxide (N_2O). Most of the options do not aim primarily on N_2O, but target at the control of other pollutants (nitrogen oxides, ammonia). Since these measures are already addressed in the RAINS model (see www.iiasa.ac.at/rains), the costs of these options do not need to be re-discussed here. Their impact on N_2O emissions has been described in Section 3.2. In only five sectors were options identified that specifically address N_2O emissions:

- selective catalytic reduction in industrial plants,
- process modification in fluidized bed combustion,
- optimization of sewage treatment,
- replacing use of N_2O as anaesthetics, and
- optimised application of fertilizer.

Even in these specific cases the control of N_2O is more often a positive side-effect rather than the driving force of any measures taken.

4.2 Industrial processes

Options to control industrial process emissions are relatively well studied. In adipic acid plants, N_2O concentrations in the flue gas are so high that N_2O can be captured relatively easily by specific equipment. Several possibilities exist for such removal, where De Soete (1993) describes these options and presents data on abatement potential. For example, N_2O may be recovered and used as raw material for nitric acid production (Hendriks *et al.*, 1998), or it can be destroyed thermally and the steam derived used elsewhere in an industrial facility.

Depending on the circumstances, the overall process may even become cost-neutral or allow cost savings. Without fully evaluating the benefits, de Beer *et al.* (2001) have estimated costs at 44 €/t N_2O abated. We will also apply this rather conservative estimate to the GAINS model. It may be argued that the implementation of abatement is more strongly driven by optimising the production process than by environmental considerations. In fact, abatement was in place already for most installations in EU-15 in 2000 as a result of voluntary agreement by industry. Without further information we expect this to be the case for all remaining plants by 2005.

Even if emissions from adipic acid production have been largely abolished in Europe, it is still important to keep this control option to demonstrate and explain the temporal change since 1990. Furthermore, no firm information exists about the situation of implementation in Eastern European countries. According to the UK based consulting and trade organisation Valetime Group (http://www.valetimegroup.com/), Ukrainian adipic acid production (at least in the larger plant - AZOT in Severodonetsk) is performed using “methods, technology and key equipment” from BASF. This can be taken as an indication that N_2O mitigation will also be introduced in the Ukraine and in Romania in the middle of the current decade.

In nitric acid production, concentrations of N_2O in flue gases are much lower, so that control measures are less efficient and more costly. Still methods have been described by de Soete (1993) and Kuiper (2001) for the catalytic reduction of N_2O. AEAT (1998) also claims a potential for a combined abatement of nitrogen oxide (NO_x) and N_2O from nitric acid plants. This would reduce N_2O abatement costs to the marginal costs over conventional NO_x reduction and improve costs and efficiency from the values presented in Table 4.1.

At this time GAINS Version 1.0 follows the suggestions of Kuiper (2001), who converted investment costs to running costs. This cost figure is consistent with the estimate by de Beer *et al.* (2001). However, the actual level of abatement remains to be estimated for individual countries. GAINS Version 1.0 assumes no abatement for the current legislation scenario. The application potential of catalytic reduction (CR) is assumed to cover all plants.

Table 4.1: Options implemented for controlling nitrous oxide (N_2O) emissions from industrial processes in GAINS.

Abatement option	*Removal efficiency [%]*	*Controlled emission factor [kt N_2O/Mt]*	*Costs [€/t N_2O]*	*Source*
Adipic acid – catalytic reduction (CR)	95	15	44	de Soete (1993), de Beer *et al.* (2001)
Nitric acid – catalytic reduction (CR)	80	1.14	130	Kuiper (2001)

4.3 Fluidized bed combustion

Fluidized bed combustion (FBC) is a convenient option to reduce NO_x and particulate matter (PM) emissions. Consequently, a strong increase of the application of FBC is predicted for Europe. Without the introduction of specific abatement measures, this would cause an associated increase in N_2O emissions since the specific combustion conditions of FBC (long residence time, lower combustion temperature) favour N_2O formation.

Hendriks *et al.* (2001) report on N_2O abatement techniques specifically introduced to FBC. The most promising options are the use of an afterburner to increase the temperature in the flue gas to destroy N_2O, and a reversed air staging to optimize oxygen availability. Figures for costs, removal efficiencies and emission factors are similar. Table 4.2 presents both options together as “Modifications in FBC”. Both options have only been demonstrated at small scale and pilot plants. They are not yet used in practice, so that in the GAINS Version 1.0 calculations it is assumed that the introduction of this technology would not start before 2010.

Since retrofitting of existing installations is not possible, introduction is hampered by the natural turnover rate of the fluidized bed boilers (assuming that they have a typical technical life time of 30 years). Therefore, at maximum feasible reduction, GAINS estimates that in 2020 no more than 40 percent and in 2030 no more than 80 percent of all installations may have modified combustion equipment installed.

Table 4.2: Options for reducing nitrous oxide (N_2O) emissions at fluidized bed combustion plants in GAINS.

Abatement option	*Removal efficiency [%]*	*Controlled emission factor [kt N_2O/PJ]*	*Costs [€/t N_2O]*	*Source*
Modifications in FBC	80	0.016	1000	Hendriks *et al.* (2001)

4.4 Nitrous oxide (N_2O) use

The dominant direct application of N_2O is as an anaesthetic gas for surgery. However, due to potential side-effects on patients and especially hospital personnel, alternative options have been sought. Low-flow techniques and even complete abolishment have been suggested as alternatives (Baum 1999; 2004). To illustrate, Nakata *et al.* (1999) provide cost estimates for replacement with Xenon, an extremely expensive alternative. As this is still the only abatement option for which such cost data could be found in the literature, it is included in Table 4.3.

Table 4.3. Options for controlling emissions from direct application of nitrous oxide (N_2O) in GAINS

Abatement option	*Removal efficiency [%]*	*Controlled emission factor [kt N_2O / Mperson]*	*Costs [€/t N_2O]*	*Source*
N_2O use: replace by Xe	100	0	200,000	Nakata *et al.* (1999)

Ultimately, decisions will be made in terms of medical reasoning, as not even the high costs for Xenon will be relevant compared to overall operation costs. Still, GAINS Version 1.0 uses these high costs for Xenon replacement to indicate that an option does exist, even if there is the possibility that autonomous development will cause significant decreases of emissions in the near future without costs being assigned to emission abatement.

Past development proves that such a process has started already. National data indicate that N_2O use and consequently emissions have been decreasing since the early 1990s (see Section 3.2.4). This is reflected in GAINS through a partial penetration of the “replacement” option (34 percent for all countries for 2000 and later). At the specific costs given for replacement by Xenon, this yields extremely high costs for emission abatement already taken. It can be safely assumed that such costs are not realistic, even if they were applied for medical reasons. Nevertheless, GAINS will maintain this approach as the conclusions of the model analysis will be derived from relative differences in emission control costs and not from estimates of the costs of options that have already been introduced.

4.5 Sewage treatment

Sewage treatment plants take advantage of microbial nitrification and denitrification processes to decompose nitrogen compounds. Processes are strictly controlled and currently optimized towards removing nitrogen. Hendriks *et al.* (1998) claim that, without compromising on this main target, process parameters (temperature, residence time, pH) could be altered to move the N_2/N_2O ratio of the effluent gases towards N_2. This would not change operation costs. GAINS Version 1.0 applies this reduction factor despite of the fact that the emissions as estimated by Hendriks *et al.* (1998) are only a third of those assessed here (see Section 3.2.7).

GAINS Version 1.0 also adopts the assumption of zero costs as suggested (Table 4.4) even if more detailed evaluations may show that some transaction costs (research into optimization parameters, training of personnel) will occur in reality. At this time, no quantitative information on such transaction costs is available.

Table 4.4: Options to control nitrous oxide (N_2O) emissions from sewage treatment in GAINS

Abatement option	*Removal efficiency [%]*	*Controlled emission factor [kt N_2O / million persons]*	*Costs [€/t N_2O]*	*Source*
Sewage treatment: optimization	40	0.031	0	Hendriks *et al.* (1998)

4.6 Agricultural soils

Options to reduce N_2O emissions from agriculture generally attempt to reduce nitrogen availability in soils. Consequently, these options aim to reduce fertilization, specifically the application of mineral fertilizer. Application of nitrogen on soils is also the key driving variable in the emission calculations. Any mitigation option will then apply to the activity rate rather than the emission factor (as described by Equation 2.1), and may have consequences on NH_3 emissions (see Section 5). Such interactions remain to be considered even as the focus of NH_3 abatement is on animal manure, and N_2O abatement rather refers to mineral fertilizer.

Additionally, a feedback would also effect fertilizer production. GAINS Version 1.0 does not consider these feedbacks, even if a decrease in fertilizer production would result in a CO_2 emission reduction of a similar magnitude as the N_2O reductions (in terms of CO_2-equivalents) as suggested by Wood and Cowie (2004).

Focussing on options to reduce nitrogen input is not only be the most straightforward strategy with discernable effects (Kuikman *et al.*, 2004), but it is also fully compatible with current emission reporting. Possible emission reduction strategies, which do not involve a reduction of nitrogen input or which focus on reducing mineral nitrogen in soil instead, would not be recognized in emission inventories produced according to the IPCC methodology. Thus, it would not be considered a reduction of greenhouse gas emissions by the UNFCCC.

Four groups of options (outlined below) with similar technical and economic features can be distinguished (de Jager *et al.*, 1996; Hendriks *et al.*, 1998; Bates, 2001; Gibson, 2001).

Reduced application of fertilizer includes a set of relatively simple “good practice” options to reduce fertilizer consumption. Generally, it is safe to assume that the amount of fertilizer applied is considerably larger than what is required for optimum plant growth. Any measure for a more effective distribution of fertilizer that results in a lower overall consumption is beneficial. A good overview on available options has been compiled by de Jager *et al.* (1996). Among these are maintenance of fertilizer spreader, fertilizer free zones on edges of fields (to reduce loss into ditches), row application, or fertilizer need analysis (soil testing) to account for nitrogen already available in soil or applied otherwise (manure, atmospheric deposition). Set-aside agricultural policy also falls into this category, where some of these options overlap. Following the estimates of Hendriks *et al.* (1998), Bates (2001), and Gibson (2001), GAINS estimates the potential of decreased fertilizer input and lower emissions at about six percent.

Timing of fertilizer application is normally optimized to fit the internal work procedures of a farmer, not the needs of plants. *Optimized timing of fertilizer application* would result in a reduced availability of nitrogen in soil that would reduce emissions and leaching and allow a further decrease in nitrogen application (Hendriks *et al.*, 1998). This group includes the application of slow-release fertilizers (e.g., coated fertilizers; Gale and Freund, 2002) or the use of catch crops to shorten the fallow period and subsequently use them as green manure (Bates, 2001). Procedural changes in manure application also include an increased frequency of slurry spreading and the ban of manure application during off-season (while increasing storage capabilities of slurry tanks) to decrease surplus nitrogen in soils. An additional five percent decrease in fertilizer application is expected from this option.

Application of *nitrification inhibitors* suppresses the conversion of ammonium to nitrate. As nitrogen in the form of ammonium is less prone to leaching than nitrate, nitrification inhibitors allow for a significantly more efficient application of fertilizers. However, inhibitors are substances that affect the soil microflora (Freibauer, 2001) and may exhibit possible unintentional side effects that could make them undesirable. The proven efficiency of this option is high and emission reductions between 50 and 70 precent have been shown. As the effect of the inhibitor is temporally limited to a few months, Weiske *et al.* (2004) estimate an emission reduction of about 12 percent that is in line with the estimate of Gibson (2001).

The aim of *precision farming* is to provide a plant with exactly the amount of nitrogen that it needs using the latest available technology to allow variable N-input according to specific plant needs. Ideally, this would make surplus nitrogen application unnecessary and avoid the release of excess nitrogen compounds to the environment. Bates (2001) reports on an analysis performed for one specific German farm, but no generally applicable result is yet available. GAINS uses precision farming as a proxy for further measures and assigns another 10 percent reduction potential, consistent with the overall potential claimed by Gibson (2001).

Several authors (Hendriks *et al.*, 1998; Bates, 2001; Gibson, 2001) suggest significant cost-savings of nitrogen abatement options due to the fertilizer nitrogen consumption. Based on Bates’ fertilizer costs of 330 €/t of N in fertilizer (in 1990 prices), a reduction of fertilizer and subsequent the reduction of N_2O (if 1.25 percent of fertilizer nitrogen N is emitted as N_2O) would yield negative costs of 17,000 €/t N_2O.

Nitrification inhibitors, which are priced at 20,000 €/t N_2O, are attributed zero costs by Gibson (2001), indicating savings in the same range. The literature reports even higher savings (Hendriks *et al.*, 1998; Gibson, 2001). However, as Bates (2001) points out, these estimates seem to overlook important cost elements such as the potential of under-fertilization and consequential yield losses. As such cost savings could be directly taken advantage of by the farmers, GAINS assumes such measures would have already been implemented if it were not for important barriers (i.e., farmers' risk assessment or additional workload not considered in the calculation). GAINS assumes these "transaction costs" at the same level as the cost savings to be expected from fertilizer reductions, i.e., 17,000 €/t N_2O.

The above approach is consistent with the conservative estimate that has been taken for adipic acid production (Section 4.4), where indications on actual cost savings are even larger as measures have been implemented already on a voluntary basis. Interestingly, studies describing the implementation costs of the water framework directive (Footit, 2003) do not consider any savings in terms of fertilizer use when discussing decreased application of N as an important option to reduce the groundwater concentrations of nitrate. GAINS uses the figures presented by Gale and Freund (2002), which seem to ignore any cost savings.

Under this assumption, cost numbers from Gale and Freund (2002) are quite similar to other estimates in the literature. 1,500 €/t N_2O are estimated for the cheap options (Bates' figure, when neglecting cost reductions, is roughly 4,000 €/t N_2O, and 20,000 €/t N_2O for nitrification inhibitors. For fertilizer timing, GAINS uses 10,000 €/t N_2O, which is somewhat different from Gale and Freund's intermediate set (at 15,000 €/t N_2O), in order to better cover the estimate by Hendriks *et al.* (1998) of 6,000 €/t N_2O. No cost estimates are available for precision farming other than significant cost savings, which seems to neglect the barriers and risks. As precision farming is meant to describe further measures, GAINS Version 1.0 uses the costs of Gale and Freund's most expensive option (see Table 4.5).

Table 4.5: Options to control nitrous oxide (N_2O) emissions in agriculture in GAINS. Options presented are additive, i.e., they can be taken on top of each other (except the option for histosols).

Abatement option	*Emission reduction**	*Controlled emission factor [kt N_2O/ kt N-fertilizer]*	*Costs* [€/t N_2O]*	*Source*
Reduced application of fertilizer	6 %	0.029	1500	Gale and Freund (2002)
Optimized timing of fertilizer application	5 %	0.027	10,000	Gale and Freund (2002), adapted
Application of nitrification inhibitors	12 %	0.024	20,000	Gale and Freund (2002)
Precision farming	10 %	0.021	60,000	Gale and Freund (2002)
Histosols: Discontinue cultivation	94 %	0.8 [kt N_2O/Mha]	42,000	Penman *et al.* (2000); own estimates

*) All emission reductions and costs are given as additive, i.e. applicable in addition to any previous option. Thus also costs are identical to marginal costs.

Within agriculture, organic soils take a special position in terms of N_2O emissions. According to the calculation procedure for histosols accepted by GAINS, emissions are directly related to the cultivated area. Thus discontinuing cultivation will reduce emissions. Abatement costs will be equal to the revenue lost due to agricultural products not grown. Assuming a revenue of 500 €/ha will yield specific costs of 42,000 €/t N_2O, if a world market price between 500 and 1,000 €/ha is assumed (based on EUROSTAT production statistics (EUROSTAT, 2004) and agricultural market publications (Riester *et al.*, 2002; Bauernverband, 2004)).

The actual implementation of this measure will depend on the future subsidy system of the European agricultural policy (see Section **Error! Reference source not found.**). Recent studies on abandoned Finnish histosols (Maljanen *et al.*, 2004) indicate that banning cultivation may in reality not return the emission situation to natural background. High nitrogen levels remain in the soil, which lead to N_2O emissions that can be higher in afforested areas than in agriculturally used histosols even 30 years after abandonment. Potentially, this option needs reconsideration and might not prove useful. However, at this time GAINS Version 1.0 remains with the IPCC approach.

5 Interactions with other emissions

Emissions of nitrous oxide (N_2O) are linked to emissions of other pollutants of GAINS in two areas. They occur in the formation and destruction of gaseous nitrogen oxides (NO_x), and they are an intrinsic part in the soil nitrogen cycle (see Table 5.1).

Nitrogen oxides formation during combustion processes is favoured by very high temperatures. Longer residence times and lower temperatures, which are typical for fluidised bed combustion, suppress NO_x but may increase nitrous oxide (NO) formation. In a similar way, N_2O evolves as a side product of the destruction of NO_x in (catalytic and non-catalytic) end-of-pipe emission control technologies.

In soils, microbial processes that produce *inter alia* NO rely on the availability of mineralised nitrogen. Spreading of manure is one important pathway of nitrogen input, which is also responsible for considerable ammonia (NH_3) emissions and some methane (CH_4) emissions. Measures on NH_3 abatement (specifically, deep injection of manure) will decrease NH_3 emissions, but increase excess nitrogen in soils (i.e., nitrogen not used by plants) and consequently also N_2O formation. Reducing manure application to a level that accounts for the increased availability of nitrogen may counterbalance this adverse effect for N_2O.

Additional effects on NH_3 emissions might be expected from an N_2O-induced change in nitrogen fertilisation. As NH_3 abatement options focus on manure (see Brink *et al.*, 2001), and N_2O options are rather directed towards mineral fertilizer, this effect should not be strong.

Table 5.1: Interactions of sectors in GAINS emitting nitrous oxide (N_2O) with emissions of other environmental issues.

Sector		Important interactions with other pollutants in GAINS
Power plants and Industry	SCR and NSCR technologies	NO_x
	Fluidised bed combustion	NO_x
Power plants / Agriculture	Increased fertilizer consumption due to energy crop plantation	CO_2
Transport	Catalytic converter	NO_x
Agriculture	Manure spreading (deep injection)	NH_3 (CH_4)
Agriculture	Anaerobic digestion of manure	CH_4
Agriculture	Fertilizer production	CO_2

Reducing mineral fertilizer application will have consequences on the fertilizer industry. Reduction of production-induced carbon dioxide (CO_2) emissions may be of a similar magnitude (in terms of CO_2-equivalants) as N_2O reductions due to decreased availability of N in soils. Furthermore, nitric acid is one important raw product in fertilizer production, and reducing this production will lead to decreased N_2O emissions from this source. While overproduction in Europe promotes plans like the Common Agricultural Policy (CAP) to reduce activities (and fertilizer consumption), introducing biomass fuel may counteract this trend. Energy plantations to replace fossil fuels (and reduce CO_2 emissions) can under certain conditions increase fertilizer consumption and associated emissions of greenhouse gases.

Another important interaction concerns the relationship between the availability of nitrogen in soils and leaching of nitrate into groundwater and surface water. Nitrate water pollution is considered a serious issue with regard to drinking water quality and has triggered legislation like the Water Framework Directive. The most important factor for nitrate pollution is input from agricultural soils. Thus, there is a very strong synergy between activities to reduce nitrate in waters and abatement of N_2O emissions into the atmosphere. Nonetheless, a quantification of this interaction requires further work and is beyond the current scope of GAINS.

6 Initial results

6.1 Baseline emission estimates

6.1.1 GAINS estimates

With the approach described in the preceding sections, the GAINS model allows calculation of historic and future emissions of nitrous oxide (N_2O) in Europe. Obviously, national inventories reported to United Nations Framework Convention on Climate Change (UNFCCC) provide an important benchmark for the GAINS Version 1.0 estimates.

Emissions from forest soils and semi-natural land have been attributed to a sector "Forest_indir". While the UNFCCC system does not account for emissions from natural sources and from forest soils, GAINS collects these emissions as a basis for further studies on important interactions with nitrogen deposition from air pollution. However, when comparing GAINS Version 1.0 results with other estimates, these emissions should not be included.

Table 6.1 shows the national emission estimates from the GAINS model and compares them to other emission estimates (see Section 6.1.2). Detailed data by source sector are available in the Annex (Table A1). The GAINS emission estimates rely on activity statistics from the RAINS database as of August 2004 (http://www.iiasa.ac.at/rains/), land use activity information (as described in Section 2.3.3), and the emission factors (as described in Section 3.2). Assumptions were made on the implementation of abatement techniques.

For 1990, none of the N_2O-specific options described in Section 4 were assumed to be present. For 2000 (in accordance with the third national assessment reports to UNFCCC), the adipic acid production sector in Germany, France and the UK was considered to be fully controlled. In addition, a reduction of N_2O use of 34 percent has been applied to all countries. The extent of emission abatement developed for other gases than N_2O (specifically, concerning nitrogen oxides, NO_x, for mobile sources and power plants) has been taken from the recent RAINS baseline calculations for the Clean Air For Europe (CAFE) programme of the European Union.

6.1.2 Comparison with other emission estimates

Emission estimates for N_2O are available from a number of sources. This report compares the country/sector totals obtained from GAINS Version 1.0 with data from the official national communications (UNFCCC, 2002) and with the EDGAR inventory, which is a scientific emission inventory of global emissions with a country and grid information (Olivier, 2002). For comparison, the UNFCCC online database as of the end of 2004 has been used. A comparison to the IMAC data developed by the United States EPA (2001) produced very similar conclusions as the UNFCCC data, as it is based on official national information.

Table 6.1 presents the GAINS estimates for 1990 and 2000 in absolute terms and compares them in relative terms with the UNFCCC and EDGAR emissions data. Note, values are larger than 100 percent when the GAINS emission estimate is higher, and vice versa. Additionally, lack of data is caused by incomplete data submission.

The comparison in Table 6.2 points to the fundamental problem of current N_2O emission assessment, i.e., that emissions from soils are associated with very high uncertainty (Winiwarter and Rypdal, 2001). This leads to, in part, extremely large discrepancies for certain countries. Furthermore, country information is not always very consistent (see below). In terms of total emissions, GAINS Version 1.0 tends to produce higher estimates, especially for many important countries. With soil emissions contributing most strongly to the total, the same feature is shown when comparing soil emissions only (see Annex).

Table 6.1: Comparison of GAINS Version 1.0 estimates of nitrous oxide (N_2O) emissions with other emission inventories.

	1990			*2000 (EDGAR, 1995)*		
	GAINS [kt N_2O/yr]	*Ratio GAINS / UNFCCC*	*Ratio GAINS / EDGAR*	*GAINS [kt N_2O/yr]*	*Ratio GAINS / UNFCCC*	*Ratio GAINS / EDGAR*
Albania	7		81%	6		87%
Austria	25	331%	117%	22	271%	105%
Belarus	63		119%	44		120%
Belgium	32	76%	80%	36	84%	91%
Bosnia-Herzegovina	7		189%	6		298%
Bulgaria	36	45%	77%	26	43%	95%
Croatia	12	137%	102%	13	208%	118%
Cyprus	1		65%	1		58%
Czech Republic	34	93%	90%	29	110%	115%
Denmark	32	90%	112%	26	87%	105%
Estonia	9	282%	177%	4	310%	159%
Finland	25	89%	129%	25	106%	134%
France	281	96%	95%	218	88%	75%
Germany	347	124%	122%	194	103%	77%
Greece	35	102%	78%	30	83%	66%
Hungary	29	226%	78%	25	61%	104%
Ireland	28	93%	68%	28	89%	63%
Italy	129	98%	118%	130	93%	121%
Latvia	12	107%	136%	5	119%	137%
Lithuania	21	2220%	157%	16	80%	260%
Luxembourg	2	251%	1135%	2	540%	853%
Macedonia	4		135%	4		98%
Malta	0		141%	0		114%
Moldova	10		94%	8	1884%	108%
Netherlands	62	117%	100%	57	104%	104%
Norway	12	69%	109%	12	71%	106%
Poland	99	140%	90%	89	116%	88%
Portugal	18	70%	78%	19	72%	81%
Romania	75	181%	99%	64	356%	114%
Russia-Kaliningrad	3			2		
Russia-Kola/Karelia	3			2		
Remaining Russia	297	4601%	72%	181	145%	88%
Russia-St. Petersburg.	12			9		
Serbia - Montenegro	21		69%	17		79%
Slovakia	18	89%	122%	10	99%	107%
Slovenia	5	99%	147%	5		143%
Spain	109	128%	92%	124	125%	106%
Sweden	30	131%	144%	30	131%	137%
Switzerland	17	153%	167%	16	140%	166%
Turkey	133		93%	123		93%
Ukraine	182		98%	131		124%
United Kingdom	229	104%	101%	135	95%	63%
TOTAL	2505			1924		

Sources: UNFCCC (2002), EDGAR, RIVM (2001)

Differences between GAINS Version 1.0 and national estimates are smaller for the other sectors, although large differences occur for a few sectors in a few countries. In absence of insight into the detailed national calculation methodology, it is difficult to explain such discrepancies since they have been compiled separately by individual national experts.

Discrepancies between GAINS and EDGAR are much smaller, at least for the dominant category of soil emissions. The consistently lower estimates of EDGAR for the transport sector can be attributed to the introduction of catalytic converters to a major part of the car fleets after 1995. Since the EDGAR estimates relate to 1995 and GAINS estimates refer to 2000, EDGAR estimates do not include these changes. Likewise, EDGAR has not included the important decrease of industrial process emissions from improvements in adipic acid production. In addition, there were important structural breaks in some countries in this time period (e.g., Bosnia/Herzegovina) that lead to large differences between emissions of 1995 and 2000.

Further comparisons of emission details helped to identify the difficulties associated with using official emission reports. Focusing on agricultural emissions, which are responsible for the largest overall share, it should be noted that the national reports of these emission are currently under scrutiny. For Austria, the number of 3.2 kt originally submitted has been recently changed to 9.5 kt by the Federal Environment Agency in the official inventory (Anderl *et al.*, 2003). This change follows a more detailed national emission assessment by Strebl *et al.* (2003), with the revised results now quite close to the GAINS estimate.

For Germany, Kiese and Butterbach-Bahl (2004) arrive at a value of 173 kt/yr from soil modelling with a Denitrification-Decomposition (DNDC) based model. This estimate is between the 195 kt/yr (118 kt of which are direct emissions) reported by Boeckx and van Cleemput (2001) who also use a simplified version of the Intergovernmental Panel on Climate Change (IPCC) methodology and the GAINS estimate of 124 kt/yr. However, the official German figure (UNFCCC, 2002) is only 88 kt N_2O/yr and emission abatement estimates are based on this or on a previous version of this figure (Bates, 2001, Hendriks *et al.*, 1998). In addition, Germany reported emissions of 45 kt N_2O from manure management, a number that is fairly high compared to the GAINS estimate of 8 kt N_2O, which corresponds to the results from Boeckx and van Cleemput (2001).

It is possible that the German report on manure management includes emissions attributed to manure spread on fields, while these emissions are usually attributed to soils. Adding about 35 kt from this source would yield 125 kt/yr N_2O emissions, almost identical to the GAINS estimate. More information on this subject could improve the basis for assessing the efficiency of abatement measures. The quite diverse approaches to assess German soil N_2O emissions, ranging from process modelling to empirical relationships to an emission factor approach, result in a considerable range of the estimates. However, even this large range is much smaller than the general uncertainty of two orders of magnitude as suggested in Houghton *et al.* (1997). The GAINS Version 1.0 estimate is well within the bandwidth of other approaches.

Several studies have been published for the UK emissions in the scientific literature. Table 6.2 compares the results obtained by Sozanka *et al.* (2002) with those by Brown *et al.* (2002) on N_2O emissions from soils, which seemingly have been developed independently at about the same time. In addition, an official emission report is available for the UK (87 kt/yr soil emissions and 5 kt/yr manure management). Estimates by Boeckx and van Cleemput suggest 130 kt/yr soil emissions, of which 81 kt/yr are direct emissions and 5 kt/yr from manure management. As the national inventories and the estimates by Boeckx and van Cleemput (2001) basically rely on the same methodology, it seems useful to compare the numbers presented for agricultural soils and relate them to the GAINS Version 1.0 results (Figure 6.1).

Table 6.2: Estimates of nitrous oxide (N_2O) emissions from agriculture for the UK [kt N_2O/yr].

Sozanska et al. (2002)		*Brown et al. (2002)*		*Chadwick et al., 1999 (animal husbandry only)*		*GAINS Version 1.0*	
Arable	33	Soil	50			4D_soils	85
Grassland	55	Background	53				
Manure applied	79	Indirect	20				
		Manure	9	Manure	5.6	4B_manure	11
				Housing	4.9		
Semi-natural	33					Forest_indir	1
Total agriculture	200		134				97

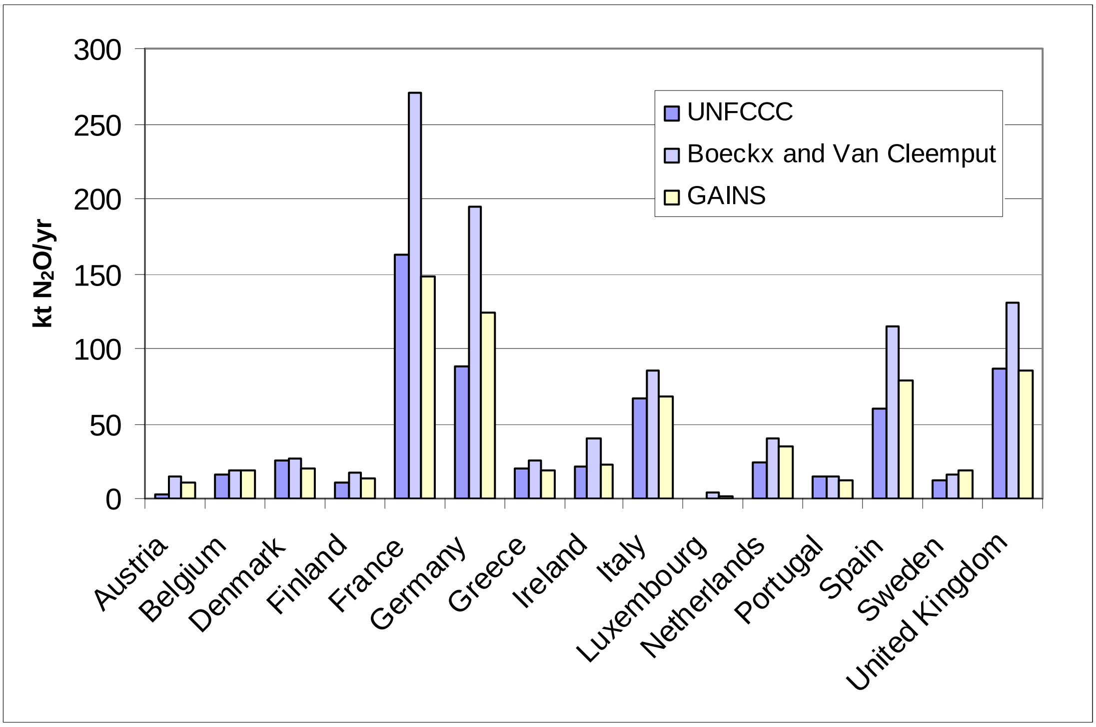

Figure 6.1: Comparison of different emission assessments for the 15 EU countries as of 2000.

Considering the fact that both the UNFCCC data and the results of Boeckx and van Cleemput (2001) rely on different interpretations of the IPCC guidelines, differences are remarkably high for some countries. However, GAINS estimates (even with simplified approaches) seem to match the national assessments quite well and are within the range of other estimates.

Sectoral GAINS estimates are presented in Figure 6.2. This figure clearly shows that the largest contribution of N_2O, more than half of total emissions, originates from agricultural soils including those that previously have been termed indirect emissions. Consequently, countries with large (agricultural) areas dominate the European picture. The fraction of soil emissions is consistent with previous reports (Behrend *et al.*, 2004) - for a detailed comparison see Section 6.1.2. Emissions from forests (caused by deposition of anthropogenic nitrogen compounds) contribute only a few percent, but are not the smallest sector. Changes between 1990 and 2000 are obvious for industrial processes (sectors 2B), where emissions decreased due to introduction of abatement in adipic acid production, and the transport sector (1A3) because of increasing emissions with the introduction of catalytic converters.

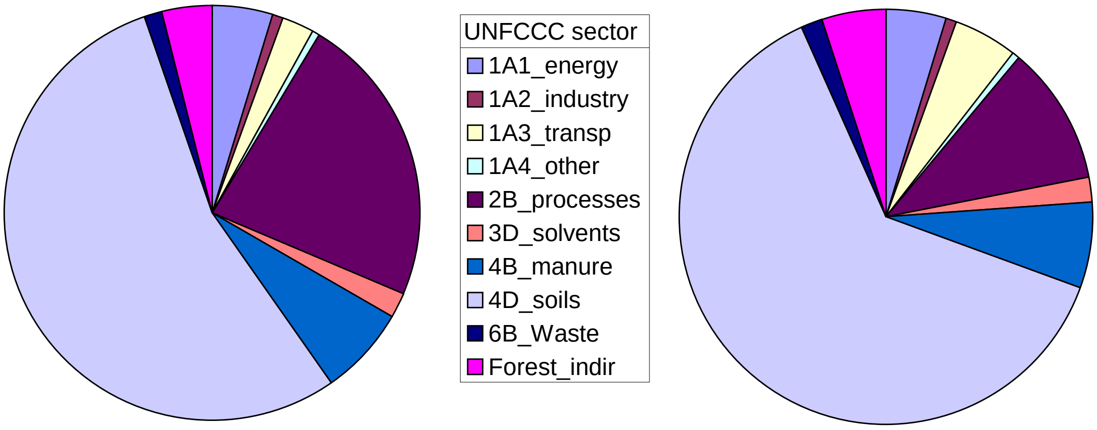

Figure 6.2: Source attribution of European nitrous oxide (N_2O) emissions for 39 countries in GAINS: (a) 1990 (left panel), and (b) 2000 (right panel).

6.2 Projections of future emissions

The GAINS model provides a methodology to estimate future emissions resulting from assumptions on sectoral economic development and on the implementation of mitigation measures. For this report, a “baseline” emission projection has been developed that explores the future evolution of N_2O emissions in the model domain. This “current legislation” baseline projection assumes the presently expected economic growth and the implementation of all emission control measures that are currently laid down in national and international legislation.

6.2.1 Assumed baseline development and current legislation

The GAINS Version 1.0 baseline estimate of future N_2O emissions relies for the 25 EU Member States on the projected activity levels of the baseline scenario of the "Energy Outlook" developed in 2003 by the Directorate General for Energy and Transport of the European Commission (Mantzos *et al.*, 2003). As one basic assumption, this economic projection does not include any climate policy measures beyond those that were already in force in 2003. For the non-EU countries, national reports of activity projections have been used. Details on projected fuel consumption and production levels are available from the RAINS website (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/).

In addition to changes in activity rates, a number of emission control measures directed at other pollutants will influence future levels of N_2O emissions in Europe. The GAINS baseline projection includes all measures that are currently decided and form part of national or EU-wide emission control legislation, the "Current Legislation" (CLE) case. The GAINS baseline assessment of N_2O emissions takes account of the side impacts of these measures.

There are also N_2O specific measures that will influence future N_2O emissions. Further implementation of control equipment in adipic acid production (which is widely in place already in 2000 and expected to be introduced in all countries) and a reduction in fertilizer application (as a consequence of current European common agricultural policy) have been found worthy for inclusion (see Section 4.2). Adipic acid abatement measures are expected to be in place by 2005.

Fertilizer application reduction will start from 2010. Fertilizer application is determined by the need to promote plant growth, but also by the farmers' inclination to insure themselves against crop failure. Both motives support a tendency to over fertilize, despite potential savings in fertilizer costs from a more accurate dose. Changes in the European agricultural system (Common Agricultural Policy of the EU, or CAP) will make subsidies in part independent of production, diminishing at least one reason of applying too much fertilizer.

Nitrate (and phosphate) in groundwater and surface water have been the topic of environmental legislation on water quality, with agricultural practice and fertilizer application being a key contributor. Ultimately, two issues independent of climate change (CAP as currently determined by the Agenda 2000 and the EU Water Framework Directive) will influence emissions of N_2O. Measures that are discussed in the connection with the Water Framework Directive (Footit, 2003) are very similar to those proposed to abate N_2O.

However, no immediate implementation of measures can be expected from the timeline and scope of the Water Framework Directive. Action plans need only to be developed by 2009, implementation is to follow until 2015, with revisions to be audited in 2021 and 2027. Hence, it is presently difficult to assess specific measures from this directive. Experience from the Nitrates Directive indicates a very slow implementation by individual countries (EC, 2002), so that N_2O emissions might only be influenced after 2020. As specific abatement options can not be assessed on a firm basis, GAINS Version 1.0 neglects at this point in time any legislative effects resulting from the Water Directive.

The implementation of the CAP and its reform has been assessed by an EU-supported project CAPRI-DYNASPAT. Results indicate a six percent decrease in N_2O emissions linked to reduced fertilizer use between 2001 and 2009 (Agenda 2000 scenario), with an additional three percent to be achieved after implementation of the MTR (CAPRI-DYNASPAT, 2004). The six percent reduction coincides with the reduction potential of “reduced application of fertilizer”. Furthermore, Bates (2001) assumes a reduction in nitrogenous fertilizer application of eight percent between 1997/8 and 2007/8 due to the impact of agro-environmental schemes. This reduction is already factored in the fertilizer forecasts, which Bates has derived from the European Fertilizer Manufacturers Association.

Potential effects of the CAP reform are not considered in the PRIMES model, which provide the economic projections of the RAINS and GAINS baseline scenarios. Thus, if changes are expected, they need to be fully considered in GAINS. GAINS Version 1.0 applies the full reduction potential of the option “reduced application of fertilizer” in its CLE scenario from 2010 onward. Despite the fact that effects differ from country to country (Bates, 2001), GAINS assumes the same factors for all countries of the EU-25, Norway and Switzerland. For all other countries we do not consider any abatement option. CAP is not part of their current legislation, not even in the EU candidate countries (Bulgaria, Croatia, Rumania, Turkey).

6.2.2 Emissions for the current legislation projection

The resulting baseline projections of N_2O emissions is presented in Table 6.3. Total European N_2O emissions are calculated to decline in the current legislation case without additional climate policies from around 2,400 kt N_2O 1990 to around 2,000 kt in 2010. Afterwards, emissions are calculated to remain constant.

In general, discrepancies identified between the GAINS Version 1.0 base year estimates and other emission inventories propagate over the full time horizon of the emission projections. It is noteworthy that these discrepancies are significantly larger than the changes calculated for current legislation scenario for the next 20 years. This is an important aspect when GAINS emission projections are compared with base year emission estimates from other sources on an absolute basis (Bates, 2002; Hendriks *et al.*, 1998; EPA, 2001).

The graphical display (Figure 6.3) illustrates the expected changes in N_2O emissions by source category. After an initial drop of emissions due to process emissions (adipic acid) and a drop of fertilizer consumption in Eastern Europe, further decreases are more than compensated by the expected growth in fertilizer consumption for the recovering economy in Eastern Europe. In addition, calculations suggest a slight increase in N_2O emissions from transport due to progressing implementation of NO_x control , and an even higher increase in emissions from the energy sector due to increasing shares of fluidized bed combustion.

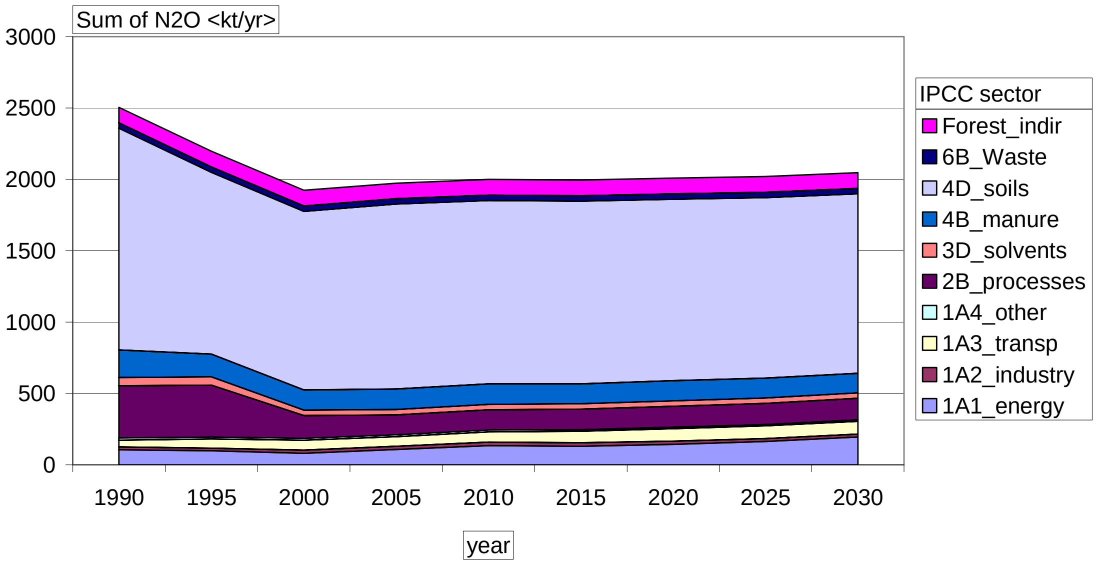

Figure 6.3: Nitrous oxide (N_2O) emissions by source category in Europe (39 countries).

Full details of emissions by sector for the years 2010, 2015 and 2020 are provided in the Annex (Tables A4 – A6). There are no major differences in trends across countries, where emerging differences are caused by changes in the sectoral composition of the emission sources. Additionally, the current legislation (CLE) baseline projection does not reveal significant changes in the sectoral contributions beyond the year 2000 (Figure 6.4).

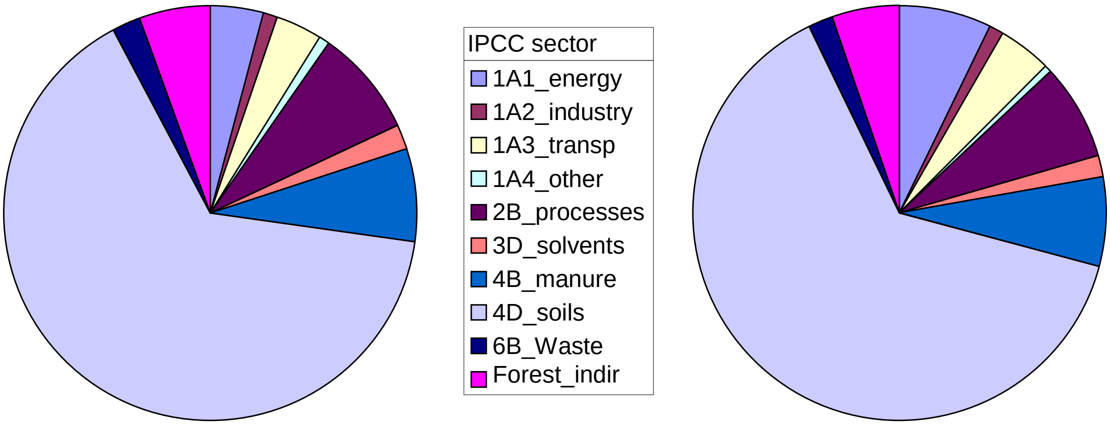

Figure 6.4: Source attribution of European nitrous oxide (N_2O) emissions in GAINS: (a) 2000 (left panel), and (b) 2020 (right panel).

Table 6.3: Baseline emission projections for nitrous oxide (N_2O) and the maximum application of the GAINS Version 1.0 measures [kt N_2O/yr].

			Baseline projection with current legislation (CLE)		*Maximum application of GAINS measures (MTFR)*	
	1990	*2000*	*2010*	*2020*	*2010*	*2020*
Albania	7	6	7	7	5	5
Austria	25	22	21	22	15	15
Belarus	63	44	53	53	28	28
Belgium	32	36	36	36	22	21
Bosnia-Herzegov.	7	6	7	7	6	5
Bulgaria	36	26	35	35	25	23
Croatia	12	13	14	14	9	9
Cyprus	1	1	1	1	1	1
Czech Republic	34	29	30	30	23	21
Denmark	32	26	23	21	18	16
Estonia	9	4	5	5	4	4
Finland	25	25	24	26	17	17
France	281	218	211	210	155	153
Germany	347	194	185	184	131	128
Greece	35	30	31	31	24	21
Hungary	29	25	27	27	19	19
Ireland	28	28	27	25	19	18
Italy	129	130	106	107	78	77
Latvia	12	5	5	6	4	5
Lithuania	21	16	18	19	12	13
Luxembourg	2	2	2	2	1	1
Macedonia	4	4	4	4	3	3
Malta	0	0	0	0	0	0
Moldova	10	8	13	13	9	9
Netherlands	62	57	51	50	29	28
Norway	12	12	11	11	8	8
Poland	99	89	103	105	80	74
Portugal	18	19	20	21	15	15
Romania	75	64	80	79	57	55
Russia-Kaliningrad	3	2	4	4	2	2
Russia-Kola/Karelia	3	2	2	2	2	2
Remaining Russia	297	181	216	216	150	148
Russia St.Petersburg	12	9	10	10	6	6
Serbia-Montenegro	21	17	22	22	16	16
Slovakia	18	10	11	12	8	8
Slovenia	5	5	5	5	4	4
Spain	109	124	114	113	85	82
Sweden	30	30	29	32	22	24
Switzerland	17	16	15	14	10	10
Turkey	133	123	125	131	89	91
Ukraine	182	131	163	162	115	111
United Kingdom	229	135	135	136	99	97
TOTAL	2,505	1,924	2,000	2,009	1,430	1,395

6.2.3 *Mitigation potential from the maximum application of the options*

The current legislation baseline projection has been contrasted with a scenario that explores the extent to which N_2O emissions could be lowered through full application of all mitigation measures that are currently included in GAINS Version 1.0. This is also known as the maximum technologically feasible reduction (MTFR) scenario. For N_2O, such an assessment is complicated by the fact that some control measures directed at other pollutants have positive or negative side impacts on N_2O emissions. For a first assessment, the results presented in this report focus on the N_2O-specific mitigation measures, i.e., the options described in Sections 4.2 to 4.6, and assume the current legislation situation for the other pollutants.

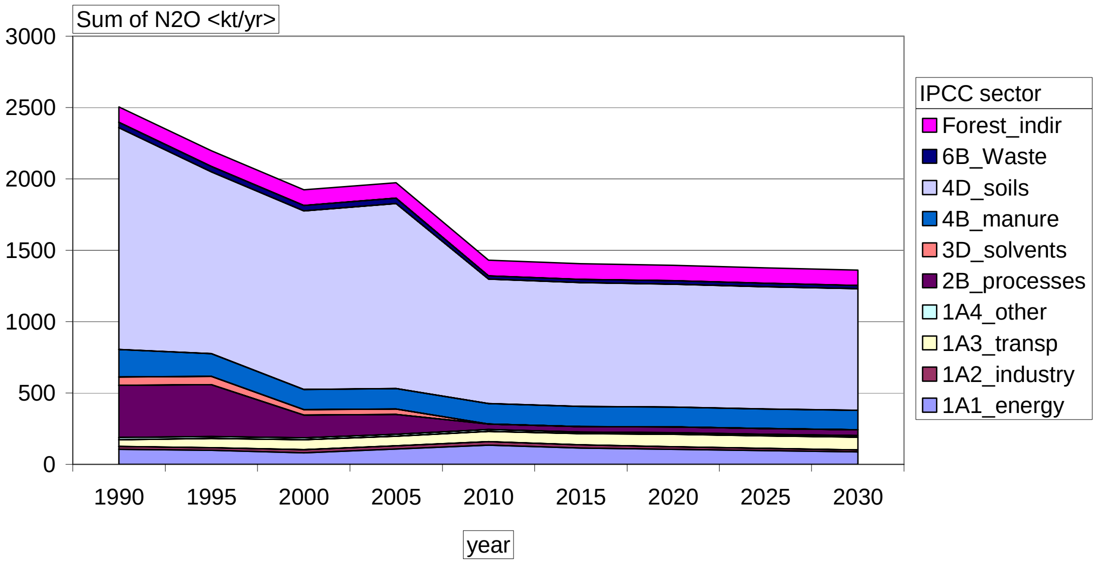

Figure 6.5: Nitrous oxide (N_2O) emissions in Europe (39 countries) after implementation of all N_2O emission control measures considered in the GAINS Version 1.0 model [kt N_2O].

Full application of all N_2O measures contained in the GAINS database could bring lower N_2O emissions of the 39 European countries in 2010, approximately 30 percent below the "current legislation" level (Table 6.3). As shown in Figure 6.5, the largest potential for reductions is computed for soil emissions through lower fertilizer application associated with precision farming, and for industrial processes. Meanwhile, emissions from energy combustion are expected to increase even in the maximum reduction case due to continuing penetration of fluidized bed combustion. The estimated potential for N_2O reduction from precision farming is rather sensitive to the assumption on the possible rate of introduction of such measures in the agricultural sector, which requires a radical change in agricultural practices. Detailed sectoral information for the years 2010, 2015 and 2020 is included in the Annex as Tables A7 to A9.

Table 6.4 compares sectoral emission estimates for different control scenarios from the literature. Unfortunately, a direct comparison of country specific figures is not possible because the studies do not always cover all source categories. Based on information available as of 2004, GAINS Version 1.0 projects a 27 percent decline of N_2O emissions in the EU-15 between 1990 and 2010 for the "current legislation" case. The AEAT estimate of 1998 envisaged for its "business as usual" case a 12 percent decline for the same time horizon, and a 30 percent potential from the application of readily available measures.

An important reason for this difference is related to different assumptions on autonomous changes in the industrial sector. Where GAINS extrapolates actual trends observed between 1990 and recent years, the less optimistic AEAT estimate from 1998 is based on earlier statistics. In addition, in the meantime new information on emission factors from catalyst cars has become available, which is not incorporated in the AEAT (1998) calculation.

Table 6.4: Comparison of emission estimates for historical nitrous oxide (N_2O) emissions, for the current legislation (CLE) and the maximum technologically feasible reduction (MTFR) scenarios in 2020 for the EU-15 by sector [kt N_2O].

		GAINS Version 1.0			*AEAT, 1998*		
	IPCC sector	*1990*	*2020 CLE*	*2020 MFR*	*1990*	*2020 Business as usual*	*2020 with measures*
Energy	1A1	66	73	54	72	72	67
Industry	1A2	12	10	8	30	31	26
Transport	1A3	34	61	61	41	176	167
Other	1A4	7	6	6	36	36	31
Industrial processes	2B	315	104	30	356	145	87
Solvents	3D	29	19	0	9	10	10
Manure	4B	95	65	65			
Soils	4D	754	603	423	612	538	418
Waste	6B	19	19	12	12	13	13
Indirect emission	7				42	44	44
Forest indirect emissions		53	53	53			
Total		1383	1014	713	1215	1071	867

Country-specific estimates are compared in Table 6.5. Again, earlier estimates (Hendriks *et al.*, 1998) have less optimistic expectations on the baseline development that does not take into account the reductions in industrial process emissions that occurred in recent years. EPA (2001) suggests emission reductions primarily due to the common agricultural policy of the EU. All estimates agree that no large changes in N_2O emissions in the EU-15 are expected between 2010 and 2020, unless further measures are introduced. Studies agree on a potential for further reduction of about 300 kt/yr. While both Hendriks *et al.* and GAINS see this potential related to further specific control measures beyond present legislation, the AEAT estimate assumes part of this potential taking place autonomously between 1990 and 2020.

Table 6.5: Comparison of estimates of national emissions of nitrous oxide (N_2O) for the EU-15 countries [kt N_2O].

	GAINS Version 1.0			*Hendriks et al., 1998*			*EPA (2001)*	
	1990	*CLE 2010*	*MFR 2010*	*1990*	*Baseline 2010*	*2010 with measures*	*1990*	*Baseline 2010*
Austria	25	21	15	12	8	8	7	8
Belgium	32	36	22	31	34	23	42	43
Denmark	32	23	18	35	38	37	36	30
Finland	25	24	17	17	19	13	27	27
France	281	211	155	182	178	90	291	257
Germany	347	185	131	226	274	182	226	152
Greece	35	31	24	13	18	17	34	33
Ireland	28	27	19	27	24	20	30	35
Italy	129	106	78	166	156	122	133	140
Luxembourg	2	2	1	0	0	0	1	1
Netherlands	62	51	29	64	78	61	64	77
Portugal	18	20	15	14	14	11	24	28
Spain	109	114	85	95	104	87	136	145
Sweden	30	29	22	9	25	23	24	24
UK	229	135	99	119	131	46	215	143
Total	1383	1014	731	1010	1101	740	1290	1142

A comparison of the contribution of different source sectors (according to GAINS) to overall emissions is presented in Figure 6.6. While overall emissions decline, the sectoral shares do not dramatically change since a significant decrease in soil emissions is matched by a change in process emissions (nitric acid production). Sectors with stable emissions (manure, forest, energy) will become somewhat more important in relative terms, while the share of transport emissions is expected to increase. The disappearance of N_2O use ("solvents") is evident. Overall, soil emissions still remain dominant, even after considerable reductions.

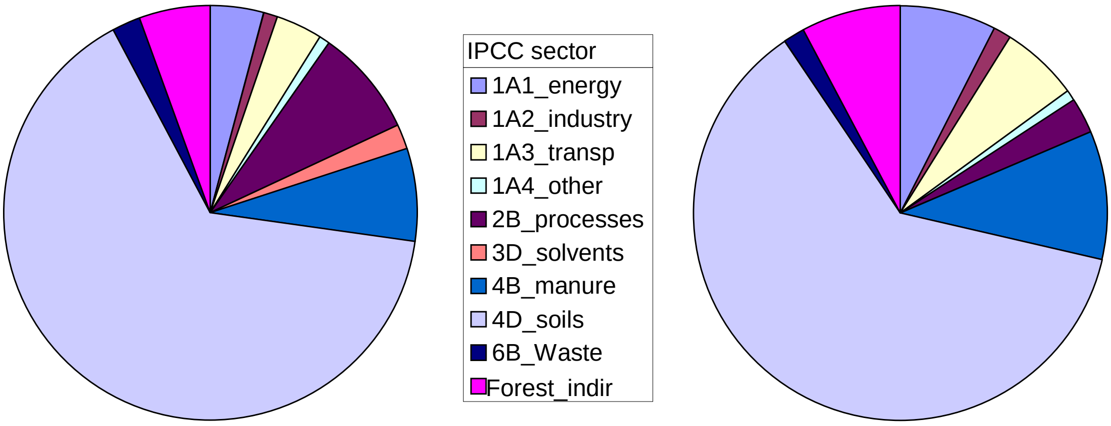

Figure 6.6: Source attribution of European nitrous oxide (N_2O) emissions in GAINS: (a) 2000 (left panel), and (b) 2020 (right panel).

6.3 Costs estimates

6.3.1 Unit costs of mitigation

As mentioned in Section 2.4 , for N_2O all mitigation costs are expressed in a simplified manner as operating costs related to a ton of CO_2-equivalent. Table 6.6 summarizes the costs estimates for the N_2O specific measures that are included in the GAINS N_2O module. Costs of measures that are principally directed at other pollutants but have side impacts on N_2O emissions are discussed elsewhere in the documentation of the GAINS/RAINS model framework.

Table 6.6: Costs of the N_2O mitigation options in GAINS. For the calculation of costs per CO_2-equivalents, a global warming potential of N_2O at 296 times that of CO_2 has been assumed. Agricultural measures are additive, i.e., they can be applied on top of each other.

	Mitigation option	*Abatement costs*	
		[€/t N_2O]	*[€ /t CO_2eq]*
Adipic acid	Catalytic reduction	44	0.15
Nitric acid	Catalytic reduction	130	0.44
Fluidized bed combustion	Combustion modification	1000	3.4
Sewage treatment plants	Process optimization	0	0
Use of N_2O (anaesthetics)	Replacement	200,000	676
Agriculture	Fertilizer reduction	1500	5
Agriculture	Fertilizer timing	10,000	34
Agriculture	Nitrification inhibitors	20,000	68
Agriculture	Precision farming	60,000	203
Agriculture – organic soils	Stop agricultural use	42,000	142

6.3.2 Cost estimates for individual countries

For each country, costs for implementing the current legislation case as well as for applying all measures contained in the GAINS Version 1.0 database can be estimated by combining the unit costs presented above with the country-specific application factor. With unit costs given in Table 6.6 and the interpretation of which measures are included in national legislation (i.e., the reduction in fertilizer use in the EU-25, Switzerland and Norway), national mitigation costs are presented in Table 6.7 for the current legislation (CLE) and the maximum technologically feasible reduction (MTFR) application cases.

As previously mentioned, these estimates do not consider side impacts from other emission control measures directed at other pollutants, and consequently do not include such costs. Further details are given in Annex Tables A6 and A9. The current legislation case will lead to largest changes in N_2O emissions in countries with sizable adipic acid production. Overall, the CLE costs are estimated at 80 million €/year, while the GAINS Version 1.0 databases hold further measures at total costs of 20.5 billion €/year, which could reduce two times more N_2O emissions or about 17 percent of the emissions under the CLE scenario.

Table 6.7: GAINS Version 1.0 estimates of national emission reductions and mitigation costs for nitrous oxide (N_2O) for the year 2020.

	Emission reduction CLE [kt N_2O]	*Cost CLE* [million €/year]*	*Emission reduction MTFR additional to CLE [kt N_2O]*	*Cost of measures MTFR in addition to CLE [million €/year]*
Albania	0.08	0.0	1.93	77.9
Austria	0.86	1.0	6.22	178.0
Belarus	0.26	0.0	24.83	804.8
Belgium	1.33	1.6	14.79	261.9
Bosnia- Hercz..	0.10	0.0	1.45	61.6
Bulgaria	0.21	0.0	11.69	280.2
Croatia	0.12	0.0	5.02	118.3
Cyprus	0.07	0.1	0.30	15.5
Czech Republic	1.34	1.6	9.03	263.7
Denmark	1.21	1.6	5.51	213.0
Estonia	0.24	0.3	1.25	43.8
Finland	0.82	1.0	8.65	195.1
France	66.94	15.1	57.47	1846.8
Germany	90.32	13.7	56.27	2031.1
Greece	1.24	1.5	9.49	252.5
Hungary	1.43	1.8	8.02	274.2
Ireland	1.33	1.8	7.23	220.6
Italy	24.37	6.7	29.89	1156.2
Latvia	0.35	0.4	1.56	66.9
Lithuania	1.05	1.4	5.95	178.8
Luxembourg	0.07	0.1	0.30	12.5
Macedonia	0.05	0.0	1.03	40.2
Malta	0.02	0.0	0.06	4.7
Moldova	0.11	0.0	3.82	134.5
Netherlands	2.05	2.5	22.00	528.0
Norway	0.60	0.7	2.66	117.2
Poland	4.27	4.9	30.44	880.2
Portugal	0.96	1.1	5.50	206.1
Romania	2.10	0.1	23.89	731.2
Russia-Kaliningr.	0.03	0.0	1.12	37.9
Russia-Kola-K	0.18	0.0	0.88	79.0
Remaining Russia	2.68	0.0	67.60	2681.9
Russia-St.Petersb.	0.10	0.0	3.84	155.1
Serbia-Monten.	0.27	0.0	6.60	207.1
Slovakia	0.45	0.5	3.11	101.5
Slovenia	0.22	0.2	1.07	44.5
Spain	5.24	6.3	30.47	1027.0
Sweden	1.35	1.7	8.09	256.0
Switzerland	0.59	0.6	4.23	132.9
Turkey	1.58	0.0	39.59	1412.1
Ukraine	5.50	0.2	51.52	1740.9
UK	76.45	11.1	39.13	1451.0
Total	298.53	79.6	613.53	20522.5

*) Costs for CLE given here do not include costs for reducing N_2O application in hospitals, as this option is assumed to be taken for medical reasons (see section 4.4).

6.3.3 Cost functions

The relation between emission control costs and the associated emission control potentials can be displayed in form of cost functions. Cost functions are specific to each source region reflecting the different relative contributions from the different emission sources. Figure 6.7 presents such cost functions for the Czech Republic, the Ukraine and Norway for the year 2020, showing the measures that remain after implementation of the current legislation. These curves present for different levels of emission reductions (relative to the emissions in the year 1990) and the marginal abatement costs in €/t N_2O.

In all cases, the cost curves start from levels below the 1990 emissions, albeit for different reasons. Similar to the situation of the countries in the EU-15, autonomous technology changes in industry are expected to reduce emissions by 2020 compared to the 1990 levels. In the Czech Republic, a significant potential for cheap reductions exist beyond current legislation through control of nitric acid production and fluidized bed boilers, which are expected to gain a considerable market potential in this country. For the Ukraine, many of the measures that form part of the current legislation in the EU countries (specifically in agriculture) are not yet required by law and thus offer an even larger reduction potential.

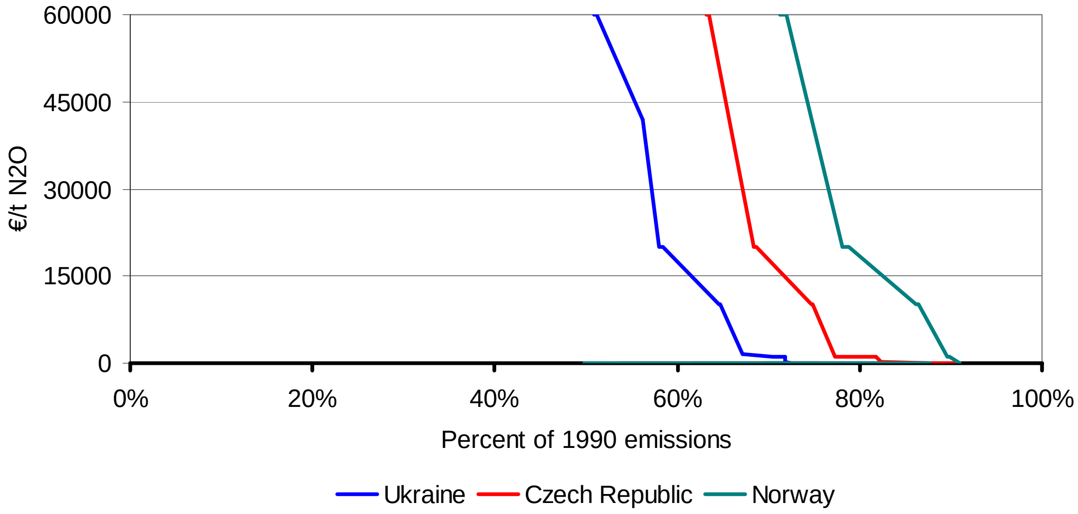

Figure 6.7: National cost curves for N_2O mitigation for the year 2020 for the Czech Republic, the Ukraine and Norway. These curves present marginal abatement costs [€/t N_2O] in relation to the emission levels in the year 1990.

Table 6.9 presents the underlying information for the Czech Republic. In the maximum technologically feasible reduction (MTFR) case, full application of the GAINS measures would achieve a reduction of more than 9 kt out of totally 30 kt N_2O. Only three options are available at moderate costs (i.e., at less than 3,000 €/t N_2O, which is about 10 €/t CO_2eq.). Still, these three options cover more than one third of the total mitigation potential. For comparison, Table 6.9 presents the aggregated cost curve for all 39 countries of the GAINS Version 1.0 model domain.

Table 6.8: Costs and emission reductions for individual nitrous oxide (N_2O) mitigation measures in the Czech Republic in 2020. Options listed in the shaded fields form part of the current legislation (CLE) scenario.

		Unit costs [€/t N_2O]	*Emissions abated [kt N_2O]*	*Total costs [mio €/yr]*	*Incremental abatement [kt N_2O]*	*Incremental costs [mio €/year]*
Arable land	Fertilizer reduction	1,500	1.02	1.53	1.02	1.53
Grassland	Fertilizer reduction	1,500	0.05	0.08	1.07	1.60
Use of N_2O	Replacement	200,000	0.27	53.08	1.34	* 54.69
Sewage treatment plants	Process optimization	0	0.21	0.00	0.21	0.00
Nitric acid	Catalytic reduction	130	1.79	0.23	1.99	0.23
Industry – other combustion	Modifications in FBC	1,000	0.21	0.21	2.20	0.44
Power plants – existing	Modifications in FBC	1,000	0.63	0.63	2.83	1.07
Power plants – new	Modifications in FBC	1,000	0.87	0.87	3.70	1.94
Arable land	Fertilizer timing	10,000	0.85	8.49	4.55	10.43
Grassland	Fertilizer timing	10,000	0.04	0.42	4.59	10.86
Arable land	Nitrification inhibitors	20,000	2.04	40.77	6.63	51.63
Grassland	Nitrification inhibitors	20,000	0.10	2.03	6.73	53.65
Arable land	Precision farming	60,000	1.70	101.92	8.43	155.58
Grassland	Precision farming	60,000	0.08	5.07	8.52	160.65
Use of N_2O (anaesthetics)	Replacement	200,000	0.52	103.05	9.03	263.69

*) Although N_2O replacement will happen for health safety reasons, costs are allocated here to GHG mitigation– see Section 4.4.

While mitigation options exist for the countries in the European Union which form part of the current legislation baseline (reduction of fertilizer use), they offer a considerable potential for further reductions in the other countries. For the entire model domain, about one third of the full mitigation potential considered in GAINS Version 1.0 is assumed to be adopted in the current legislation baseline. A third of the remaining potential represents measures with moderate costs (below 3,000 €/t N_2O, or less than 10 €/t CO_2-eq), while costs start rising quickly for the remaining measures.

Table 6.9: Costs and emission reductions for individual nitrous oxide (N_2O) mitigation measures in the entire GAINS model domain (39 countries) in 2020. Options listed in the shaded fields form part of the current legislation (CLE) scenario.

		Unit costs [€/t N_2O]	*Emissions abated [kt N_2O]*	*Total costs [mill €/yr]*	*Incremental mitigation [kt N_2O]*	*Incremental costs [million €/yr]*
Adipic acid production	Catalytic reduction	0	233	10	233	10
Arable land	Fertilizer reduction	1,500	36	54	269	65
Grassland	Fertilizer reduction	1,500	10	15	279	80
Use of N_2O	Replacement	200,000	20	3920	299	4000
Sewage treatment plants	Process optimization	5	15	0	15	0
Nitric acid production	Catalytic reduction	130	107	14	122	14
Conversion / combustion	Modifications in FBC	1,000	0	0	122	14
Industrial Boilers	Modifications in FBC	1,000	0	0	122	14
Industry – other combustion	Modifications in FBC	1,000	5	5	127	19
Power plants – existing	Modifications in FBC	1,000	12	12	139	31
Power plants – new	Modifications in FBC	1,000	26	26	165	57
Grassland	Fertilizer reduction	1,500	27	40	192	98
Arable land	Fertilizer reduction	1,500	4	6	196	103
Grassland	Fertilizer timing	10,000	53	527	249	630
Arable land	Fertilizer timing	10,000	12	116	260	746
Grassland	Nitrification inhibitors	20,000	126	2527	386	3273
Arable land	Nitrification inhibitors	20,000	28	556	414	3829
Agriculture – organic soils	Stop agricultural use	42,000	33	1376	447	5205
Grassland	Precision farming	60,000	105	6319	552	11524
Arable land	Precision farming	60,000	23	1389	575	12913
Use of N_2O (anaesthetics)	Replacement	200,000	38	7610	614	20522

7 Conclusions

GAINS Version 1.0 assesses present and future emissions of nitrous oxide (N_2O) from anthropogenic sources in Europe and estimates the available potential for mitigation and the associated costs. From this first implementation, the following conclusions can be drawn:

- In Europe, emissions from soils are generally considered the most important source of N_2O, followed by industrial process emissions.
- There are important inconsistencies in the existing national emission inventory (at least those published in 2003). Although these inventories are supposedly based on the same standard guidelines to assess emissions, the interpretation of these guidelines by different experts leads to inconsistent results, e.g., concerning the differentiation of animal manure and soil emissions. GAINS attempts a consistent methodology, which unavoidably results in discrepancies with some national estimates.
- A number of emissions controls directed at other pollutants (e.g., nitrogen oxides, NO_x, or methane, CH_4) have positive or negative impacts on N_2O emissions. Some of the earlier projections of N_2O emissions have not taken full account of these interactions. The GAINS approach puts its focus on these linkages.
- There is new insight into some autonomous technological developments that lead as a side-effect to reduced N_2O emissions. Consequently, recent information on technological changes indicates for the past years a significant decline in N_2O emissions, especially from adipic and nitric acid production.
- Catalytic reduction of N_2O from industrial processes (adipic and nitric acid production), optimizing sewage treatment, modifications in fluidized bed combustion, and reduction of fertilizer application in agriculture can reduce N_2O at unit costs of between 1,500 to 6,000 €/t N_2O, which corresponds to 5 to 20 €/t CO_2 –equivalent. Current legislation in EU countries addresses only some of these measures, which leaves an additional potential for further mitigation.
- The remaining two thirds of the overall mitigation potential (on top of current legislation) are associated with high or even excessive costs. However, since some of these options address other critical issues at the same time (e.g., soil nitrogen in connection with the water framework directive, N_2O use in hospitals for medical reasons), they might materialize in the future.
- N_2O emissions from non-agricultural soils induced from the atmospheric deposition of NO_x and ammonia (NH_3) - though of clearly anthropogenic origin - have not been counted as anthropogenic emissions by the Intergovernmental Panel on Climate Change (IPCC) methodology. However, the inclusion of such emissions to obtain full coverage of man-made N_2O flows would not strongly alter N_2O emissions from European countries.

Until recently, there was only little attention paid to the greenhouse gas mitigation potential offered by controlling N_2O emissions. Some actions that have been taken in the past for other reasons lead, as a side-effect, to lower N_2O emissions. Also in the future, changes in agricultural policy and concerns about water quality will have major influence on the application of nitrogen on soils, and consequently on N_2O emissions from agriculture. Advancement in anaesthesia practice of hospitals may also reduce N_2O consumption. Process changes in wastewater plants and in chemical industry may – as a side effect – avoid N_2O formation. Furthermore, a few options still exist (i.e., modifications in NO_x abating technologies like fluidized bed combustion, or catalytic reduction in nitric acid production), that could offer cost-effective potentials for reducing greenhouse gas emissions.

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Annex – detailed information

List of annex tables:

Table A1. N_2O emissions (kt/yr) according to GAINS by IPCC source sector for 2000

Region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Albania	0.010	0.006	0.038	0.048		0.157	0.459	4.245	0.160	1.016	6.139
Austria	0.624	0.144	1.199	0.362	2.850	0.405	2.143	11.043	0.412	2.854	22.035
Belarus	0.819	0.039	0.339	0.120	3.711	0.511	3.051	32.949	0.520	1.623	43.680
Belgium	1.157	0.983	1.309	0.187	10.089	0.514	2.854	18.083	0.523	0.572	36.270
Bosnia & Herzegovina	0.712	0.019	0.055	0.010		0.199	0.482	2.370	0.203	1.916	5.967
Bulgaria	1.745	0.153	0.192	0.117	3.933	0.399	1.249	15.074	0.405	2.953	26.220
Croatia	0.122	0.054	0.154	0.094	2.006	0.233	0.615	7.588	0.237	1.837	12.940
Cyprus	0.022	0.017	0.153	0.002		0.037	0.102	0.819	0.038	0.006	1.196
Czech Republic	3.266	1.105	0.610	0.102	1.744	0.515	1.484	18.220	0.524	1.462	29.033
Denmark	1.676	0.167	0.930	0.114		0.267	1.741	20.505	0.271	0.197	25.868
Estonia	0.522	0.037	0.085	0.062		0.070	0.195	2.293	0.071	0.822	4.157
Finland	2.710	1.067	0.738	0.225	3.466	0.259	1.581	12.996	0.264	1.535	24.841
France	2.760	2.108	7.496	1.752	17.090	2.971	20.642	147.651	3.021	12.123	217.615
Germany	9.341	2.059	13.819	1.585	18.193	4.114	7.901	124.353	4.183	8.536	194.084
Greece	3.342	0.330	1.301	0.192	2.457	0.532	0.548	18.401	0.541	2.162	29.806
Hungary	0.689	0.062	0.505	0.110	1.756	0.500	1.349	17.699	0.508	1.668	24.846
Ireland	0.780	0.071	0.671	0.085	1.357	0.191	2.106	22.437	0.194	0.180	28.070
Italy	3.133	0.907	6.375	0.869	27.593	2.886	7.672	68.349	2.934	8.800	129.518
Latvia	0.056	0.034	0.070	0.024		0.121	0.453	3.555	0.123	0.512	4.949
Lithuania	0.027	0.011	0.140	0.100	1.476	0.185	0.598	13.033	0.189	0.527	16.284
Luxembourg	0.005	0.043	0.351	0.012		0.022	0.091	0.956	0.022	0.119	1.620

Region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Macedonia (FYROM)	0.350	0.010	0.052	0.002		0.102	0.297	2.189	0.104	0.634	3.742
Malta	0.013		0.052	0.001		0.018	0.023	0.105	0.019	0.001	0.232
Moldova	0.228	0.077	0.057	0.056		0.215	0.700	6.200	0.219	0.536	8.289
Netherlands	2.273	0.454	2.666	0.117	13.167	0.796	1.297	35.079	0.809	0.260	56.918
Norway	0.052	0.538	0.898	0.116		0.224	0.195	8.592	0.228	1.013	11.856
Poland	9.060	1.846	1.912	0.914	7.530	1.936	11.033	50.056	1.969	2.910	89.165
Portugal	1.558	0.247	0.965	0.220	1.060	0.502	1.080	11.605	0.511	1.497	19.245
Romania	1.738	0.271	0.338	0.477	5.469	1.125	4.951	43.104	1.144	5.233	63.850
Russia (Kaliningrad)	0.034	0.009	0.025	0.009		0.049	0.164	2.030	0.050	0.059	2.430
Russia (Karelia/Kola)	0.186	0.052	0.123	0.042		0.347	0.087	0.602	0.352	0.316	2.108
Remaining Russia	2.661	0.985	3.367	1.728	2.377	5.209	14.920	129.678	5.297	15.132	181.354
Russia (St. Petersburg)	0.285	0.068	0.171	0.182		0.186	0.653	6.208	0.189	0.794	8.737
Serbia / Montenegro	1.557	0.086	0.200	0.020	0.809	0.529	1.882	9.566	0.538	2.206	17.394
Slovakia	0.571	0.189	0.230	0.033	0.769	0.271	0.569	5.134	0.275	1.788	9.830
Slovenia	0.283	0.024	0.273	0.078		0.100	0.296	2.605	0.101	1.189	4.949
Spain	8.150	0.753	4.022	0.488	7.336	2.002	9.828	79.138	2.035	10.049	123.802
Sweden	1.048	1.137	1.929	0.159	1.037	0.444	1.620	18.882	0.451	2.877	29.582
Switzerland	0.163	0.327	2.043	0.172	2.987	0.360	1.247	7.262	0.366	1.569	16.494
Turkey	2.497	2.351	1.769	1.566	3.688	3.075	11.088	90.180	3.126	3.554	122.893
Ukraine	3.992	2.237	1.238	0.419	5.859	2.486	11.258	96.969	2.528	4.174	131.161
United Kingdom	11.104	0.880	8.981	0.415	10.831	2.980	10.654	84.959	3.030	1.304	135.138
TOTAL	81.317	21.956	67.841	13.384	160.641	38.048	141.159	1252.762	38.686	108.514	1924.307

Table A2. Comparison of GAINS N_2O emissions to UNFCCC data: ration expressed in % by IPCC source sector for the year 2000.

Ratio to UNFCCC <%>	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Grand Total
Austria	416%	27%	67%	35%	491%	54%		347%	412%	271%
Belgium	126%	79%	56%	10%	76%	214%	46%	115%	83%	84%
Bulgaria	25%	28%	160%	49%	167%		83%	31%	71%	43%
Croatia	407%	180%	513%	157%			77%	144%		208%
Czech Republic	151%	170%	37%	33%	48%	75%	109%	119%	81%	110%
Denmark	202%	93%	75%	39%			123%	81%		87%
Estonia	1044%		851%	88%			650%	194%		310%
Finland	261%	63%	33%	24%	81%	130%	122%	115%	98%	106%
France	151%	78%	63%	39%	55%	149%	226%	91%	86%	88%
Germany	77%	55%	83%	84%	111%		18%	141%	105%	103%
Greece	48%	21%	60%	14%	134%		64%	90%	773%	83%
Hungary	405%	103%	389%	110%	135%		53%	48%	635%	61%
Ireland	40%	14%	56%	7%	52%		96%	104%	92%	89%
Italy	44%	24%	62%	8%	110%		62%	103%	78%	93%
Latvia	112%	114%	47%	29%		1214%	92%	116%	51%	119%
Lithuania	46%	106%	698%	100%	8%			790%		80%
Luxembourg		214%	219%	58%					74%	540%
Moldova	2280%		192%	23%				5167%	730%	1884%
Netherlands	541%	649%	133%	167%	57%	159%	206%	148%	142%	104%
Norway	65%	384%	47%	48%	0%	187%		105%	63%	71%
Poland	358%	177%	101%	53%	54%		59%	145%	74%	116%

Ratio to UNFCCC <%>	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Grand Total
Portugal	487%	95%	59%	12%	54%		28%	78%	28%	72%
Romania	27%	19%	121%	16%				662%	498%	356%
Russian Federation	67%				238%			124%	46%	145%
Slovakia	634%	189%	46%	110%	160%		34%	73%	918%	99%
Spain	193%	12%	60%	16%	99%	141%	210%	132%	43%	125%
Sweden	71%	59%	95%	14%	47%		86%	162%		131%
Switzerland		817%	99%	90%	963%	92%	91%	104%	111%	140%
United Kingdom	131%	30%	66%	26%	54%		230%	98%	80%	95%

Table A3. Comparison of GAINS N_2O emissions to EDGAR data: ration expressed in % by IPCC source sector for the year 2000. Note that EDGAR data are for 1995

Ratio to EDGAR <%>	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Grand Total
Albania	929%	212%	559%	65%	0%		45%	84%	796%	87%
Austria	414%	224%	327%	189%	51%	202%	137%	86%	1697%	105%
Belarus	597%	52%	637%	63%	35%		47%	180%	103%	120%
Belgium	477%	578%	313%	86%	76%	203%	124%	101%	11%	91%
Bosnia & Herzegovina	4204%	58%	499%	10%			117%	169%	886%	298%
Bulgaria	231%	78%	2512%	81%	30%		121%	124%	147%	95%
Croatia	48%	66%	557%	63%	53%		78%	133%	146%	118%
Cyprus	137%	168%	1242%	119%	0%		78%	52%	36%	58%
Czech Republic	385%	485%	617%	126%	29%		56%	124%	89%	115%
Denmark	426%	262%	462%	149%	0%	204%	64%	111%	11%	105%
Estonia	310%	145%	724%	112%			34%	132%	137%	159%
Finland	664%	1011%	435%	114%	69%	203%	232%	125%	22%	134%
France	487%	356%	496%	172%	23%	205%	208%	82%	15%	75%
Germany	215%	209%	307%	112%	29%	202%	77%	82%	29%	77%
Greece	694%	263%	429%	117%	53%	204%	64%	49%	205%	66%
Hungary	336%	144%	866%	50%	42%		87%	105%	72%	104%
Ireland	538%	257%	763%	100%	49%	215%	95%	60%	10%	63%
Italy	317%	189%	452%	155%	203%	202%	162%	82%	1328%	121%
Latvia	309%	151%	383%	19%			60%	135%	275%	137%
Lithuania	118%	22%	489%	72%			39%	299%	148%	260%

Ratio to EDGAR <%>	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Grand Total
Luxembourg	919%	285%	556%	131%		215%			30%	853%
Macedonia (FYROM)	415%	66%	690%	2%			69%	70%	354%	98%
Malta	95%	0%	885%	342%			76%	74%	4751%	114%
Moldova	564%	409%	543%	99%			60%	99%	203%	108%
Netherlands	544%	175%	494%	109%	109%	206%	29%	117%	14%	104%
Norway	80%	507%	548%	167%	0%	207%	34%	94%	30%	106%
Poland	425%	160%	971%	105%	31%		105%	82%	115%	88%
Portugal	608%	245%	894%	376%	41%	205%	93%	65%	58%	81%
Romania	359%	151%	487%	234%	37%		90%	127%	116%	114%
Russian Federation	39%	68%	696%	28%	46%		30%	98%	145%	88%
Serbia/Montenegro	321%	61%	1138%	27%	43%		39%	68%	184%	79%
Slovakia	488%	195%	756%	42%	87%		47%	85%	38%	107%
Slovenia	533%	210%	827%	145%			46%	101%	119%	143%
Spain	740%	207%	497%	174%	74%	202%	171%	92%	19%	106%
Sweden	568%	954%	408%	59%	32%	202%	159%	131%	31%	137%
Switzerland	731%	769%	381%	100%	664%	201%	120%	99%	3166%	166%
Turkey	462%	671%	643%	501%	73%	202%	68%	86%	161%	93%
Ukraine	280%	195%	225%	36%	230%		48%	132%	156%	124%
United Kingdom	503%	132%	480%	85%	16%	205%	171%	71%	27%	63%

Table A4. N_2O emissions (kt/yr) by country and source sector at current legislation – projection for 2010

region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Albania	0.013	0.007	0.056	0.042		0.157	0.459	5.164	0.160	1.016	7.075
Austria	0.913	0.051	1.203	0.388	2.896	0.405	1.683	10.411	0.412	2.854	21.216
Belarus	0.706	0.070	0.443	0.124	4.241	0.511	3.051	41.559	0.520	1.623	52.847
Belgium	0.457	1.261	1.651	0.159	10.744	0.514	2.733	17.281	0.523	0.572	35.894
Bosnia & Herzegovina	1.451	0.025	0.077	0.010		0.199	0.482	2.370	0.203	1.916	6.735
Bulgaria	3.496	0.154	0.301	0.128	3.654	0.399	1.820	22.160	0.405	2.953	35.472
Croatia	0.240	0.052	0.181	0.080	2.257	0.233	0.615	7.925	0.237	1.837	13.657
Cyprus	0.029	0.021	0.207	0.004		0.037	0.111	0.843	0.038	0.006	1.297
Czech Republic	5.733	1.168	0.803	0.060	2.035	0.515	1.351	16.468	0.524	1.462	30.119
Denmark	2.345	0.136	0.890	0.112		0.267	1.400	17.434	0.271	0.197	23.053
Estonia	1.068	0.068	0.131	0.050		0.070	0.188	2.604	0.071	0.822	5.072
Finland	2.950	0.807	0.769	0.293	3.562	0.259	1.596	11.979	0.264	1.535	24.015
France	4.875	2.471	8.224	1.639	17.997	2.971	20.097	137.198	3.021	12.123	210.616
Germany	11.983	2.225	12.472	1.601	18.667	4.114	6.677	114.046	4.183	8.536	184.504
Greece	6.864	0.305	1.507	0.217	2.753	0.532	0.560	15.947	0.541	2.162	31.388
Hungary	2.029	0.117	0.746	0.082	1.813	0.500	1.417	17.662	0.508	1.668	26.542
Ireland	1.171	0.104	0.803	0.103	1.419	0.191	2.210	20.207	0.194	0.180	26.581
Italy	4.821	0.659	7.375	0.664	8.923	2.886	7.378	61.950	2.934	8.800	106.389
Latvia	0.180	0.029	0.134	0.025		0.121	0.460	3.856	0.123	0.512	5.440
Lithuania	0.437	0.012	0.222	0.090	1.391	0.185	0.608	14.060	0.189	0.527	17.720
Luxembourg	0.031	0.040	0.327	0.010		0.022	0.084	0.936	0.022	0.119	1.591
Macedonia (FYROM)	0.660	0.011	0.070	0.002		0.102	0.297	2.189	0.104	0.634	4.071

region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Malta	0.018		0.074	0.001		0.018	0.022	0.110	0.019	0.001	0.263
Moldova	0.510	0.157	0.072	0.050		0.215	0.700	10.153	0.219	0.536	12.613
Netherlands	1.731	0.553	2.432	0.110	12.808	0.796	1.368	30.206	0.809	0.260	51.074
Norway	0.096	0.596	0.740	0.095		0.224	0.188	7.736	0.228	1.013	10.916
Poland	21.160	2.497	2.269	0.790	7.649	1.936	11.986	50.005	1.969	2.910	103.172
Portugal	2.455	0.170	1.293	0.263	1.026	0.502	1.059	11.184	0.511	1.497	19.961
Romania	4.805	0.305	0.802	0.434	3.671	1.125	6.418	56.160	1.144	5.233	80.097
Russia (Kaliningrad)	0.071	0.016	0.032	0.009		0.049	0.178	3.111	0.050	0.059	3.575
Russia (Karelia/Kola)	0.427	0.079	0.139	0.044		0.347	0.098	0.634	0.352	0.316	2.437
Remaining Russia	6.196	1.722	3.937	2.160	2.713	5.209	16.326	157.150	5.297	15.132	215.842
Russia (St. Petersburg)	0.613	0.114	0.215	0.203		0.186	0.715	7.154	0.189	0.794	10.182
Serbia / Montenegro	3.982	0.164	0.242	0.014	0.912	0.529	1.882	11.098	0.538	2.206	21.568
Slovakia	1.649	0.340	0.359	0.049	0.787	0.271	0.554	4.782	0.275	1.788	10.854
Slovenia	0.647	0.017	0.314	0.054		0.100	0.278	2.597	0.101	1.189	5.296
Spain	6.927	0.534	5.609	0.414	8.048	2.002	9.721	68.789	2.035	10.049	114.129
Sweden	1.909	1.189	1.366	0.134	1.111	0.444	1.389	17.777	0.451	2.877	28.646
Switzerland	0.233	0.364	1.228	0.118	2.468	0.360	1.206	6.604	0.366	1.569	14.515
Turkey	8.279	3.298	3.095	1.232	3.676	3.075	9.217	86.512	3.126	3.554	125.065
Ukraine	9.502	3.621	1.480	0.425	1.846	2.486	13.209	123.507	2.528	4.174	162.778
United Kingdom	8.999	0.632	8.755	0.352	11.224	2.980	11.320	86.708	3.030	1.304	135.306
TOTAL	132.664	26.162	73.044	12.834	140.292	38.048	143.111	1286.228	38.686	108.514	1999.583

Table A5. N_2O emissions (kt/yr) by country and source sector at current legislation – projection for 2015

region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Albania	0.014	0.008	0.065	0.043		0.157	0.459	5.164	0.160	1.016	7.086
Austria	0.966	0.052	1.286	0.388	2.918	0.405	1.645	10.296	0.412	2.854	21.222
Belarus	0.289	0.067	0.503	0.075	4.503	0.511	3.051	41.559	0.520	1.623	52.701
Belgium	0.616	1.184	1.687	0.157	10.836	0.514	2.648	17.001	0.523	0.572	35.739
Bosnia & Herzegovina	1.397	0.024	0.090	0.010		0.199	0.482	2.370	0.203	1.916	6.692
Bulgaria	3.165	0.154	0.384	0.120	3.637	0.399	1.820	22.160	0.405	2.953	35.197
Croatia	0.256	0.052	0.200	0.074	2.383	0.233	0.615	7.925	0.237	1.837	13.811
Cyprus	0.035	0.023	0.228	0.004		0.037	0.112	0.848	0.038	0.006	1.332
Czech Republic	5.509	1.019	0.835	0.047	2.143	0.515	1.318	16.605	0.524	1.462	29.977
Denmark	2.035	0.098	0.840	0.107		0.267	1.370	17.178	0.271	0.197	22.363
Estonia	0.903	0.068	0.142	0.043		0.070	0.185	2.858	0.071	0.822	5.163
Finland	4.396	0.805	0.769	0.294	3.574	0.259	1.554	11.882	0.264	1.535	25.332
France	5.332	2.119	9.326	1.598	18.322	2.971	19.562	134.798	3.021	12.123	209.173
Germany	11.914	2.030	12.687	1.620	18.895	4.114	6.466	112.867	4.183	8.536	183.312
Greece	6.519	0.290	1.467	0.219	2.867	0.532	0.553	15.664	0.541	2.162	30.813
Hungary	1.903	0.125	0.826	0.076	1.841	0.500	1.423	17.997	0.508	1.668	26.867
Ireland	0.933	0.103	0.881	0.101	1.442	0.191	2.120	19.772	0.194	0.180	25.914
Italy	4.772	0.658	7.375	0.578	9.043	2.886	7.207	61.528	2.934	8.800	105.781
Latvia	0.254	0.029	0.176	0.024		0.121	0.476	4.107	0.123	0.512	5.823
Lithuania	0.659	0.014	0.266	0.087	1.414	0.185	0.602	14.491	0.189	0.527	18.434
Luxembourg	0.029	0.041	0.371	0.010		0.022	0.083	0.899	0.022	0.119	1.596
Macedonia (FYROM)	0.611	0.014	0.079	0.003		0.102	0.297	2.189	0.104	0.634	4.033

region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Malta	0.024		0.083	0.002		0.018	0.022	0.111	0.019	0.001	0.280
Moldova	0.485	0.163	0.078	0.039		0.215	0.700	10.153	0.219	0.536	12.587
Netherlands	1.412	0.569	2.703	0.110	12.757	0.796	1.356	29.644	0.809	0.260	50.415
Norway	0.123	0.568	0.762	0.080		0.224	0.191	7.689	0.228	1.013	10.879
Poland	20.839	2.660	2.391	0.728	7.666	1.936	11.934	50.626	1.969	2.910	103.660
Portugal	2.392	0.164	1.420	0.292	1.026	0.502	1.034	11.142	0.511	1.497	19.980
Romania	5.362	0.306	1.149	0.353	3.728	1.125	6.418	56.160	1.144	5.233	80.978
Russia (Kaliningrad)	0.070	0.016	0.036	0.009		0.049	0.178	3.111	0.050	0.059	3.578
Russia (Karelia/Kola)	0.429	0.076	0.147	0.043		0.347	0.098	0.634	0.352	0.316	2.443
Remaining Russia	6.201	1.331	4.264	2.118	2.884	5.209	16.326	157.150	5.297	15.132	215.914
Russia (St. Petersburg)	0.596	0.105	0.238	0.199		0.186	0.715	7.154	0.189	0.794	10.176
Serbia / Montenegro	4.260	0.215	0.260	0.011	0.963	0.529	1.882	11.098	0.538	2.206	21.964
Slovakia	1.987	0.309	0.438	0.036	0.792	0.271	0.550	4.850	0.275	1.788	11.298
Slovenia	0.648	0.016	0.289	0.047		0.100	0.270	2.582	0.101	1.189	5.242
Spain	5.956	0.587	6.105	0.421	8.385	2.002	9.553	67.605	2.035	10.049	112.698
Sweden	2.989	1.225	1.357	0.129	1.134	0.444	1.347	17.657	0.451	2.877	29.608
Switzerland	0.213	0.356	1.181	0.096	2.383	0.360	1.189	6.522	0.366	1.569	14.232
Turkey	8.961	2.310	4.706	1.200	3.842	3.075	9.217	86.512	3.126	3.554	126.504
Ukraine	8.921	3.609	1.698	0.428	1.949	2.486	13.209	123.507	2.528	4.174	162.510
United Kingdom	6.405	0.542	9.156	0.366	11.537	2.980	10.961	86.181	3.030	1.304	132.463
TOTAL	130.779	24.105	78.944	12.382	142.863	38.048	141.200	1280.249	38.686	108.514	1995.770

Table A6. N_2O emissions (kt/yr) by country and source sector at current legislation – projection for 2020

region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Albania	0.015	0.009	0.075	0.043		0.157	0.459	5.164	0.160	1.016	7.097
Austria	1.506	0.055	1.369	0.371	2.935	0.405	1.599	10.163	0.412	2.854	21.670
Belarus	0.252	0.065	0.566	0.040	4.765	0.511	3.051	41.559	0.520	1.623	52.952
Belgium	1.171	1.097	1.875	0.149	10.881	0.514	2.559	16.623	0.523	0.572	35.964
Bosnia & Herzegovina	1.342	0.023	0.103	0.011		0.199	0.482	2.370	0.203	1.916	6.650
Bulgaria	3.062	0.145	0.443	0.106	3.648	0.399	1.820	22.160	0.405	2.953	35.142
Croatia	0.273	0.052	0.212	0.068	2.508	0.233	0.615	7.925	0.237	1.837	13.960
Cyprus	0.042	0.022	0.244	0.004		0.037	0.113	0.853	0.038	0.006	1.359
Czech Republic	5.264	0.807	0.859	0.039	2.234	0.515	1.295	16.762	0.524	1.462	29.762
Denmark	1.325	0.061	0.844	0.105		0.267	1.335	16.823	0.271	0.197	21.228
Estonia	0.848	0.065	0.144	0.034		0.070	0.184	3.119	0.071	0.822	5.358
Finland	4.907	0.815	0.808	0.285	3.585	0.259	1.504	11.760	0.264	1.535	25.723
France	9.107	2.008	10.227	1.458	18.572	2.971	18.923	131.807	3.021	12.123	210.219
Germany	14.089	1.745	13.117	1.589	19.105	4.114	6.242	111.211	4.183	8.536	183.931
Greece	6.601	0.236	1.558	0.215	2.987	0.532	0.544	15.188	0.541	2.162	30.563
Hungary	1.884	0.119	0.861	0.067	1.870	0.500	1.430	18.321	0.508	1.668	27.228
Ireland	0.923	0.079	0.955	0.102	1.465	0.191	2.028	19.222	0.194	0.180	25.338
Italy	6.586	0.651	7.758	0.525	9.157	2.886	6.989	60.869	2.934	8.800	107.155
Latvia	0.381	0.028	0.192	0.019		0.121	0.503	4.489	0.123	0.512	6.368
Lithuania	0.836	0.015	0.309	0.076	1.465	0.185	0.598	14.932	0.189	0.527	19.131
Luxembourg	0.061	0.039	0.383	0.009		0.022	0.079	0.855	0.022	0.119	1.589
Macedonia (FYROM)	0.561	0.016	0.087	0.002		0.102	0.297	2.189	0.104	0.634	3.993

region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Malta	0.023		0.091	0.002		0.018	0.022	0.106	0.019	0.001	0.282
Moldova	0.459	0.168	0.084	0.027		0.215	0.700	10.153	0.219	0.536	12.562
Netherlands	1.181	0.541	2.945	0.107	12.717	0.796	1.341	28.851	0.809	0.260	49.549
Norway	0.165	0.523	0.804	0.068		0.224	0.195	7.623	0.228	1.013	10.842
Poland	21.065	2.726	2.702	0.627	7.763	1.936	11.887	51.256	1.969	2.910	104.842
Portugal	2.815	0.157	1.621	0.321	1.026	0.502	1.004	11.058	0.511	1.497	20.513
Romania	2.989	0.309	1.435	0.303	3.785	1.125	6.418	56.160	1.144	5.233	78.900
Russia (Kaliningrad)	0.069	0.016	0.041	0.008		0.049	0.178	3.111	0.050	0.059	3.581
Russia (Karelia/Kola)	0.431	0.073	0.155	0.042		0.347	0.098	0.634	0.352	0.316	2.448
Remaining Russia	6.207	0.946	4.591	2.077	3.055	5.209	16.326	157.150	5.297	15.132	215.992
Russia (St. Petersburg)	0.580	0.096	0.267	0.195		0.186	0.715	7.154	0.189	0.794	10.176
Serbia / Montenegro	4.538	0.267	0.277	0.011	1.015	0.529	1.882	11.098	0.538	2.206	22.362
Slovakia	2.187	0.276	0.507	0.024	0.798	0.271	0.549	4.921	0.275	1.788	11.595
Slovenia	0.664	0.027	0.277	0.036		0.100	0.260	2.573	0.101	1.189	5.226
Spain	6.669	0.661	6.962	0.394	8.658	2.002	9.344	65.899	2.035	10.049	112.673
Sweden	5.624	1.151	1.368	0.110	1.157	0.444	1.300	17.498	0.451	2.877	31.979
Switzerland	0.233	0.342	1.217	0.077	2.326	0.360	1.160	6.414	0.366	1.569	14.063
Turkey	8.819	1.745	6.722	1.254	4.047	3.075	10.115	88.300	3.126	3.554	130.757
Ukraine	8.339	3.595	1.917	0.431	2.052	2.486	13.209	123.507	2.528	4.174	162.238
United Kingdom	10.329	0.475	9.615	0.360	11.845	2.980	10.595	85.530	3.030	1.304	136.064
TOTAL	144.422	22.247	86.587	11.790	145.422	38.048	139.947	1273.363	38.686	108.514	2009.025

Table A7. N_2O emissions (kt/yr) by country and source sector at maximum feasible reduction – projection for 2010

region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Albania	0.013	0.007	0.056	0.042		0.000	0.459	3.460	0.097	1.016	5.150
Austria	0.913	0.051	1.203	0.388	0.579	0.000	1.683	7.421	0.250	2.854	15.342
Belarus	0.706	0.070	0.443	0.124	0.848	0.000	3.051	21.277	0.316	1.623	28.457
Belgium	0.457	1.261	1.651	0.159	2.149	0.000	2.733	12.317	0.318	0.572	21.616
Bosnia & Herzegovina	1.451	0.025	0.077	0.010		0.000	0.482	1.588	0.123	1.916	5.674
Bulgaria	3.496	0.154	0.301	0.128	0.731	0.000	1.820	14.847	0.246	2.953	24.678
Croatia	0.240	0.052	0.181	0.080	0.451	0.000	0.615	5.310	0.144	1.837	8.909
Cyprus	0.029	0.021	0.207	0.004		0.000	0.111	0.601	0.023	0.006	1.003
Czech Republic	5.733	1.168	0.803	0.060	0.407	0.000	1.351	11.738	0.318	1.462	23.040
Denmark	2.345	0.136	0.890	0.112		0.000	1.400	12.426	0.165	0.197	17.672
Estonia	1.068	0.068	0.131	0.050		0.000	0.188	1.856	0.043	0.822	4.226
Finland	2.950	0.807	0.769	0.293	0.712	0.000	1.596	7.884	0.160	1.535	16.708
France	4.875	2.471	8.224	1.639	5.999	0.000	20.097	97.790	1.836	12.123	155.055
Germany	11.983	2.225	12.472	1.601	7.162	0.000	6.677	78.018	2.543	8.536	131.217
Greece	6.864	0.305	1.507	0.217	0.551	0.000	0.560	11.367	0.329	2.162	23.860
Hungary	2.029	0.117	0.746	0.082	0.363	0.000	1.417	12.589	0.309	1.668	19.320
Ireland	1.171	0.104	0.803	0.103	0.284	0.000	2.210	14.403	0.118	0.180	19.375
Italy	4.821	0.659	7.375	0.664	2.585	0.000	7.378	44.156	1.783	8.800	78.220
Latvia	0.180	0.029	0.134	0.025		0.000	0.460	2.748	0.075	0.512	4.163
Lithuania	0.437	0.012	0.222	0.090	0.278	0.000	0.608	10.022	0.115	0.527	12.310
Luxembourg	0.031	0.040	0.327	0.010		0.000	0.084	0.667	0.014	0.119	1.292
Macedonia (FYROM)	0.660	0.011	0.070	0.002		0.000	0.297	1.467	0.063	0.634	3.206

region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Malta	0.018		0.074	0.001		0.000	0.022	0.078	0.011	0.001	0.205
Moldova	0.510	0.157	0.072	0.050		0.000	0.700	6.803	0.133	0.536	8.961
Netherlands	1.731	0.553	2.432	0.110	2.562	0.000	1.368	19.486	0.492	0.260	28.995
Norway	0.096	0.596	0.740	0.095		0.000	0.188	5.514	0.139	1.013	8.380
Poland	21.160	2.497	2.269	0.790	1.530	0.000	11.986	35.642	1.197	2.910	79.981
Portugal	2.455	0.170	1.293	0.263	0.205	0.000	1.059	7.972	0.310	1.497	15.225
Romania	4.805	0.305	0.802	0.434	0.798	0.000	6.418	37.627	0.696	5.233	57.117
Russia (Kaliningrad)	0.071	0.016	0.032	0.009		0.000	0.178	2.084	0.031	0.059	2.479
Russia (Karelia/Kola)	0.427	0.079	0.139	0.044		0.000	0.098	0.349	0.214	0.316	1.667
Remaining Russia	6.196	1.722	3.937	2.160	0.543	0.000	16.326	100.785	3.220	15.132	150.019
Russia (St. Petersburg)	0.613	0.114	0.215	0.203		0.000	0.715	3.724	0.115	0.794	6.492
Serbia / Montenegro	3.982	0.164	0.242	0.014	0.182	0.000	1.882	7.436	0.327	2.206	16.436
Slovakia	1.649	0.340	0.359	0.049	0.157	0.000	0.554	3.409	0.167	1.788	8.473
Slovenia	0.647	0.017	0.314	0.054		0.000	0.278	1.851	0.062	1.189	4.411
Spain	6.927	0.534	5.609	0.414	1.610	0.000	9.721	49.030	1.237	10.049	85.132
Sweden	1.909	1.189	1.366	0.134	0.222	0.000	1.389	12.671	0.274	2.877	22.030
Switzerland	0.233	0.364	1.228	0.118	0.494	0.000	1.206	4.707	0.222	1.569	10.140
Turkey	8.279	3.298	3.095	1.232	0.735	0.000	9.217	57.963	1.900	3.554	89.274
Ukraine	9.502	3.621	1.480	0.425	0.547	0.000	13.209	80.153	1.537	4.174	114.647
United Kingdom	8.999	0.632	8.755	0.352	5.173	0.000	11.320	60.904	1.842	1.304	99.281
TOTAL	132.664	26.162	73.044	12.834	37.856	0.000	143.111	872.138	23.515	108.514	1429.838

Table A8. N_2O emissions (kt/yr) by country and source sector at maximum feasible reduction – projection for 2015

region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Albania	0.013	0.008	0.065	0.043		0.000	0.459	3.460	0.097	1.016	5.161
Austria	0.853	0.052	1.286	0.388	0.584	0.000	1.645	7.339	0.250	2.854	15.251
Belarus	0.281	0.062	0.503	0.075	0.901	0.000	3.051	21.277	0.316	1.623	28.088
Belgium	0.552	1.019	1.687	0.157	2.167	0.000	2.648	12.118	0.318	0.572	21.238
Bosnia & Herzegovina	1.196	0.022	0.090	0.010		0.000	0.482	1.588	0.123	1.916	5.429
Bulgaria	2.711	0.137	0.384	0.120	0.727	0.000	1.820	14.847	0.246	2.953	23.946
Croatia	0.223	0.052	0.200	0.074	0.477	0.000	0.615	5.310	0.144	1.837	8.930
Cyprus	0.035	0.021	0.228	0.004		0.000	0.112	0.604	0.023	0.006	1.034
Czech Republic	4.722	0.884	0.835	0.047	0.429	0.000	1.318	11.836	0.318	1.462	21.850
Denmark	1.775	0.089	0.840	0.107		0.000	1.370	12.244	0.165	0.197	16.786
Estonia	0.776	0.061	0.142	0.043		0.000	0.185	2.037	0.043	0.822	4.109
Finland	3.837	0.756	0.769	0.294	0.715	0.000	1.554	7.815	0.160	1.535	17.436
France	4.617	1.881	9.326	1.598	6.064	0.000	19.562	96.079	1.836	12.123	153.088
Germany	10.644	1.795	12.687	1.620	7.207	0.000	6.466	77.178	2.543	8.536	128.676
Greece	5.559	0.258	1.467	0.219	0.573	0.000	0.553	11.165	0.329	2.162	22.284
Hungary	1.632	0.111	0.826	0.076	0.368	0.000	1.423	12.828	0.309	1.668	19.240
Ireland	0.800	0.094	0.881	0.101	0.288	0.000	2.120	14.093	0.118	0.180	18.673
Italy	4.184	0.606	7.375	0.578	2.609	0.000	7.207	43.855	1.783	8.800	76.997
Latvia	0.224	0.028	0.176	0.024		0.000	0.476	2.928	0.075	0.512	4.443
Lithuania	0.569	0.013	0.266	0.087	0.283	0.000	0.602	10.329	0.115	0.527	12.790
Luxembourg	0.026	0.035	0.371	0.010		0.000	0.083	0.641	0.014	0.119	1.298
Macedonia (FYROM)	0.522	0.014	0.079	0.003		0.000	0.297	1.467	0.063	0.634	3.079

region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Malta	0.024		0.083	0.002		0.000	0.022	0.079	0.011	0.001	0.222
Moldova	0.419	0.140	0.078	0.039		0.000	0.700	6.803	0.133	0.536	8.847
Netherlands	1.256	0.492	2.703	0.110	2.551	0.000	1.356	19.085	0.492	0.260	28.306
Norway	0.116	0.495	0.762	0.080		0.000	0.191	5.481	0.139	1.013	8.276
Poland	17.848	2.294	2.391	0.728	1.533	0.000	11.934	36.085	1.197	2.910	76.919
Portugal	2.064	0.151	1.420	0.292	0.205	0.000	1.034	7.942	0.310	1.497	14.915
Romania	4.610	0.300	1.149	0.353	0.810	0.000	6.418	37.627	0.696	5.233	57.195
Russia (Kaliningrad)	0.061	0.014	0.036	0.009		0.000	0.178	2.084	0.031	0.059	2.471
Russia (Karelia/Kola)	0.379	0.069	0.147	0.043		0.000	0.098	0.349	0.214	0.316	1.615
Remaining Russia	5.475	1.252	4.264	2.118	0.577	0.000	16.326	100.785	3.220	15.132	149.148
Russia (St. Petersburg)	0.528	0.094	0.238	0.199		0.000	0.715	3.724	0.115	0.794	6.406
Serbia / Montenegro	3.645	0.187	0.260	0.011	0.193	0.000	1.882	7.436	0.327	2.206	16.148
Slovakia	1.702	0.275	0.438	0.036	0.158	0.000	0.550	3.457	0.167	1.788	8.573
Slovenia	0.556	0.016	0.289	0.047		0.000	0.270	1.840	0.062	1.189	4.269
Spain	5.196	0.552	6.105	0.421	1.677	0.000	9.553	48.186	1.237	10.049	82.977
Sweden	2.654	1.193	1.357	0.129	0.227	0.000	1.347	12.585	0.274	2.877	22.642
Switzerland	0.213	0.341	1.181	0.096	0.477	0.000	1.189	4.649	0.222	1.569	9.935
Turkey	7.680	2.001	4.706	1.200	0.768	0.000	9.217	57.963	1.900	3.554	88.991
Ukraine	7.676	3.155	1.698	0.428	0.567	0.000	13.209	80.153	1.537	4.174	112.598
United Kingdom	5.543	0.507	9.156	0.366	5.235	0.000	10.961	60.528	1.842	1.304	95.442
TOTAL	113.396	21.524	78.944	12.382	38.371	0.000	141.200	867.876	23.515	108.514	1405.721

Table A9. N_2O emissions (kt/yr) by country and source sector at maximum feasible reduction – projection for 2020

region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Albania	0.012	0.009	0.075	0.043		0.000	0.459	3.460	0.097	1.016	5.171
Austria	1.115	0.055	1.369	0.371	0.587	0.000	1.599	7.244	0.250	2.854	15.445
Belarus	0.245	0.055	0.566	0.040	0.953	0.000	3.051	21.277	0.316	1.623	28.126
Belgium	0.881	0.792	1.875	0.149	2.176	0.000	2.559	11.848	0.318	0.572	21.170
Bosnia & Herzegovina	0.958	0.019	0.103	0.011		0.000	0.482	1.588	0.123	1.916	5.201
Bulgaria	2.190	0.113	0.443	0.106	0.730	0.000	1.820	14.847	0.246	2.953	23.449
Croatia	0.201	0.052	0.212	0.068	0.502	0.000	0.615	5.310	0.144	1.837	8.940
Cyprus	0.042	0.018	0.244	0.004		0.000	0.113	0.608	0.023	0.006	1.058
Czech Republic	3.763	0.600	0.859	0.039	0.447	0.000	1.295	11.948	0.318	1.462	20.732
Denmark	1.030	0.054	0.844	0.105		0.000	1.335	11.991	0.165	0.197	15.720
Estonia	0.609	0.051	0.144	0.034		0.000	0.184	2.223	0.043	0.822	4.111
Finland	3.616	0.717	0.808	0.285	0.717	0.000	1.504	7.728	0.160	1.535	17.070
France	6.550	1.570	10.227	1.458	6.114	0.000	18.923	93.948	1.836	12.123	152.750
Germany	11.027	1.357	13.117	1.589	7.249	0.000	6.242	75.998	2.543	8.536	127.658
Greece	4.658	0.190	1.558	0.215	0.597	0.000	0.544	10.825	0.329	2.162	21.078
Hungary	1.347	0.093	0.861	0.067	0.374	0.000	1.430	13.058	0.309	1.668	19.207
Ireland	0.657	0.071	0.955	0.102	0.293	0.000	2.028	13.701	0.118	0.180	18.104
Italy	4.837	0.552	7.758	0.525	2.631	0.000	6.989	43.386	1.783	8.800	77.262
Latvia	0.283	0.028	0.192	0.019		0.000	0.503	3.200	0.075	0.512	4.811
Lithuania	0.603	0.013	0.309	0.076	0.293	0.000	0.598	10.643	0.115	0.527	13.177
Luxembourg	0.045	0.028	0.383	0.009		0.000	0.079	0.609	0.014	0.119	1.286
Macedonia (FYROM)	0.399	0.016	0.087	0.002		0.000	0.297	1.467	0.063	0.634	2.965

region	1A1_ energy	1A2_ industry	1A3_ transp	1A4_ other	2B_ processes	3D_ solvents	4B_ manure	4D_ soils	6B_ Waste	Forest_ indir	Grand Total
Malta	0.023		0.091	0.002		0.000	0.022	0.076	0.011	0.001	0.226
Moldova	0.334	0.121	0.084	0.027		0.000	0.700	6.803	0.133	0.536	8.738
Netherlands	0.946	0.394	2.945	0.107	2.543	0.000	1.341	18.520	0.492	0.260	27.549
Norway	0.135	0.392	0.804	0.068		0.000	0.195	5.434	0.139	1.013	8.178
Poland	15.017	1.979	2.702	0.627	1.553	0.000	11.887	36.534	1.197	2.910	74.405
Portugal	2.034	0.134	1.621	0.321	0.205	0.000	1.004	7.882	0.310	1.497	15.009
Romania	2.187	0.295	1.435	0.303	0.821	0.000	6.418	37.627	0.696	5.233	55.013
Russia (Kaliningrad)	0.052	0.012	0.041	0.008		0.000	0.178	2.084	0.031	0.059	2.464
Russia (Karelia/Kola)	0.330	0.059	0.155	0.042		0.000	0.098	0.349	0.214	0.316	1.563
Remaining Russia	4.749	0.898	4.591	2.077	0.611	0.000	16.326	100.785	3.220	15.132	148.389
Russia (St. Petersburg)	0.448	0.075	0.267	0.195		0.000	0.715	3.724	0.115	0.794	6.332
Serbia / Montenegro	3.228	0.196	0.277	0.011	0.203	0.000	1.882	7.436	0.327	2.206	15.766
Slovakia	1.561	0.218	0.507	0.024	0.160	0.000	0.549	3.507	0.167	1.788	8.481
Slovenia	0.475	0.024	0.277	0.036		0.000	0.260	1.834	0.062	1.189	4.156
Spain	4.925	0.591	6.962	0.394	1.732	0.000	9.344	46.970	1.237	10.049	82.204
Sweden	4.156	1.098	1.368	0.110	0.231	0.000	1.300	12.472	0.274	2.877	23.886
Switzerland	0.233	0.317	1.217	0.077	0.465	0.000	1.160	4.572	0.222	1.569	9.832
Turkey	6.329	1.324	6.722	1.254	0.809	0.000	10.115	59.161	1.900	3.554	91.169
Ukraine	6.014	2.691	1.917	0.431	0.588	0.000	13.209	80.153	1.537	4.174	110.714
United Kingdom	7.432	0.427	9.615	0.360	5.297	0.000	10.595	60.064	1.842	1.304	96.935
TOTAL	105.676	17.697	86.587	11.790	38.882	0.000	139.947	862.891	23.515	108.514	1395.499