



ABATEMENT OF OTHER GREENHOUSE GASES – NITROUS OXIDE

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Background to the Study

The IEA Greenhouse Gas R&D Programme (IEA GHG) is systematically evaluating the cost and potential for reducing emissions of greenhouse gases arising from anthropogenic activities, especially the use of fossil fuels. To date the programme has looked in great detail at the reduction of carbon dioxide emissions (in phases 1 and 2) and methane emissions (in Phase 2). The Phase 3 plan has included a study of other greenhouse gases. This evaluation has been split into two separate studies, one on nitrous oxide (N₂O) and a second on the "engineered chemicals". The gases to be studied in the second study include: chlorofluorocarbons (CFC's), hydrofluorocarbons (HFC's), hydrochlorofluorocarbons (HCFC's), perfluorocarbons (e.g. CF₄ and C₂F₆), sulphur hexafluoride (SF₆) and methyl bromide. Each study aims to examine the current sources and levels of emissions of the greenhouse gas(es) in question, the technologies available for emissions abatement, the technical potential for emissions abatement, and the corresponding costs and economic feasibility. This study has focused on the abatement and mitigation options for N₂O. N₂O is a significant greenhouse gas with around 310 times the global warming potential of CO₂ over a 100-year time horizon. Overall, N₂O contributes some 5% of the anthropogenic greenhouse effect, considerably less than CO₂ (65%) and CH₄ (20%)¹. ICF Consulting of the USA undertook the study.

Results and Discussion

The following areas are described in the report:

- The global emissions of Nitrous Oxide
- Sources of emissions of nitrous oxide.
- Options for the reduction of N₂O emissions
- The costs of abatement of N₂O
- The impact of implementation of N₂O abatement measures

Global Emissions of Nitrous Oxide.

The global average N₂O concentration in the atmosphere has increased from 275 parts per billion (ppb) in pre-industrial times to 311 ppb in 1992. Global anthropogenic emissions of N₂O grew from 2.7 Mt/y in 1900 to 12.6 Mt/y in 1990 but it is noted that there is considerable uncertainty in current N₂O emission estimates. The emissions values are at the higher end of the range of emission estimates published in scientific journals. The values quoted here are based on recent analysis of the link between emissions and observed atmospheric concentrations, which suggests that emissions are more likely to be near the high end of published emission estimates².

¹ Second Assessment Report to IPCC, 1995.

² Kroeze, C., Mosier, and Bouwman, L., Closing the Global N₂O budget: A Retrospective Analysis 1500-1994, Global Biogeochemical Cycles, Vol. 13, No.1, pp 1-8, 1999.

The projected growth in emissions was estimated by the contractor to be 14.49 Mt/y in 2020 a growth of 22% against baseline estimates for 1990 (10.2 Mt/y). These figures correspond to an average rate of growth of 1.2% per year based on IPCC methodologies. The contractor notes that the shares in production will increase significantly by 2020 in Asia and Latin America compared to OECD and western countries due to increased population growth

Sources of Emissions of Nitrous Oxide.

The main anthropogenic emission sources for N₂O are summarised in Table 1³below.

Global Emissions by Sector	1990	2020
	% of total emission	% of total emissions
Agriculture	80	78
Industrial processes	9	7
Mobile sources	3	6
Stationary sources	5	6
Waste treatment	2	2

Table 1 Main Anthropogenic Sources of N₂O.

The agricultural sector is currently and will remain the most significant source of N₂O emissions over the forecast period. The industrial sector is the next most significant emission source. Emissions from the transport sector (mobile sources), power plant (stationary sources) and waste treatment are considered to be minor sources. Emission projections for 2020 show little overall change, however emissions from mobile sources will potentially double in percentage terms.

The main sources of agricultural emissions in 1990 are summarised in Table 2 below.

Agricultural emission sources	% of total emissions
Direct emission from soils	54
Indirect emissions	32
Manure management	5
Biomass burning	9

Table 2: Main Sources of N₂O Emissions from the Agricultural Sector.

N₂O is produced naturally in soils through the microbial processes of nitrification (the aerobic microbial oxidation of ammonium to nitrate) and de-nitrification (the anaerobic microbial reduction of nitrate to nitrous oxide gas). The principal source of emissions is the addition of nitrogen to the soil principally by the application of synthetic nitrogen based fertilisers or by nitrogen deposited by grazing animals. Fertiliser application also leads to indirect emissions resulting from fertiliser volatilisation and N₂O production due to surface run off and sub-surface leaching of nitrogen from soils. Manure management systems produce direct N₂O emissions by the chemical and biochemical processes of manure decomposition. Emissions from manure management systems vary considerably based on a number of factors such as: cattle type, their diet and manure collection system. Indirect emissions from manure management arise from nitrogen volatilisation and run off to water-courses. Biomass burning produces N₂O in situations where incomplete combustion occurs. Anthropogenic sources of N₂O from biomass burning arise from burning of crop residues, savannah burning and deforestation.

The principal industrial emissions of N₂O arise primarily from the production of adipic acid and nitric acid. Adipic acid is the main constituent of nylon but is also used in a variety of other synthetic

³ Note: totals may not add to 100 due to rounding.

products. Adipic acid manufacture is a two-stage process. The first involves the oxidation of cyclohexane to form a cyclohexanone/cyclohexanol mixture. This mixture is then oxidised with nitric acid to produce adipic acid. N₂O is generated as a concentrated by-product of this nitric acid oxidation stage. In Nitric acid manufacture, the acid is produced by the high temperature catalytic oxidation of ammonia and N₂O is generated as a low concentration by-product along with NO and NO₂ in the process offgas.

N₂O is also a by-product of fuel combustion both from mobile sources (road vehicles, rail, and aviation) and stationary sources, principally power plants. The principal sources of emissions from waste treatment are domestic and industrial wastewater and waste incineration.

Options for the Reduction of N₂O Emissions

The methods identified for the abatement of nitrous oxide from the two major N₂O sources, agriculture and industry, are discussed below. Abatement options and costs from minor sources (mobile/stationary combustion and waste treatment) are summarised only.

Abatement options for the agricultural sector

Two basic strategies can be applied to reduce N₂O emissions from agricultural soils. First are measures that result in an improvement in the efficiency with which nitrogen is used in farming. These types of measures can include technologies and/or practices that improve plant uptake of applied nitrogen and thereby reduce the amount of residual nitrogen in the soil. Measures that can be considered include: altering the timing/frequency of fertiliser application, use of controlled release fertilisers and reducing excess application of fertiliser by field-testing. These options result in a reduction in the application of nitrogen to soils and will have an impact on both direct and indirect soil emissions.

The second set of measures, are those that inhibit the processes of nitrification and de-nitrification.. Measures identified include; altering the depth at which nitrogen is injected into soils, the type of tillage system used, site specific irrigation practices and choice of fertiliser type. All these measures can be instrumental in reducing the rate of biogenic production of N₂O. These measures, however, will only reduce direct emissions. The use of nitrification and urease inhibitors were also identified as potential mitigation measures are examples of technologies that have the potential to limit N₂O production, however further analysis of these options needs to be undertaken to evaluate the cost implications of these types of abatement measures.

All of the abatement options identified for both strategies have yet to be tested at the farm scale; this would have to be done before they can be applied globally with confidence.

For manure management systems, only a limited number of potential abatement measures were identified by the consultants. The abatement measures listed included chemical treatment of animal waste (i.e. use nitrification and urease inhibitors) and changes in animal diets to alter the amount of nitrogen excreted. For chemical treatment it was noted that costs are likely to be high and the effects of inhibitors have a limited time horizon (several weeks only). On the dietary measure only exploratory work has been undertaken to date and its impact on N₂O emissions is uncertain. Abatement options for burning of crop residues include improved fire management practices, ploughing under or composting. Abatement measures for savannah clearance and deforestation would both need national and international government action to bring about the necessary changes in practice.

It is noted that changes in established agricultural practices are not easy to facilitate. Farmers will not readily adopt alternative practices unless there is some economic incentive. In addition, there will undoubtedly be conflicts in situations where population growth requires additional production of food and the easiest option to achieve this is increased nitrogen fertiliser use. To introduce the necessary

agricultural abatement options incentives such as subsidies and penalties for non-adoption may be required. In addition, education and training programmes will be necessary.

To justify the introduction of these abatement options, abatement must be verifiable. In the agricultural case, the only feasible verification method is to measure changes of N inputs into soils. Though indirect, this method should be relatively inexpensive (in comparison with instrumental measurements of N₂O emissions) and has the potential to confirm emission reductions for a majority of the agricultural abatement strategies. At the same time, N₂O flow measurements have to be taken if options associated with N₂O inhibitors are to be verified. Overall, compared to other sectors for example industry; verification of N₂O abatement will be less readily achievable.

Abatement options for the industrial sector

In the industrial sector, in adipic acid plant a concentrated offgas stream containing 23% N₂O is produced. For adipic acid plants both catalytic and thermal destruction techniques for N₂O abatement are commercially proven and extensively employed throughout the world. Reduction efficiencies range from 90-99%. In comparison, in nitric acid plants, the concentration of N₂O in the off-gas stream is low (500-2000 ppm⁴). Most nitric acid plants throughout the world are regulated to control NO_x and not N₂O emissions and use NSCR⁵ or SCR⁶ to control these emissions. Whilst NSCR can reduce N₂O emissions by up to 90%, it requires additional fuel and hence additional operating costs. SCR can actually increase N₂O emissions. NSCR is not favoured in modern plants because of high-energy costs. A catalyst to reduce N₂O emissions from SCR plant is being developed by ECN of the Netherlands. BASF (a manufacturer of nitric acid) is testing a catalyst for use in the ammonia burners on nitric acid plants. Both catalysts are claimed to be capable of reducing N₂O emissions by up to 90% and are easily installed on existing plant. Industry sources indicate that catalysts will be available for commercial application by 2010. Another manufacturer, Norsk Hydro, has developed an integrated destruction process, however, this process is only considered suitable for use on new plants because of the high capital costs and long operational downtimes needed to retrofit existing plants.

Abatement options for minor sources

In the transport sector, N₂O emissions are greater from vehicles with catalytic converters than from those without, and vehicles with old catalysts produce greater emissions than those with new catalysts. At present there is no technology available to abate N₂O emissions from this sector. Development of new catalysts to reduce N₂O emissions from road transport is, therefore, needed. The catalyst (referred too earlier) being developed by ECN for nitric acid plant also has a potential application for reducing N₂O emissions from vehicle exhausts.

A variety of measures are under development to reduce emissions from stationary combustion and waste water treatment. In both cases, the report highlighted that there are no commercial applications of abatement options and further R&D is required before they can be deployed commercially.

Costs of Abatement of N₂O

For the agricultural sector, the consultant noted that there was insufficient information available to estimate abatement costs for many of the measures identified. Whilst measures such as soil testing could produce net savings (-\$1 500/t N₂O abated - equivalent to -\$5/t CO₂), others such as have costs as high as \$248 000/t N₂O abated (equivalent to \$800/t CO₂ abated). It was also noted that there is considerable uncertainty in the abatement costs quoted in the study because none of the abatement options proposed have been field-tested and, therefore, their actual impact on N₂O emissions can only be estimated at this stage. In the industrial sector, abatement costs can be considered as firm because

⁴ Parts per million

⁵ Non selective catalytic reduction

⁶ Selective catalytic reduction

they are based on actual plant cost data, although retrofit costs are, to a large degree, plant specific. For adipic acid plants abatement costs are some \$20-60/t N₂O abated for catalytic destruction and \$40/t N₂O abated for thermal destruction. Abatements cost for NSCR on nitric acid plants are \$754/t N₂O abated. Costs for other abatement techniques on nitric acid plants were not available, nor were costs for abatement in the transport sector. Costs of abatement for stationary combustion were estimated to range from \$50 to \$180/t N₂O abated, because these options remain untested.

The impact of Implementation of N₂O Abatement Measures

To determine the impact on global emissions, a package of abatement measures in the agricultural, industrial and waste sectors were identified for potential implementation. In total, 8 agricultural options, 2 industrial options and 1 waste sector abatement option were selected on the basis of availability and reliability/scalability of available cost data. The range of cost data was extremely large, -\$60 000 to \$ 248 000/t N₂O abated (equivalent to -\$193 to \$800/t CO₂ abated). The very low figure of -\$60 000/t N₂O abated was drawn from a study by the European Commission and relates to a package of measures to reduce fertiliser use within the European Union. This figure has been excluded from the cost curve because of concerns regarding the applicability to farming systems not governed by a common agricultural policy as is the case within the European Union. An upper band of \$10 000/t N₂O abated (equivalent to \$300/t CO₂ abated) was also placed on the cost curve because it was considered that measures above this price band would not be considered economically viable. The potential emission reduction is presented as an abatement cost-curve in Figure 1 below.

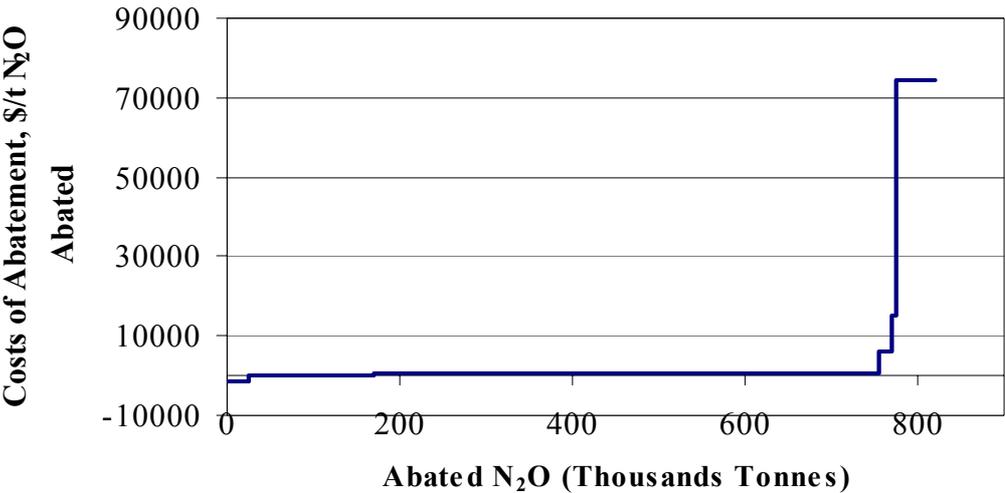


Figure 1 Cost Abatement Curve for N₂O for 2020.

The abatement cost curve indicates the technical abatement potential to be some 0.82 Mt/y in 2020 at costs up to \$75 000/t of N (equivalent to \$242/t CO₂). It was found that cumulatively implementing all the package of measures would reduce global anthropogenic emissions of N₂O by 5.4% by 2020. Some 0.033 Mt/y could be abated at net savings in the agricultural sector, whilst a further 0.21 Mt/y could be abated at a cost of up to \$50/t N₂O (equivalent to \$0.16/T CO₂). This latter abatement measure relates to the introduction of thermal reduction technology at the remaining adipic acid plants throughout the world that have no abatement equipment currently in place. A further 0.58 Mt/y can be abated at costs of up to \$750/t N₂O (equivalent to \$2.4/t CO₂) by implementing NSCR at nitric acid plants worldwide. Cumulatively, the biggest impact of implementation of the package of measures would be in the industrial sector, where global anthropogenic N₂O emissions could be reduced by some 5.2 % by 2020. The biggest impact of an individual measure would be in the nitric acid industry where the introduction of NSCR technology could reduce 3.8% of global anthropogenic N₂O emissions. The package of agricultural measures would reduce anthropogenic N₂O emissions by only

0.2% cumulatively by 2020, with a small fraction (<0.1%) of this reduction achieved at a net saving, because so many of the possible techniques are as yet unproven.

Expert Group Comments

The expert reviewers who assisted in the review were drawn from all sectors covered by the study, which is important since the study reviewed a diverse number of sectors and sources.

The comments drawn from the experts were generally complimentary of the study. A number of comments received were editorial. It was noticeable that, in some sectors but particularly the agricultural sector, there were contrasting opinions about which abatement measure was most effective. Also the comments indicated that many of the agricultural measures would have varying impacts depending on the region of application, which is probably not surprising. This debate was considered to reflect the early stage of development of the knowledge base on the impact of agricultural measures on the abatement of N₂O.

It was also noted that the study relied heavily on IPCC⁷ methodologies for estimating emissions from sectors such as agriculture and transport and that these methodologies are still under development. This point was accepted but, currently, the IPCC methodologies are the only internationally accepted standard for estimating emissions from the sectors concerned in the absence of hard data. The fact that the IPCC methodologies are under near-continuous revision reflects the fact that knowledge on emissions from these sectors is developing, as new research becomes available.

Major Conclusions

The study has clearly shown that the dominant source for global anthropogenic emissions of N₂O is the agricultural sector, responsible for some 80% of global anthropogenic emissions. The industrial sector is the next most significant emission source responsible for 9% of global anthropogenic emissions. Whilst abatement options are available to significantly reduce N₂O emissions from the industrial sector, globally the impact of these measures will be small. In the agricultural sector considerable further research is needed to develop abatement options for the agricultural sector that can have a major impact on reducing global N₂O emissions. Consideration also needs to be given to ensure the abatement measures adopted are readily verifiable.

Recommendations

It is clear that considerable further research is needed, particularly in the agricultural sector, to develop cost-effective and verifiable options that will significantly reduce global anthropogenic N₂O emissions. There is little that IEA GHG can contribute to this R&D activity.

In the industrial sector where new plant is considered in the future in developing countries there is a need to ensure the best available abatement technology is installed. This can be achieved through mechanisms such as Joint Implementation and the Clean Development Mechanisms.

At this point in time it is considered that further work is not warranted in this area, other than for IEA GHG to maintain an awareness of N₂O abatement technology developments. In several years time, when the state of knowledge on global anthropogenic emissions of N₂O and methods of abating these emissions has developed substantially, IEA GHG could consider updating this report.

⁷ International Panel on Climate Change

**ABATEMENT OF EMISSIONS OF OTHER
GREENHOUSE GASES –
NITROUS OXIDE**

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ABATEMENT OF EMISSIONS OF OTHER GREENHOUSE GASES – NITROUS OXIDE

Prepared by ICF Consulting

EXECUTIVE SUMMARY

The purpose of the current study is to characterize the potential to reduce (abate) anthropogenic emissions of nitrous oxide (N₂O), which is one of the major greenhouse gases (GHG) contributing to an increase of the radiative forcing of the earth's atmosphere. This potential is viewed here as a function of the present and future emissions, the technical potential to reduce production of N₂O, and, finally, costs of this reduction. The study estimates the current and future N₂O emissions from the following sectors: agriculture, stationary combustion, mobile combustion, industrial processes, and waste management. The current emissions are calculated based on the revised Emission Inventory Guidelines produced by the International Panel on Climate Change (IPCC) and on the Best Inventory Practices that are also being developed by the IPCC. Emissions for the years 2005, 2010, 2015, and 2020 were estimated using a common set of emission drivers, such as population, GDP, and energy use. The current and future anthropogenic N₂O emissions are estimated at the global level and also at the level of four macro-regions: countries of the Organization of Economic Cooperation and Development (as of 1990) [OECD90], reforming economies of the Eastern and Central Europe and the Former Soviet Union [REF], the rest of Asian countries [ASIA], and countries of Africa, Middle East, and Latin America [ALM]. Emission-abatement options are described separately for each emission sector and some of these options are characterized in terms of the technical potential to reduce emissions and costs of these reductions. Finally, selected abatement options are assembled in the global marginal abatement curve, which shows how much reductions can be achieved at a given cost level.

The analysis conducted here confirms the leading role of agricultural sources in producing global and regional N₂O emissions. Agricultural sources are estimated to emit about 8100 Gg N₂O or over 80% of the global anthropogenic N₂O in 1990, while by 2020 their global share is expected to decrease to about 77% in 2020, due to a faster growth of emissions from mobile sources and stationary combustion. Emissions of N₂O from industrial processes represented in this study by adipic and nitric acid production, amounted to 904 Gg N₂O or about 9% of the global emissions in 1990 and are estimated to produce about 7.5% in 2000 and 2020. In 1990, mobile combustion sources produced about 330 Gg N₂O (3% of the global emissions), while by 2020 emissions from this source are estimated to increase to about 890 Gg (6% of the global emissions). Emissions from stationary combustion sources are estimated to increase from 520

Gg N₂O in 1990 (5% of the global emissions) to 917 Gg N₂O in 2020 (6.6% of the global emissions). Estimates of emissions from this source are highly sensitive to the assumed percentage of coal burned using the fluidized bed technology. Finally, emissions from waste management sources are estimated to change from 220 in 1990 to 290 Gg N₂O in 2020, with their global share remaining at about 2%.

The global total N₂O emissions from major anthropogenic sources are estimated to grow from about 10,170 Gg N₂O in 1990 to 11,000 Gg in 2000, to 13,920 in 2020. This corresponds to an average annual rate of growth of about 1.2% per year starting from 2000. In 1990, the OECD90 and ASIA regions produced about 30% of the global N₂O emissions each. The ALM region produced about 21% and the REF region -- 11%. By 2020, the shares of the ASIA and ALM regions are estimated to grow to 39 and 27% with the shares of OECD90 and REF regions dropping to 24 and 4%, respectively.

The current study revealed a general lack of region-specific activity data for such emission sectors as mobile combustion and waste management. Also missing are disaggregated source-specific emission factors for agriculture, stationary and mobile combustion and waste management sectors. The resulting uncertainty of emission estimates in all the emissions sectors but industrial processes is very high and can be substantially reduced only by extensive analyses of factors that affect emissions in different regions of the world.

Recent international studies describe many proven and potential options to reduce of N₂O emissions. More quantitative information is generally available for technological options that are applicable to industrial processes. At the same time, options that involve changes of underlying practices leading to emissions are described mostly at the qualitative level.

The abatement cost analysis performed in the current study included 8 agricultural options, 2 industrial options, and 1 waste management option. Marginal abatement costs of these options at the 10% discount rate are estimated to range widely from -\$60,780 per metric tonne N₂O (indicating profitable reductions) in the EU agricultural sector to over \$438,000/t N₂O in the U.S. Waste Management Sector. The total cumulative reduction of N₂O emissions if all the 11 options are implemented is estimated at 650 Gg N₂O in 2005 and at 947 Gg N₂O in 2020.

I. INTRODUCTION

A. Contribution of N₂O to Global Warming and Sources of N₂O Emissions

Nitrous oxide (N₂O) is one of the most important greenhouse gases contributing to an increase in the radiative forcing of the atmosphere. The global average N₂O concentration in the atmosphere has increased from 275 ppb in pre-industrial times to 311 ppb in 1992 and its current radiative forcing contribution is estimated at about 0.14 Wm⁻² (IPCC, 1995). Anthropogenic emissions of N₂O were estimated to grow from 1.7 Tg N₂O-N in 1900 to 8.0 Tg N₂O-N in 1990, or 4.7 times (Kroeze, et al., 1999). While in the 21st century this rate of growth is not likely to be sustained, by 2020, emissions of this gas might increase by as much as 20-30% over current levels if additional measures to reduce N₂O are not implemented (Pepper, et al., 1998, Sankovski, et al., 2000).

Such factors as a long atmospheric lifetime (about 120 years), strong prospects for continued growth in emissions, and a diversity of anthropogenic sources, make nitrous oxide one of the primary targets for the abatement potential analysis. Such analysis, however, is compounded by the high degree of uncertainty attached to anthropogenic N₂O emission estimates, which ranges from 15-30% for national estimates of N₂O from industrial sources to two orders of magnitude (!) for agricultural soils (Subak, 1999). The uncertainty in current N₂O emissions is reflected by a wide range of emission estimates reported in several recent studies (Table I-1).

Table I-1. Global Anthropogenic Nitrous Oxide Emission Estimates For 1990 From Different Sources (Tg N₂O-N¹)

Emission Source	IPCC (1995)	SRES (2000)	Lawson and Braatz (1999)	Kroeze et al. (1999) and Moiser et al. (1999)	Oliver et al. (1999)
Agricultural soils	3.5 (1.8-5.3)	NA	1.53	2.1	1.0
Biomass burning	0.5 (0.2-1.0)	NA	0.27	0.5	0.6
Industrial and energy sources	1.3 (0.7-1.8)	NA	0.56	1.2	0.6
Cattle and feed lots	0.4 (0.2-0.5)	NA	2.82	2.1	1.0
Indirect emissions	-	NA	NA	2.0 ^a	-
Total	5.7 (3.7-7.7)	6.7	5.17 ^b	8.0	3.2

^a Includes human wastes.

^b Excludes mobile sources and some agricultural and waste management sources.

The wide range of estimated global anthropogenic emissions from 3.2 to 8.0 Tg N₂O-N is attributable, primarily, to large uncertainties associated with agricultural and indirect emission sources. However, a recent analysis of the link between emissions and observed atmospheric concentrations suggests that N₂O emissions are more likely to be closer to the high end of this range than to the low end (Kroeze et al., 1999).

¹ N₂O-N stands for molecular nitrogen.

B. Overview of Selected Studies on N₂O Emissions and Abatement Options

Several recent studies, some of which are still in progress, examined global and regional N₂O emissions and documented the existing potential for mitigation.

As part of the process of constructing the Emission Database for Global Atmospheric Research (EDGAR), 1990 N₂O emissions from different sectors and regions were estimated at a spatial resolution of 1° x 1° (Oliver et al., 1999) (Table I-1). This analysis was based on a wide variety of sources for activity levels and emission factors. The global anthropogenic N₂O emissions estimated for EDGAR were slightly lower than those reported in the first IPCC scientific assessment (3.2 vs. 3.9) (IPCC, 1992). The uncertainty level of most of the N₂O emissions sources was assessed at ± 100%, except for fossil fuel combustion and chemical production, where uncertainty was assessed at ± 50%.

A study of historic N₂O emissions was conducted to “balance” emissions with observed atmospheric concentrations (Kroeze et al., 1999) (Table I-1). The study concluded that an increase in atmospheric N₂O over time can be attributed primarily to an increase in nitrogen inputs in the agricultural sector. Emissions from this sector were assumed to grow from 1.3 Tg N₂O-N in 1850 to 6.2 Tg N₂O-N by 1994. At the same time, emissions from natural sources were assumed to be almost constant over the last 150 years and equal to about 9.6 Tg N₂O-N per year. Net additions of N₂O into the atmosphere were estimated to increase from 0 in 1850 to 6.7 Tg N₂O-N per year in 1994, with the fastest increase occurring during the past 50 years (Kroeze et al., 1999). Total anthropogenic N₂O emissions were estimated to have grown from 3.9 Tg N in 1960 to 8 Tg N in 1990 or by 2.4% per year.

Another study of historic emissions compiled preliminary estimates of CO₂, CH₄, and N₂O emissions from 1961 to 1990 for two country groups – developing and industrialized – and compared each group’s relative contribution to global GHG emissions over time (Lawson and Braatz, 1999). Anthropogenic sources of N₂O included agricultural soil management, management of livestock and other animal wastes, nitric and adipic acid production, biomass burning (i.e., prescribed burning of savannas, field burning of agricultural crop residues, and burning associated with deforestation), and liquid waste management. The study did not estimate emissions from mobile sources, production of nitrogen fixing crops (i.e., beans, pulses, and alfalfa), sewage sludge input into the soil, or the cultivation of high organic content soils. The study also found that total N₂O emissions grew continuously from 1961 to 1990, at about 2.4% per year. Emissions in industrialized countries grew at 1.9% and in developing countries at 2.9% per year.

A comprehensive analysis of potential GHG emissions for the next 100 years was performed in the framework of the Special Report on Emission Scenarios (SRES), which is one of the contributions to the Third IPCC Scientific Assessment of Climate Change (SRES, 2000). The total of 40 long-range scenarios, which belong to four scenario families with different socio-economic, demographic, and technological assumptions, cover a widening range of N₂O emissions over the next century. The base year (1990) emissions across the different models used in the analysis ranged from 4.8 to 6.9 Tg N₂O-N, with a common value set at 6.7 Tg N₂O-N. By 2020, global anthropogenic N₂O emissions in all of the 40 scenarios ranged from 5.8 to 12.2 Tg N₂O-N.

Major options to reduce anthropogenic N₂O emissions were discussed in the framework of the EU-15 GHG analysis (AEA Technology Environment, 1998). The corresponding report evaluated a variety of abatement options in the chemical industry, agriculture, waste management, and fuel combustion sectors (both mobile and stationary sources). Main findings of the EU-15 report are outlined in Table I-2.

Table I-2. N₂O Emissions And Abatement Potential In The EU-15 Countries

Sector	1990 Emissions (Gg N ₂ O/%)	2020 Emissions (Business-As-Usual) (Tg N ₂ O/%)	Abatement Potential in 2020 (Gg N ₂ O/% of baseline)	Cost of Abatement (ECU/tonne CO ₂ eq.)
Stationary combustion	138 (11%)	139 (13%)	26 (19%)	3-4
Mobile combustion	41 (3%)	176 (16%)		
Agriculture and land Use	612 (50%)	538 (50%)	120 (22%)	22-480
Land use and forestry (including biomass burning)	42 (3%)	44 (4%)		
Industrial processes	356 (29%)	145 (14%)	58 (40%)	0.1
Waste management	12 (1%)	13 (1%)		
Other processes	14 (1%)	15 (1%)		
Total	1215	1071		

The EU-15 report findings suggest that N₂O emissions from the industrial sector can be reduced substantially at a reasonable cost. In the agricultural sector, the size of potential reductions is also significant but, costs remain highly uncertain. The report also assumes that some measures leading to N₂O reductions (e.g., lower use of nitrogen fertilizer, partial abatement of industrial N₂O) are being or will be implemented and should be part of the “business-as-usual” scenario. Therefore, the 2020 “business-as-usual” EU emissions are lower than in 1990. Mobile combustion is the only sector where emissions are expected to increase from 1990 to 2020 (Table I-2).

C. Report Objectives and Organization

The objectives of this report include developing global and regional estimates of current and future N₂O emissions from anthropogenic sources, describing options to reduce emissions, and summarizing potential reductions and costs of these reductions using global marginal abatement cost curves. The report does not cover all the potential N₂O sources. For example, such sources as soils with high-organic content, sludge deposition into soils, and atmospheric nitrogen deposition are excluded from the analysis. The primary reason for this exclusion is a lack of background data and highly uncertain or non-existent methodologies for developing emission estimates. These and other sources, can be added to the current analysis as soon as corresponding data and methods become available.

The report consists of the Executive Summary and the following nine sections:

- I. Introduction
- II. General Methodology
- III. Agriculture
- IV. Industry
- V. Mobile Combustion
- VI. Stationary Combustion
- VII. Waste Management
- VIII. Integration of Results
- IX. Conclusions and Recommendations for Future Work

References are provided at the end of each section.

D. References

- AEA Technology Environment (1998), *Options to Reduce Nitrous Oxide Emissions (Final Report)*. Prepared for Environment Directorate-General XI, European Commission. Document number: AEAT-3773: Issue 3. (Available on the Internet at <http://europa.eu.int/comm/environment/enveco/studies2.htm#9>.)
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II. GENERAL METHODOLOGY

A. Current Emissions

Current N₂O emissions were estimated for the following sectors: agriculture, industrial sources, mobile combustion, stationary combustion, and waste management. In most cases, emissions were estimated for the years 1990, 1995, and 1998. The estimation procedure was based on the revised IPCC guidelines for GHG emission inventories (IPCC, 1997). Emissions from most of the source categories were estimated using the IPCC's Tier 2 approach, which relies on sectoral and region-specific emission factors. In cases where sectoral data were not available, the more aggregated IPCC Tier 1 approach was adopted.

The geographic resolution of emission analysis was sector- and source-dependent. The final emission estimates for each source were aggregated to the level of four regions: OECD90 (Organization for Economic Cooperation and Development, as of 1990), REF (reforming economies), ASIA (the rest of Asia), and ALM (Africa, Latin America, and Middle East). Countries comprising each of these regions are listed in Appendix II-1.

B. Emission Projections

Nitrous oxide emissions for the years 2000, 2005, 2010, 2015, and 2020 were estimated using aggregate emission “drivers” with an adjustment factor calculated using 1990 and 1995 emissions estimates. The emission drivers included: population (UN, 1998; Medium Scenario), GDP (EIA, 1999; Reference Scenario), and energy consumption (EIA, 1999; Reference Scenario). Future emissions in a given year *i* (*FE_i*) were estimated according to the following formula:

$$FE_i = E95 * (D_i/D95) * k,$$

where *E95* is 1995 emissions, *D_i* and *D95* are levels of the selected driver in the years *i* and 1995. The adjustment factor *k* reflects the non-linearity of the relationship between emissions and corresponding drivers and is estimated as:

$$k = E95 / (E90 * D95/D90),$$

where *E90* and *D90* are emission and driver levels in 1990. If the relationship between emissions from a given source and a corresponding driver is strictly linear then *k* = 1, if emissions grow faster than the driver then *k* > 1, if slower—then 0 < *k* < 1.

Unlike some recent N₂O studies (e.g., the EU-15 report), baseline emission projections developed here do not include any mitigation measures, policies, or assumptions that may lead to a decrease in N₂O emissions. These baselines, therefore, represent hypothetical “maximum” cases that can be used to assess mitigation potential of various abatement options.

C. Abatement Options

Options to reduce N₂O emissions are described sector-by-sector in corresponding sections of the report. In general, N₂O emission abatement options are characterized on the basis of the following parameters:

- technical description
- state of development and current level of usage
- technically feasible level of abatement (reduction possible)
- associated technical (and other) risks and uncertainties
- capital and operating costs
- effects on emissions of other GHGs
- known barriers, constraints, and incentives
- potential for recovery and use of N₂O.

A preliminary analysis showed that a complete set of technical and economic data is available only for a handful of options. Only these options were included in the marginal abatement cost analysis presented in Section VIII of the report. Technical and partial economic descriptions of other options are presented in sector-specific sections III-VII.

D. Cost Curves

The marginal N₂O abatement cost curves were developed in a four-step process, which included the selection of options; estimation of costs and emission reductions; calculation of cost-effectiveness; and construction of the curves. The general approach is described briefly in this section, while specific information on the options and the analysis is provided in the sections below.

Nitrous oxide reduction options to be included in the cost curve were selected on the basis of data availability. Because of the dearth of comprehensive estimates of the costs and benefits of N₂O abatement options, it was not possible to limit the analysis to options for which precise, detailed data were available. Therefore, where data were lacking (e.g., regarding the relationship of costs to plant size), reasonable assumptions were made. In estimating costs and N₂O emission reductions, the analysis followed the approach used by the data sources to greatest extent possible, while extending the scope of the options to related N₂O sources (e.g., additional adipic acid plants, solid waste in other countries) and using the financial parameters provided by the IEAGHG Programme.

Capital costs of abatement options were accounted for by annualizing estimated equipment costs per plant over the estimated life of the abatement equipment using the 10 percent discount rate recommended by the IEAGHG Programme. This procedure translated the capital cost into an annual stream that could be directly combined with annual operating costs in the analysis of cost-effectiveness. To insure comparability, all net costs were adjusted to 1999 U.S. dollars using the GDP deflator provided by the U.S. Department of Commerce.

To estimate the total N₂O reductions provided by the options, the total baseline emissions to which an option would be applicable in a given year was multiplied by the percentage reduction provided by the option. Given the annual cost of each option and the reductions in N₂O provided by each, cost effectiveness was calculated by division. To produce the marginal abatement cost curves for each year, the options were sorted in order of increasing cost per metric tonne of N₂O. The ordered options were then reviewed to find instances in which the adoption of one option would reduce the scope for another option.

Finally, the cumulative marginal abatement cost curve for each year was constructed by pairing the cost per tN₂O for each option with the sum of the reductions provided by all of the options estimated to be at least as cost-effective as the given option.

E. References

- EIA (Energy Information Administration) (1999), International Energy Outlook 1999. U.S. Department of Energy, Washington, DC. www.eia.doe.gov.
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III. AGRICULTURE

A. Background

A variety of human activities related to agricultural production and land use practices give rise to a net increase in nitrous oxide emissions. These anthropogenic sources of N₂O include the preparation of land for agricultural use—e.g., savanna burning—as well as activities related to crop and livestock production.

The magnitude of the net N₂O flux attributable to agriculture and land use is determined by complex non-linear interactions among a variety of controlling factors including: physical properties of the soil, pH levels, carbon and oxygen availability, climatic conditions (such as ambient temperatures, freeze-thaw cycles, and the volume and timing of precipitation), tillage practices, irrigation systems, cropping patterns, and fertilizer types and application rates. Because these factors can vary significantly over small physical areas, N₂O emissions from agricultural soils are especially difficult to quantify.

In keeping with the IPCC methodology (IPCC, 1997), the emission sources discussed here and the emission estimates presented below are divided into three general categories: (A) Agricultural Soils; (B) Manure Management; and (C) Biomass Burning.

The IPCC identifies two **direct** pathways via which agricultural production activities result in net nitrous oxide emissions: (a) emissions from agricultural soils and (b) emissions from manure management systems. In both cases, extra N₂O formation takes place because of the additional amount of nitrogen that is introduced into the environment. Agricultural activities also give rise to net N₂O emissions via **indirect** pathways. These emissions are related to the volatilization of applied nitrogen as well as to nitrogen leaching and run-off. In the case of nitrogen losses due to volatilization, subsequent atmospheric deposition of the nitrogen compounds results in fertilization of off-site soils and surface waters and contributes to N₂O formation in these locations. Likewise, leaching and surface runoff result in agriculturally derived nitrogen being transported off-site with N₂O production in these areas enhanced as a result. In general, **direct** emissions are those that occur at a site where anthropogenic nitrogen is initially deposited (i.e., agricultural soils or manure management systems), while **indirect** emissions occur off-site and are associated with “losses” of originally deposited nitrogen.

In estimating emissions from agricultural sources, ICF structured the analysis around the regional breakdown used by Safely et al (1992)—which is also used by the IPCC to provide parameters for the default methodology. This approach greatly facilitated the process of estimating nitrous oxide emissions from animal manure and was relatively simple to adjust for the other sources. The regions include: North America, Western Europe, Eastern Europe, Oceania, Latin America, Asia and the Far East, Africa, the Near East, and the Former Soviet Union. Results of the analysis were then aggregated to the level of four regions: OECD90, REF, ASIA, and ALM (Appendix II-1).

B. Current Emissions

1. Agricultural Soils

Nitrous oxide (N₂O) is produced naturally in soils through the microbial processes of nitrification (the aerobic microbial oxidation of ammonium to nitrate) and denitrification (the anaerobic microbial reduction of nitrate to dinitrogen gas). A variety of human activities related to agricultural production systems add

nitrogen to soils, thereby increasing the amount of nitrogen available for nitrification and denitrification and contributing to increased emissions of N₂O. Anthropogenic nitrogen additions to soils take place through both direct and indirect pathways.

Direct pathways, which are addressed in this section (1), include:

- Application of organic and synthetic nitrogenous fertilizers
- Incorporation of crop residues, and
- Production of nitrogen fixing crops.

Indirect pathways, which are addressed in a separate section (3) on indirect emissions, include:

- Nitrogen volatilization and
- Surface run-off and sub-surface leaching.

Three additional sources of nitrogen inputs to soils that are not included in the estimates produced for this report are the application of sewage sludge to land, the cultivation/management of non-alfalfa forage legumes (such as clovers, trefoil, and vetch), and the cultivation of soils with high organic content. Methodologies developed for estimating emissions from these sources are in the process of being reviewed, and can be considered once the sources and methodologies are incorporated into the IPCC Guidelines or Good Practice papers and activity data become available.

(a) Emissions from the Application of Synthetic Nitrogen Fertilizers

The following steps were taken in estimating direct emissions from adding synthetic nitrogen to soil:

- For each region, fertilizer consumption data [FC] (i.e., metric tonnes of nitrogen) for the years 1990, 1995, and 1998, were obtained from the Food and Agriculture Organization of the United Nations (FAO) on-line database (Table III-1) (FAO, 1998a);
- The consumption data were multiplied by 0.9 in order to take into account the portion (10%) that volatilizes and is accounted for in the indirect emissions category (IPCC, 1997);
- The net amount of nitrogen was then multiplied by the default emissions factor—0.0125 kg N₂O-N/kg N (IPCC, 1997) (Table III-2).

The resulting formula for N₂O emissions from synthetic nitrogen fertilizers [NSF] is as follows:

$$NSF = FC * 0.9 * 0.0125 / 1,000.0 * 44/28$$

Table III-1. Nitrogen Fertilizer Consumed (thousand metric tonnes N)

Year	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East and N. Africa	Asia	FSU	World
1990	11,397	10,405	3,278	504	3,707	1,138	3,420	34,728	8,669	77,246
1995	12,738	9,722	2,030	846	3,877	927	3,534	41,661	2,652	77,986
1998	12,871	9,846	2,227	1,083	4,549	1,121	3,754	43,135	2,590	81,117

Table III-2. Direct Emissions Of Nitrous Oxide From Synthetic Nitrogen (Gg N₂O /Yr)

Year	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East and N. Africa	Asia	FSU	World
1990	202	184	58	9	65	20	60	614	153	1,366
1995	225	172	36	15	68	16	62	737	47	1,379
1998	228	174	39	19	80	20	66	763	46	1,435

(b) Emissions from the Application of Manure Nitrogen—Daily Spread

For each region and each of the years—1990,1995, and 1998—the following steps were taken to estimate nitrous oxide emissions from manure nitrogen applied to agricultural soils in the form of daily spread:

- Live animal population data for cattle, poultry, sheep, swine, and other animals were downloaded from the FAO database (FAO, 1998b);
- Live dairy cattle numbers were obtained from the FAO’s *Production YearBook (FAO 1998a)* and used to divide the cattle population data into dairy cattle and non-dairy cattle;
- Total nitrogen excreted [NE] was computed based on the default values for nitrogen excretion per head of animal type (Table III-3);
- Nitrogen allocated to the “daily spread” manure management system was estimated according to the proportions provided in Safely et al (1992) (Table III-4);
- Nitrogen excreted and applied as daily spread (Table III-5) was adjusted for volatilization—by multiplying by the default value of 0.8 (IPCC, 1997);
- Manure nitrogen in daily spread—net of the amount that volatilizes—was multiplied by the default emissions factor (0.0125 kg N₂O-N/kg N) (Table III-6).

The resulting formula for N₂O emissions from the daily spread of manure nitrogen [MNDS] is as follows:

$$MNDS = NE * \%MNDS * 0.8 * 0.0125 / 1,000.0 * 44/28$$

where %MNDS is the region and animal type-specific percentage of manure applied as daily spread (Table III-4).

Table III-3. Default Values for N Excretion per Head of Animal by Region (kg/animal/year) (IPCC, 1997)

Region	Dairy Cattle	Other Cattle	Poultry	Sheep	Swine	Other animals
North America	100	70	0.6	10	20	25
W. Europe	100	70	0.6	20	20	25
E Europe	70	50	0.6	16	20	25
Oceania	80	60	0.6	20	16	25
Latin America	70	40	0.6	12	16	40
Africa	60	40	0.6	12	16	40
N. East & Med.	70	50	0.6	12	16	40
Asia & Far East	60	40	0.6	12	16	40

Table III-4. Percentage Of Manure N Produced In Different Animal Waste Management Systems In Different Regions Of The World

Region	Animal type	Animal Waste Management System /Method					
		Anaerobic Lagoon	Liquid System	Daily Spread	Solid Storage & Drylot	Pasture, Range, & Paddock	Other Systems
North America	non dairy cattle	0.00%	1.00%	0.00%	14.00%	84.00%	1.00%
	dairy	10.00%	23.00%	37.00%	23.00%	0.00%	7.00%
	poultry	5.00%	4.00%	0.00%	0.00%	1.00%	90.00%
	sheep	0.00%	0.00%	0.00%	2.00%	88.00%	10.00%
	swine	25.00%	50.00%	0.00%	18.00%	0.00%	6.00%
	other	0.00%	0.00%	0.00%	0.00%	92.00%	8.00%
Western Europe	non dairy cattle	0.00%	55.00%	0.00%	2.00%	33.00%	9.00%
	dairy	0.00%	46.00%	24.00%	21.00%	8.00%	1.00%
	poultry	0.00%	13.00%	0.00%	1.00%	2.00%	84.00%
	sheep	0.00%	0.00%	0.00%	2.00%	87.00%	11.00%
	swine	0.00%	77.00%	0.00%	23.00%	0.00%	0.00%
	other	0.00%	0.00%	0.00%	0.00%	96.00%	4.00%
Eastern Europe	non dairy cattle	8.00%	39.00%	0.00%	52.00%	0.00%	1.00%
	dairy	0.00%	18.00%	1.00%	67.00%	13.00%	0.00%
	poultry	0.00%	28.00%	0.00%	0.00%	1.00%	71.00%
	sheep	0.00%	0.00%	0.00%	0.00%	73.00%	27.00%
	swine	0.00%	29.00%	0.00%	0.00%	27.00%	45.00%
	other	0.00%	0.00%	0.00%	0.00%	92.00%	8.00%
Oceania	non dairy cattle	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%
	dairy	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%
	poultry	0.00%	0.00%	0.00%	0.00%	3.00%	97.00%
	sheep	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%
	swine	55.00%	0.00%	0.00%	17.00%	0.00%	28.00%
	other	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%
Latin America	non dairy cattle	0.00%	0.00%	0.00%	0.00%	99.00%	1.00%
	dairy	0.00%	1.00%	62.00%	0.00%	36.00%	0.00%
	poultry	0.00%	9.00%	0.00%	0.00%	42.00%	49.00%
	sheep	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%
	swine	0.00%	8.00%	2.00%	51.00%	0.00%	40.00%
	other	0.00%	0.00%	0.00%	0.00%	99.00%	1.00%
Africa	non dairy cattle	0.00%	0.00%	1.00%	3.00%	96.00%	0.00%
	dairy	0.00%	0.00%	12.00%	0.00%	83.00%	5.00%
	poultry	0.00%	0.00%	0.00%	0.00%	81.00%	19.00%
	sheep	0.00%	0.00%	0.00%	1.00%	99.00%	1.00%
	swine	0.00%	7.00%	0.00%	93.00%	0.00%	0.00%
	other	1.00%	0.00%	0.00%	0.00%	99.00%	1.00%
Near East & Mediterranean	Non-dairy cattle	0.00%	0.00%	2.00%	0.00%	77.00%	2.00%
	Dairy Cattle	0.00%	0.00%	3.00%	3.00%	77.00%	0.00%
	Poultry	0.00%	1.00%	0.00%	0.00%	71.00%	28.00%
	Sheep	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%
	Swine	0.00%	32.00%	0.00%	68.00%	0.00%	0.00%
	Others	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%
Asia & Far East	Non-dairy cattle	0.00%	0.00%	16.00%	14.00%	29.00%	0.00%
	Dairy Cattle	6.00%	4.00%	21.00%	0.00%	24.00%	0.00%
	Poultry	1.00%	2.00%	0.00%	0.00%	44.00%	52.00%

Table III-4. Percentage Of Manure N Produced In Different Animal Waste Management Systems In Different Regions Of The World

Region	Animal type	Animal Waste Management System /Method					
		Anaerobic Lagoon	Liquid System	Daily Spread	Solid Storage & Drylot	Pasture, Range, & Paddock	Other Systems
	Sheep	0.00%	0.00%	0.00%	0.00%	83.00%	17.00%
	Swine	1.00%	38.00%	1.00%	53.00%	0.00%	0.00%
	Others	0.00%	0.00%	0.00%	0.00%	95.00%	5.00%

Table III-5: Manure Nitrogen Excreted (Thousand Metric Tonnes/Year) (1990, 1995 and 1998)

Manure Management System	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East & N. Africa	Asia	FSU	World
1990										
ana. Lagoon	434,610	0	69,905	41,375	0	75,677	0	237,747	276,993	1,136,308
liquid system	970,238	5,770,389	835,347	4	121,989	18,491	1,916	2,765,364	2,064,710	12,548,449
daily spread	420,561	670,857	8,752	0	1,720,000	278,883	47,245	2,765,628	248,498	6,160,425
solid stor & dry lot	1,433,877	1,300,611	1,040,767	12,789	602,810	448,179	32,955	5,545,415	3,208,076	13,625,478
pasture, range, paddock	5,979,519	4,210,254	1,021,118	6,623,347	16,579,988	16,891,868	6,611,360	24,827,183	2,904,588	85,649,224
other systems	259,610	725,653	715,847	21,086	617,166	187,779	18,465	1,392,173	1,140,177	5,077,957
1995										
ana. Lagoon	462,298	0	40,212	45,358	0	85,530	0	262,063	199,408	1,094,868
liquid system	1,030,014	5,393,957	587,629	5	132,209	24,122	2,366	3,208,814	1,493,871	11,872,985
daily spread	396,283	572,935	6,680	0	1,883,129	299,649	46,973	3,019,866	203,607	6,429,123
solid stor & dry lot	1,531,965	1,191,204	708,933	14,020	651,228	539,621	34,423	6,324,979	2,558,154	13,554,526
pasture, range, paddock	6,486,982	4,042,877	773,309	5,672,007	17,267,431	18,641,284	6,489,649	27,862,759	2,160,371	89,396,669
other systems	266,386	694,061	546,031	23,117	662,793	206,223	17,710	1,551,059	736,402	4,703,782
1998										
ana. Lagoon	469,706	0	36,813	46,281	0	89,815	0	277,837	137,443	1,057,893
liquid system	1,042,361	5,354,601	552,408	6	132,541	24,851	2,682	3,609,247	1,059,800	11,778,496
daily spread	384,554	546,479	6,307	0	2,200,584	319,487	47,852	3,042,697	157,644	6,705,603
solid stor & dry lot	1,510,703	1,171,465	661,831	14,306	620,473	571,830	35,853	6,873,039	1,881,139	13,340,639
pasture, range, paddock	6,338,034	4,111,807	691,740	5,624,621	17,379,099	19,947,937	6,745,297	29,145,753	1,520,137	91,504,424
other systems	262,868	702,661	506,687	23,592	639,132	216,913	17,844	1,630,651	490,671	4,491,018

Table III-6. Direct Emissions Of Nitrous Oxide From Manure N Applied To Agricultural Soils As Daily Spread (Gg N₂O /Year)

Year	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East and N. Africa	Asia	FSU	World
1990	7	11	<1	0	27	4	1	44	4	97
1995	6	9	<1	0	30	5	1	48	3	101

(c) Direct Emissions from Manure Nitrogen Deposited by Grazing Animals

For each region and each of the years—1990,1995, and 1998—the following steps were taken to estimate nitrous oxide emissions from manure nitrogen deposited by grazing animals:

- Nitrogen excreted [NE] was computed based on the default values for nitrogen excretion per head of animal type (Table III-3);
- Nitrogen deposited by grazing animals [MNGA] (“pasture, range, & paddock” manure management system) was calculated according to the proportions provided in Safely et al (1992) (Table III-4);
- Nitrogen excreted by grazing animals (Table III-5) was adjusted for volatilization— by multiplying by the default value of 0.8 (IPCC, 1997);
- Manure nitrogen in daily spread adjusted for volatilization was multiplied by the default emissions factor (0.02 kg N₂O-N/kg N) (IPCC, 1997) (Table III-7).

The resulting formula for N₂O emissions from grazing animals [MNGA] is as follows:

$$MNGA = NE * \%MNGA * 0.8 * 0.02 / 1,000.0 * 44/28$$

where %MNGA is the region and animal type-specific percentage of the total manure nitrogen deposited into soil by grazing animals (Table III-4).

Table III-7. Direct N₂O Emissions From Nitrogen Deposited By Grazing Animals—Pasture, Range And Paddock (Gg/Year)

Year	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East and N. Africa	Asia	FSU	World
1990	150	105	26	167	417	424	166	624	73	2,153
1995	163	101	19	143	434	469	163	701	54	2,248
1998	159	103	17	141	437	502	170	733	38	2,301

(d) Direct Emissions from the Cultivation of Nitrogen Fixing Crops

The method used to compute direct N₂O emissions from the cultivation of nitrogen fixing crops is as follows:

- For each region and each year (1990, 1995, and 1998), annual production data on nitrogen-fixing crops [NFCR] such as pulses, soybeans, and groundnuts² were downloaded from the FAO on-line database (FAO, 1998b) (Table III-8);
- To convert from the quantity of groundnuts, pulses, and soybeans produced to the total dry biomass for these crops, the amount produced was multiplied by a factor of 2 (IPCC, 1997);

² The IPCC default methodology requires production data for pulses and soybeans only. However, groundnuts and alfalfa are also important sources of nitrogen from nitrogen fixation. Data on alfalfa production is reported along with all other types of hay and could not be used to produce this estimate. However, because of its potential importance as a substitute for commercial nitrogen sources, future efforts to estimate emissions from alfalfa should be undertaken.

- Nitrogen input from N-fixing crops was then calculated by multiplying total dry biomass by 3%. (IPCC, 1997) (Table III-9);
- N₂O emissions were then estimated by applying the default emissions factor (0.0125 kg N₂O-N/kg N) to the nitrogen input from N-fixing crops (Table III-10).

The resulting formula for N₂O emissions from cultivation of nitrogen-fixing crops [NFC] is as follows:

$$NFC = NFCR * 2 * 0.03 * 0.0125 * 1,000.0 * 44/28.$$

Table III-8. Production Of Soybeans, Pulses, And Groundnuts (Thousand Metric Tonnes/Year)

Year	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East and N. Africa	Asia	FSU	World
<i>Soybeans (thousand metric tonnes)</i>										
1990	53,678	2,084	381	77	33,689	574	379	16,697	875	108,433
1995	61,472	1,041	287	27	41,345	490	287	21,567	332	126,838
1998	77,765	1,593	520	54	54,348	879	229	22,492	340	158,220
<i>Pulses (thousand metric tonnes)</i>										
1990	2,251	6,341	1,547	1,421	5,373	5,562	3,843	23,196	8,933	58,467
1995	3,866	4,760	1,112	2,644	5,960	6,393	3,477	23,174	3,435	50,957
1998	4,807	6,037	1,020	2,380	5,249	7,494	3,319	23,531	2,298	56,135
<i>Groundnuts (thousand metric tonnes)</i>										
1990	1,634	8	11	29	732	4,277	159	16,188	4	23,043
1995	1,570	3	13	41	730	6,203	290	20,488	16	27,785
1998	1,798	3	10	41	1,361	7,004	289	21,753	22	32,282

Table III-9. Nitrogen Input From N-Fixing Crops (Thousand Metric Tonnes/Year)

Year	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East and N. Africa	Asia	FSU	World
1990	3,454	506	116	92	2,388	625	263	3,365	589	11,397
1995	4,014	348	85	163	2,882	785	243	3,914	226	8,646
1998	5,062	458	93	149	3,658	923	230	4,067	160	14,798

Table III-10. N₂O Emissions From Production Of N-Fixing Crops (Gg N₂O/Yr)

Year	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East & N. Africa	Asia	FSU	World
1990	68	10	2	2	47	12	5	66	12	224
1995	79	7	2	3	57	15	5	77	4	170
1998	99	9	2	3	72	18	5	80	3	291

(e) Incorporation of Crop Residue into Agricultural Soils

The method used to compute direct emissions from the incorporation of crop residues into agricultural soils [CRN] is as follows:

- For each region and each year (1990, 1995, and 1998) annual production (AP) of pulses, soybeans, groundnuts, and cereals/grains was downloaded from the FAO on-line database (FAO, 1998b) (Tables III-8 and III-11);
- To calculate the dry biomass content of residuals, the annual production estimates were multiplied by 2 and then by 0.85 to account for crop water content;
- The nitrogen content in crop residuals for N-fixing crops was estimated by multiplying by the fraction of N in dry biomass [FN], for N-fixing crops this fraction was equal to 0.03 and for non-N-fixing crops – to 0.015 (IPCC, 1997) (Tables III-12);
- Nitrogen from both nitrogen-fixing and other crops was then multiplied by the fraction of crop biomass remaining in the field (0.55) and then by a fraction that is not burned [FNB], which for industrial countries was set to 0.9 and for developing countries – 0.8 (IPCC, 1997);
- N₂O emissions were then estimated by applying the default emissions factor (0.0125 kg N₂O-N/kg N) to the residual crop nitrogen estimated as remaining on the field (Table III-13).

The resulting formula for N₂O emissions from the incorporation of crop residues into agricultural soils [CRN] is as follows:

$$CRN = AP * 2 * 0.85 * FN * 0.55 * FNB * 0.0125 * 1,000.0 * 44/28$$

Table III-11. Production Of Cereals/Grains Data Used To Compute N₂O Emissions From The Incorporation Of Crop Residues Into Agricultural Soils (Thousand Metric Tonnes/Year)

Year	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East and N. Africa	Asia	FSU	World
1990	369,125	199,618	93,552	23,948	99,112	71,342	79,635	815,805	209,109	1,952,813
1995	326,852	182,553	88,266	28,113	123,491	80,243	77,719	866,843	122,096	1,896,176
1998	400,853	215,914	85,940	32,990	129,094	94,964	85,100	913,247	99,882	2,057,984

Table III-12. Nitrogen Content of Cereals/grains Residuals (Thousand Metric Tonnes)

Year	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East & N. Africa	Asia	FSU	World
1990	12,348	5,305	2,484	689	4,557	2,350	2,254	23,663	5,833	59,484
1995	11,747	4,951	2,323	855	5,599	2,714	2,189	24,615	3,306	58,298
1998	14,525	5,895	2,271	967	6,401	3,206	2,366	25,848	2,683	64,161

Table III-13. Total N₂O Emissions From The Incorporation Of Crop Residues (Gg N₂O/Year)

Year	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East & N. Africa	Asia	FSU	World
1990	120	52	24	7	44	23	22	230	56	578
1995	114	48	23	8	54	27	21	247	32	575
1998	141	57	22	9	62	31	23	260	26	633

2. Direct Emissions from Manure Management Systems

Manure management systems produce N₂O via chemical and biochemical processes of manure decomposition. The amount of N₂O produced from various manure management systems varies according to numerous factors including: the type, age, size, sex, and diet of the animals producing the manure; the method of collection and storage at the site where the manure is produced; the length of time the product is held in storage; the mode of transport and handling of product during transport; temperature and moisture at the point of production; and the amount of oxygen present in the management system.

For each region and each of the years—1990, 1995, and 1998—the following steps were taken to estimate direct nitrous oxide emissions from manure management systems:

- Live animal population data for cattle, poultry, sheep, swine and other animals were downloaded from the FAO database; (FAO, 1998b).
- Live dairy cattle numbers were obtained from the FAO's *Production YearBook (FAO 1998a)* and used to divide the cattle population data into dairy cattle and non-dairy cattle.
- Nitrogen excreted [NE] was computed based on the default values for nitrogen excretion per head of animal type (Table III-5).
- Nitrogen excreted was adjusted for volatilization—the default value of 20% was used as the amount of manure N that volatilizes (IPCC, 1997).
- Total nitrogen excreted was allocated to the following manure management systems: liquid systems [LS], anaerobic lagoons [AL], solid storage and drylot [SSDL], and other systems [OS], according to the proportions provided in Safely et al (1992) (Table III-4).
- The quantity of nitrogen excreted in each type of manure management system was multiplied by the system-specific emissions factor (0.001 kg N₂O-N/kg N for liquid systems and anaerobic lagoons, 0.02 for solid storage and drylot, and 0.005 for other systems) (Table III-14).

The resulting formula for direct N₂O emissions from manure management systems [MMSN] is as follows:

$$MMSN = NE * 0.8 * [(%LS+%AL)*0.001 + \%SSDL*0.02 + \%OS*0.005] / 1,000.0 * 44/28$$

Table III-14. N₂O Emissions from Manure Management Systems (Gg/year)

Year	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East & N. Africa	Asia	FSU	World
1990	39	45	32	1	19	13	1	152	91	392
1995	42	41	22	1	21	15	1	173	71	387
1998	42	41	21	1	20	16	1	188	52	380

3. Indirect Emissions from Agricultural Soils and Manure Management Systems

(a) Synthetic and Manure Nitrogen Volatilization

For each region and for each of the years 1990, 1995, and 1998, indirect emissions from volatilized synthetic and manure nitrogen were estimated as follows:

- The total amount of nitrogen that volatilizes was calculated by multiplying the quantity of synthetic nitrogen fertilizer [FC] by 0.1 and manure nitrogen [NE] by 0.2 (the proportion that is assumed to volatilize) (IPCC, 1997).
- The total amount of volatilized nitrogen was then multiplied by the default emissions factor 0.01 to obtain an estimate of the amount of N₂O-N that is emitted as a result of volatilization (Table III-15).

The resulting formula for indirect N₂O emissions from synthetic and manure nitrogen volatilization [SMV] is as follows:

$$SMV = [FC * 0.1 + NE * 0.2] * 0.01 / 1,000.0 * 44/28$$

(b) Leaching and Run-off

For each region and each of the years 1990, 1995, and 1998, indirect emissions from leaching and run-off of synthetic and manure nitrogen were estimated as follows:

- The quantity of synthetic nitrogen was adjusted for volatilization by multiplying the quantity of synthetic nitrogen fertilizer (FC) by 0.9—i.e., synthetic nitrogen consumed was reduced by the amount that volatilizes (10%).
- Total nitrogen excreted by livestock (NE) was adjusted for volatilization by multiplying nitrogen excreted by 0.8—i.e., nitrogen excreted was reduced by the proportion that volatilizes (20%).
- The unvolatilized amounts of synthetic N and manure N were added together to obtain the total amount of agricultural nitrogen subject to leaching and run-off.
- The total amount of nitrogen subject to leaching and run-off was multiplied by 0.3 to obtain the amount of nitrogen lost to leaching run-off (IPCC, 1997).
- The total amount of nitrogen lost to leaching run-off was then multiplied by the default emissions factor 0.025 to obtain an estimate of the amount of N₂O-N that is emitted as a result of leaching and run-off (Table III-15).

The resulting formula for indirect N₂O emissions from leaching and run-off [NLR] is as follows:

$$NLR = [FC * 0.9 + NE * 0.8] * 0.3 * 0.025 / 1,000.0 * 44/28$$

Table III-15. Indirect Emissions Of N₂O From Agricultural Soils And Manure Management Systems (Gg N₂O/Year)

Year	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East & N. Africa	Asia	FSU	World
<i>Indirect Emissions from Volatilization of Synthetic and Manure Nitrogen</i>										
1990	48	56	17	22	68	58	27	195	46	536
1995	52	53	12	20	71	64	27	222	28	548
1998	52	53	12	20	73	68	28	233	22	559
<i>Indirect Emissions from Leaching and Run-off</i>										
1990		230	70	69	225	181	101	789	190	2,063
1995		215	47	63	235	197	101	913	102	2,103
1998		217	47	65	246	212	106	952	80	2,155
<i>Total Indirect Emissions from Synthetic and Manure Nitrogen</i>										
1990		286	86	90	292	239	128	983	236	2,599
1995		268	58	83	306	260	128	1,135	130	2,651
1998		269	58	85	319	280	134	1,184	102	2,713

It should be noted here, that the methodology for estimating indirect N₂O emissions from run-off and leaching is currently under revision. The major change expected from this revision is that the estimates of nitrogen subject to runoff and leaching will be based on the total amount of nitrogen applied to soils, and not only to the amount that does not volatilize, as it is done here. The rationale behind this is that volatilized nitrogen will eventually redeposit and be subject to similar biogeochemical processes in the soil as directly applied nitrogen. Additionally, the emission factor for estimating indirect N₂O emissions from soils due to leaching and runoff is currently under review. Any changes that are incorporated into the IPCC guidelines or Good Practice papers can be included in this analysis as soon as they are made available to the public.

4. Biomass Burning

Biomass burning for non-energy purposes produces nitrous oxide via incomplete oxidation of nitrogen. Anthropogenic sources of nitrous oxide emissions related to biomass burning are due to the following practices:

- field burning of crop residues,
- savanna burning, and
- deforestation.

Since biomass is composed essentially of cellulose and lignin—both of which are carbohydrates—the products of complete combustion are CO₂ and water vapor. However, for a variety of reasons, uncontrolled combustion is never complete and, as a consequence, burning generates several gaseous products, one of which is nitrous oxide. Worldwide, it is believed that 95 percent of all biomass burning is anthropogenic in origin, with savanna burning and deforestation the primary sources in this category (EPA, 1994).

In the 1995 assessment of radiative forcing, the IPCC (1995) reported that anthropogenic sources of nitrous oxide related to biomass burning equaled approximately 0.5 Tg N₂O-N or 786 Gg N₂O worldwide. However, the IPCC also noted that this estimate is subject to a substantial uncertainty. This uncertainty is largely due to the relative dearth of empirical analyses of N₂O emissions from combustion, particularly in tropical regions. In addition, there is some new evidence that current methods of estimating the contribution of biomass burning to global nitrous emissions might understate actual emissions because the methodology does not take into account the possibility that these activities might elevate biogenic emissions.

Given the high degree of uncertainty associated with available estimation techniques and difficulties with obtaining detailed information on the extent of biomass burning worldwide, this study has not included an independent analysis of this source. Moreover, no original predictions about future changes in emissions from this source are made here. This is because the factors that might contribute to a change in total emissions tend to exert opposing influences that cannot be quantified with a satisfactory level of confidence. Specifically, although savanna burning and deforestation are expected to remain relatively constant, N₂O emissions from crop residue burning can be expected to rise with increases in crop production. However, the practice of agricultural residue burning is also expected to decline as income levels rise. Thus, the IPCC's estimate of 786 Gg N₂O per year is used here as the best available estimate of past, current, and future emissions from this source.

C. Uncertainty of Emission Estimates

In spite of the significant progress in identifying and quantifying new emission sources associated with agricultural practices, emission estimates for this sector remain highly uncertain. Some sources of this uncertainty are described in Table III-16.

Table III-16. Sources Of Uncertainty For Agricultural Sources Of N₂O

Source/Subsource	Type of data	Source of uncertainty	Comments
<i>Direct emissions from agricultural soils</i>			
Application of N as synthetic fertilizer or manure	Emission factors	Missing country specific factors	Actual emission rates depend on numerous site-specific factors that cannot be taken into account when using default emission factors. For example, soil temperature and texture, seasonal rainfall patterns, ambient temperatures at the time of application, pH levels and other soil components are among the things that can have a profound influence on the rate of emissions.
	Emission factors	Missing fertilizer specific factors	There is some evidence suggesting that emission rates might vary by type of fertilizer. Additional research is needed to confirm these results and, if needed, develop emission factors for each of the various types of synthetic forms of N fertilizers.
	Emission factors	Poor understanding of the relationship between the application of manure nitrogen to soils and emission rates across time	Additional research is needed to understand how the process of mineralization of organic nitrogen contributes to emissions over time. The current methodology treats manure N as though all emissions are released in the year in which the manure is applied to soils.
Manure Nitrogen deposited by grazing animals	Emission factors	Missing factors related to method of application	The rate of N ₂ O flux is partially determined by the method used to apply N sources—e.g., conventional vs. no till cultivation; broadcast spreading vs. injection; etc.
	Activity data	Nitrogen content of animal manure	The only data available to calculate N content of manure from different animals is very general, incomplete, and is not based on a number of important variables, such as age, sex, size, and diet.
	Activity data	Types of fertilizer used by country	The FAO data report only the amount of synthetic N consumed. They do not distinguish between the various forms of synthetic N.
	Activity data	Quantity of manure applied via daily spread	Animal population data are used along with generic estimates of regional application rates to estimate the volume of manure that is applied to agricultural land on a daily basis. Country specific data need to be developed on the numbers and types of animals to which this practice actually applies.
	Emission factors	Poor understanding of the relationship between the application of manure nitrogen to soils and emission rates across time	Additional research is needed to understand how the process of mineralization of organic nitrogen contributes to emissions over time. The current methodology treats manure N as though all emissions are released in the year in which the manure is applied to soils.
	Activity data	Nitrogen content of animal manure	The only data available to calculate N content of manure from different animals is very general, incomplete, and is not based on a number of important variables, such as age, sex, size, and diet.
	Activity data	Quantity of manure produced by grazing	Animal population data were used along with generic estimates of regional application rates to estimate the volume of manure that is

Table III-16. Sources Of Uncertainty For Agricultural Sources Of N₂O

Source/Subsource	Type of data	Source of uncertainty	Comments
Incorporation of crop residues	Emission factors	animals Missing location-specific emission factors	deposited by grazing animals. Country specific data need to be developed on the numbers and types of animals to which this practice actually applies. Emission rates are determined by location-specific factors such as soil types, moisture content, local climatic factors such as temperatures and rainfall etc.
	Activity data	Missing country specific data on extent of practice.	Generic estimates of the extent of crop residue incorporation are not sufficient to produce an accurate estimate of emissions related to this practice across all regions of the world.
Cultivation of nitrogen fixing crops	Emission factors	Location specific emission factors are needed.	Site specific conditions related to soils, climate, and farming practices are needed to improve estimates of emissions from this source.
<i>Direct emissions from manure management systems</i>			
All categories—i.e., anaerobic lagoons, liquid systems, solid storage and drylot, and other systems	Emissions factors	Location specific emission factors for each type of system are needed	A single default emissions factor is used to compute emissions from all of these systems under all conditions. Location specific factors for each of the systems would be needed to generate accurate estimates from this source.
<i>Indirect emissions from agricultural soils and manure management systems</i>			
Volatilized synthetic and manure nitrogen	Emission factors	Source specific emission factors are not available.	The default emissions factor that is used to estimate emissions related to volatilization is the same for synthetic and manure sources. There are a number of reasons why this might not be appropriate—e.g., some forms of synthetic fertilizers are injected into the ground and thus have much less direct exposure to the atmosphere and might therefore be less subject to volatilization.
	Emission factors	Location specific emissions factors	Site specific conditions can affect the level of volatilization—e.g., timing of rainfall or irrigation relative to when N is added to the soil.
	Activity data	Nitrogen content of animal manure	The only data available to calculate N content of manure from different animals is very general, incomplete, and is not based on a number of important variables, such as age, sex, size, and diet.
	Activity data	Types of fertilizer consumed	FAO provides data only on the quantity of synthetic N consumed. It does not distinguish between the various forms of synthetic N.
Nitrogen leaching and run-off	Activity data	Application methods and irrigation practices	Both the method of application and the use of irrigation to wash applied N into the soil affect the volatilization rate.
	Emission factors	Site specific emission factors are not available	Leaching and run-off are both affected by a variety of location specific factors—such as soil texture, terrain, annual and seasonal rainfall, etc. Country specific emission factors would be needed to more accurately account for these factors in generating emission estimates. In addition, N ₂ O emissions from the nitrogen that is lost to leaching and run-off is strongly dependent on location specific factors such as surface and ground water temperatures.
	Activity data	Application methods and irrigation practices	The rate of nitrogen leaching and run-off are also dependent on the method of fertilizer application and irrigation practices.

D. Combined Current and Future Emissions from Agriculture

Nitrous oxide emissions from agricultural sources, with the exception of biomass burning, were projected to 2020 using the World Bank medium population forecast. An assumption that emissions from this source category are closely related to population is investigated in the Special Report on Emission Scenarios (SRES, 2000). This assumption is generally adequate only if general patterns of agricultural consumption do not change significantly with changes in welfare (e.g., GDP per capita). For example, an increase in meat consumption in developing countries might lead to larger emissions from manure management and lower emissions from crop residue, etc. On average, however, given a limited number of studies on this subject and a substantial uncertainty associated with the GDP growth, the use of population as a single N₂O driver for short-to-medium term projections appears to be justifiable. This is also illustrated by the values of the adjustment coefficient (*k*) (see Section II-B) for the agricultural sources. Global values of *k* as well as values in the OECD90 and ALM regions range from 0.93 to 1.0 suggesting almost a linear relationship between population and emissions. In other regions, variation is larger with *k* ranging from 0.54 (emissions from agricultural soils in the REF region) to 1.06 (indirect emissions in the ASIA region). Relatively slow emission growth in the reforming economies (REF) is explained by a general economic slowdown, resulting in lower fertilizer use and livestock production. At the same time, in Asian countries emissions grow faster than population due to a transition to the meat-based diet. While in the future, the exact form of a functional relationship between agricultural emissions and population is likely to change, major trends are expected to continue through 2020.

Emissions from biomass were assumed to stay constant from 1995 to 2020. This assumption reflects a high methodological uncertainty associated with this source and also corresponds to two opposing factors impacting emissions from this source. One of these factors is an increase in food production in the developing world and another is a conversion to more sustainable agricultural practices.

According to Table III-17, agricultural soils contribute more than a half of the total sectoral emissions. Another substantial sources of N₂O are indirect emission sources, and in particular leaching and run-off. The 1990 global total emission estimate for agricultural sources presented here is lower than the one recently reported by Kroeze et al. (1999) and equal to about 10,200 Gg N₂O. A preliminary analysis indicates that this difference may be explained by the use of global average emission factors in the latter study.

From 2000 to 2020, global N₂O emissions from agriculture are expected to grow by 1.1% per year, driven primarily by an increase of emissions from agricultural soils. The fastest growth is anticipated in the ALM region, followed by the ASIA region (Table III-17).

Table III-17. Nitrous Oxide Emissions from Agriculture and Land Use (Gg N₂O/year)

Year	Source Category	OECD90	REF	ASIA	ALM	WORLD
1990	Direct Emissions from Soils	1,092	409	1,578	1,339	4,418
	Manure Management	84	123	152	33	392
	Indirect Emissions	635	322	983	659	2,599
	Biomass Burning					821
	Total	1,811	854	2,713	2,031	8,230
1995	Direct Emissions from Soils	1,094	221	1,809	1,427	4,551
	Manure Management	84	93	173	37	387

Table III-17. Nitrous Oxide Emissions from Agriculture and Land Use (Gg N₂O/year)

Year	Source Category	OECD90	REF	ASIA	ALM	WORLD
	Indirect Emissions	634	188	1,135	694	2,651
	Biomass Burning					821
	Total	1,811	502	3,117	2,158	8,410
2000	Direct Emissions from Soils	1,095	119	2,061	1,503	4,777
	Manure Management	83	71	196	41	390
	Indirect Emissions	632	110	1,303	723	2,767
	Biomass Burning					821
	Total	1,809	300	3,559	2,266	8,756
2005	Direct Emissions from Soils	1,113	119	2,178	1,692	5,101
	Manure Management	84	71	207	46	408
	Indirect Emissions	642	110	1,377	813	2,942
	Biomass Burning					821
	Total	1,839	300	3,761	2,550	9,272
2010	Direct Emissions from Soils	1,131	119	2,295	1,880	5,425
	Manure Management	86	71	218	51	426
	Indirect Emissions	653	110	1,451	904	3,117
	Biomass Burning					821
	Total	1,870	300	3,964	2,835	9,789
2015	Direct Emissions from Soils	1,149	119	2,412	2,068	5,749
	Manure Management	87	71	229	56	443
	Indirect Emissions	663	110	1,525	994	3,292
	Biomass Burning					821
	Total	1,900	301	4,166	3,119	10,306
2020	Direct Emissions from Soils	1,168	120	2,529	2,257	6,073
	Manure Management	88	71	241	61	461
	Indirect Emissions	674	110	1,599	1,085	3,468
	Biomass Burning					821
	Total	1,930	301	4,368	3,403	10,822
<i>Percent Change from 1990 to 2020</i>		0.32%	0.02%	1.03%	2.05%	1.07%

E. Emission Abatement Options

1. Overview of Mitigation Options

Most of the N₂O from agricultural sources is emitted from soils. The source strength—i.e., the flux of N₂O per unit of surface of soil, is small but highly variable across time and space. Soil type, climatic conditions, and the system of soil management can have a profound impact on the strength of an N₂O source. Consequently, soil is considered a diffuse, unpredictable, and poorly manageable source of N₂O (Oenema, 1999). At the plot scale, simulation models and regression analyses can explain only about 50% of the measured variance in flux measurements (Smith, et al. 1999). Studies suggest that farm management can have an effect on emissions mainly through the effect that different practices have on nitrogen availability. Numerous options have been proposed for controlling nitrous oxide emissions from agricultural sources (Peoples, et al. 1995). These options are typically based on the results of laboratory and/or field experiments. However, most have not been tested at the farm level and none of the suggested measures has been specifically implemented on even a small scale for the sole purpose of reducing N₂O emissions (Oenema, 1998 and 1999). This study attempts to address the majority of N₂O abatement

options described to date. At the same time, certain less-known practice-oriented options (e.g., use of cover crops; avoiding fallow periods; modified pasture management, etc.) are omitted.

There are two basic types of strategies and related technologies and practices that might be useful in reducing N₂O emissions from agricultural soils (Kowalenko, 1999). First are measures that result in an improvement in the efficiency with which nitrogen is used in farming. These types of measures include technologies and/or practices that improve plant uptake of applied nitrogen and thereby reduce the amount of residual nitrogen in the soil. Altering the timing and/or frequency of fertilizer application, the use of controlled release fertilizers, and reducing excess applications of synthetic fertilizers are among the types of mitigation options that could be implemented to improve the efficiency of nitrogen use by the agricultural sector. Because these options result in a reduction in the application of nitrogen to agricultural soils, they reduce **indirect** as well as **direct** emissions of nitrous oxide.

The second general set of measures that have the potential to reduce soil emissions of N₂O includes technologies and practices that either directly or indirectly inhibit the processes—i.e., nitrification and denitrification—that result in nitrogen losses. Nitrification and urease inhibitors are obvious examples of technologies that reduce N₂O production. In addition to these, the depth of nitrogen injection into soils, the type of tillage system used, site-specific irrigation practices, and the choice of fertilizer type can also be instrumental in determining the rate of biogenic production of nitrous oxide. In many cases, only **direct** emissions are reduced by these measures—and some, e.g., no-till cultivation could result in an increase in emissions associated with run-off.

Although considerably smaller than emissions from soils (Table III-17), N₂O emissions from manure management systems are nonetheless significant. Emission reduction options range from measures that involve chemical treatments of animal wastes—e.g., the use of urease and nitrification inhibitors—to options that involve changes in animal diets—e.g., supplements such as growth hormones for dairy cattle that can be used to ensure adequate year round milk production with reduced herd size—to policies aimed at reducing the demand for livestock products. However, in some cases (e.g., the use of bovine growth hormones), there remain questions about the impacts that dietary supplements might ultimately have on human consumers of animal products. Farm level evaluations of almost all of these approaches have yet to be conducted. Moreover, in some cases, what testing has been done indicates that some options for mitigating nitrous oxide—e.g., permitting a crust to form on manure lagoons—can have adverse implications for controlling methane emissions—i.e., methane emissions tend to rise as a result of implementing the option. Thus, evaluations of the cost and effectiveness of measures for reducing N₂O emissions from manure management systems are more tenuous than similar analyses looking at the potential to reduce emissions from agricultural soils.

More difficult and uncertain still are analyses of options that might be used to reduce emissions from biomass burning. For crop residue burning, abatement options include improvements in fire management practices and plowing under or composting residues. Savanna burning and deforestation however, are driven by factors such as land tenure systems, population pressures, and national and international development priorities and policies. To generate any meaningful analyses of these types of measures would require the dedication of considerable resources. Fortunately, emissions from biomass combustion are quite small relative to total emissions from other agricultural and land use sources. Thus, excluding the abatement options that are appropriate to controlling emissions from these sources will not significantly impact the results.

2. Specific Mitigation Options

(a) Options Applicable to Agricultural Soils

(i) *Measures that Improve N-Use Efficiency*

[1] **Testing to Optimize Nitrogen Application Rates.** Carry over nitrogen from previous applications of manure and fertilizer and/or residues from nitrogen-fixing crops can be difficult for farm operators to take into account in determining how much additional nitrogen needs to be added to the soil for the current crop (Blackmer and Thomas, 1996). In addition, recommended nitrogen application rates are typically set at levels that minimize the potential for under-fertilization of the crop in a worse case scenario (Blackmer, 1999). In combination, these factors often mean that more nitrogen is applied to the soil than is needed in most conditions. In fact, agronomists at Iowa State University, found that almost half of the 119 cornfields tested over a three year period had nitrate concentration levels that were more than double the level needed to obtain maximum yields (El-Hout and Blackmer, 1990; Morris and Blackmer, 1989 and 1990).

Soil nitrogen testing can be used to help growers adjust application rates to match site-specific conditions and thereby improve their use of nitrogen fertilizers. Access to tests that measure the amount of nitrogen available when corn plants have reached a height of 6 to 12 inches might be useful in managing nitrous oxide emissions (Blackmer, 1999; Kowalenko, 1999). In the aggregate, it has been estimated that U.S. growers could reduce the quantity of nitrogen added to cornfields by as much as one third as a result of optimizing nitrogen use (Blackmer, 1999). It is not, however, at all clear that similar reductions would be possible in other regions of the world. Much depends on current practices regarding application rates and the timing of fertilizer applications.

[2] **Controlled Release Fertilizers.** Controlled release fertilizers (CRF) are intended to release nutrients at a rate that corresponds closely with nutrient demand by growing crops. These products typically work by providing a physical barrier—e.g., a polymer coating—that decreases the rate of release of nitrogen into the soil. The coatings are adjusted to match the rate of nutrient release to the requirements of specific plants. Research data indicate that CRFs have the potential to bring about substantial reductions in N₂O emissions. Field measurements indicate that N₂O emission reductions of up to 79 percent may be possible over relatively short—70 day—time horizons (Minami, 1991). In addition, a recent study of nitrogen use by rice plants found that using CRF allowed the application of nitrogen to be reduced by 50 percent without a negative impact on yield (Marnatz, et al, 1999).³ Moreover, when used in conjunction with nitrification inhibitors, CRFs have shown even greater potential to reduce nitrous oxide emission (Yagi, 1999) and CRFs have been shown to significantly reduce leaching of nitrogen (Paramasivam and Alva, 1997; Perrin, et al, 1998). At present, the costs of CRFs is prohibitive for most purposes and in fact time released products are used only in the production of high value commodities such as ornamental plants or in landscaping.

[3] **Substitute Manure for Chemical Fertilizers.** To the extent that it is possible to displace commercial fertilizers with livestock manure, N₂O emission from chemical fertilizers can be reduced without increasing emissions from manure.⁴ Thus, total emissions from agriculture soils would decline.

³ There are different opinions with regard to the use of CRF. They may be more efficient for crops with a long growing season, but less so for other crops that need most of their nitrogen early.

⁴ There are several additional factors that need to be considered when evaluating the potential change in N₂O emissions with the substitution of manure for chemical sources of nitrogen. First, manure applied to soil during fall and winter appears to generate higher emissions than when comparable amounts are applied in spring. In addition, the rate of N₂O emission from manured soil might be higher than the rate from soil receiving similar amounts of synthetic nitrogen. This happens because manure supplies carbon, which enhances the denitrification process. Moreover, manure can create anaerobic microsites through clogging soil pores and enhancing

However, about 90 percent of the manure produced by domestic animals in the United States is not currently being used in crop production (Smith et al, 1997). This is due primarily to the fact that most large-scale livestock operations are not located in proximity to farms on which the majority of field crops are produced. In general, even though manure can be obtained from livestock producers at no cost, if it must be transported more than a relatively short distance (40-50 miles) it becomes more cost-effective to use commercial sources of nitrogen (Gilliam, 1999; Bundy, 1999a). Transport costs, therefore, tend to be the main determinants of the extent of manure use on cropland (Gilliam, 1999).

Be that as it may, there are still multiple factors complicating the potential for more widespread use of livestock manure as fertilizer for crops. Each of these complicating factors has some impact on the overall cost of this option. A complete analysis of this option would require determining how each of these factors could ultimately affect the actual cost of using manure as a replacement for synthetic sources of nitrogen. The following bullet items address the main issues:

- First, manure is produced continuously whereas the demand for fertilizers tends to be seasonal. Hence, if manure is to be used to provide crop nutrients, storage facilities would be required that can hold the manure, and retain its mineral N content, until it can be applied to cropland (Smith, et al, 1997).
- Second, the level of inorganic nitrogen found in animal wastes varies by type, size, age, sex, and diet of the animal generating the waste. It is also affected by the length of time the waste is held in storage as well as the collection and storage methods used in handling the manure. Moreover, temperature, moisture, soil type, and the method used to incorporate the manure into the soil all affect the amount of nitrogen available for crop use. From the point of view of the farmer, this means that the use of manure as a source of nitrogen carries with it far more uncertainty, and therefore risks, than is associated with the use of commercial fertilizers.
- Third, the volume of manure needed to replace the average commercial fertilizer can be hundreds of times larger than volume of synthetic product the manure replaces. This alone suggests that the costs of using manure as a source of nitrogen can be considerably higher than the costs associated with commercial nitrogen sources.
- Fourth, manure contains a substantial amount of organic nitrogen. Over time mineralization occurs and the organic nitrogen component of applied manure can become available for plant nutrition. The process, however, is gradual and depends on all of the same factors listed above as affecting the level of inorganic nitrogen. Again, this causes some uncertainty for crop producers with regard to the appropriate application rate.
- Finally, nitrogen is not the only nutrient in manure that is beneficial to plants. Manure also contains potash and potassium and other types of nutrients that are useful to growing plants. Moreover, there is a good deal of empirical evidence indicating that long term use of manure as a fertilizer can have important benefits in terms of improving the condition of soils—e.g., it may help improve moisture retention—and inhibiting a variety of plant pathogens. These additional benefits would have to be quantified in order to estimate the full cost of this option.

This study does not attempt to quantify all the factors listed here. All available literature as well as the experts contacted regarding this option emphasized that the major factor driving the low level of manure

oxygen depletion. Liquid manure also increases soil moisture content and therefore increases the potential for denitrification (Paul, 1999). Another factor to consider in using manure is that there might be trade-offs between methane emissions and nitrous oxide emissions arising from storage of manure and also between reducing N₂O emissions and potentially increasing CO₂ emissions from fuel required for transportation. In particular, N₂O emissions from manure lagoon systems can be reduced by eliminating the crust that forms on the liquid containers. However, doing so can result in an increase in the amount of methane emitted into the atmosphere (Paul, 1999).

use is the cost to transport it (Smith et al., 1997; Mosier, 1999; Gilliam, 1999; Blackmer, 1999; Bundy, 1999a).

[4] Crop rotation options. Crop rotation entails the growing of different annual or perennial crops in a given field. It is often used as a strategy for improving soil conditions and as a component of pest management programs. Corn-alfalfa rotations might also be an effective means of reducing the use of synthetic fertilizers (Bundy, 1999; Mosier, 1999; McCarty, 1999).⁵ Alfalfa, which is a variety of hay, is a perennial crop that is used as feed for cattle, horses, sheep, and other domestic farm animals. Although rotation-cycles lasting as long as 10 years are not uncommon, current corn-alfalfa rotation schemes in North America often entail four- or five-year cycles where alfalfa is grown for three or four consecutive years followed by one or more years of corn. In many cases, the length of the rotation cycle could be shortened to three years—i.e., two consecutive years of alfalfa followed by a single year of corn. This would still leave enough residual nitrogen available in the soil to permit the production of a single crop of corn without adding any additional synthetic nitrogen fertilizer (Bundy, 1999b).

Although crop-rotation systems are perhaps the most promising of all of the abatement options currently available, they were excluded from the cost analysis performed here in part because it is not clear how extensive crop rotation is at present. In addition, different rotation systems—e.g., some involving three crops such as soybeans-corn-alfalfa, or longer cycles—are used in different regions and they tend to vary according to the type of farming enterprise (Bundy, 1999a). Moreover, because of the difficulty in determining the impact that different crop rotation practices have on farm income, it was not possible to approximate the full economic cost of these options. However, this is clearly very important focus area for future work.

[5] Changes in the timing and/or frequency of fertilizer application. Shifting from fall applications to spring application can reduce the interval over which fertilizer resides in the soil without any uptake by plants. Losses from volatilization, leaching and run-off might be reduced with associated reductions in indirect emissions. Smaller applications of N might also be possible. There is some evidence suggesting that when N is applied in the fall, approximately 10% more is applied as compared to spring applications in the same regions.

Altering the timing of applications to better coincide with plant nutrient up-take might also allow the reduction in the total amount of N applied. Introducing N in smaller amounts throughout the growing season can reduce losses associated with nitrification and denitrification as well as from run-off and leaching. However, multiple applications are not feasible for many of the major N using crops—e.g., once corn has achieved a height of more than 68 inches, attempting to apply fertilizer through the use of conventional application techniques will result in damage to the growing plants.

[6] Tailor Fertilizer to Local Conditions. It might be possible to develop fertilizer types that are more suitable to specific local conditions and/or adjust application rates to take into account differences in soil characteristics and/or moisture content and/or ambient and soil temperature.

(ii) *Measures that Inhibit N₂O Formation*

[1] Nitrification Inhibitors. Nitrification inhibitors (NI) are used with ammonium and ammonia-based nitrogen fertilizers to maintain applied nitrogen in a form that is suitable for uptake by growing plants. Nitrification inhibitors can reduce the loss of nitrogen and permit crop production at constant or improved

⁵ The effectiveness of crop rotation schemes (including those involving alfalfa) in reducing N₂O emissions depends on introducing less nitrogen into the system in comparison with baseline trends (e.g., relying solely on fertilizers).

yields at given fertilizer application rates (McCarty, 1999).⁶ Field experiments suggest that using nitrification inhibitors could be an effective means of achieving substantial reductions in N₂O production (Velthof, et al, 1996). Although the impact of these amendments on crop yields varies as a result of the interaction of a number of different factors (Oenema, 1999; McCarty, 1999), reported results indicate that N₂O emission reductions ranging from 43-71% (Bronson & Mosier, 1998) to 58-78% (McTaggart, et. al, 1997) are possible with no decrease in output per acre. It should be noted however, that specialized equipment is often needed to apply NIs and that the most common form of the product would approximately double the cost of fertilizer applications.

[2] Urease Inhibitors. Urease inhibitors reduce nitrogen losses that occur due to volatilization of urea that is applied to cropland (Malhi et al, 1999). At present, insufficient data are available to conduct a credible cost analysis of the emission reduction benefits of more widespread use of these products.

[3] Alternative Tillage Systems. The literature comparing conventional tillage systems of agriculture with alternatives such as no till systems suggests that cumulative N₂O emissions associated with different tillage systems might vary across time due to changes in soil composition following a shift in farming practices (MacKenzie, et. al, 1996). Some studies suggest that in the long run, N₂O emissions could decline as a result of reduced nitrogen application rates following a shift to no till agriculture (Lemke et. al, 1999). However, at present there is insufficient empirical evidence to substantiate this change and in fact, most studies have found an increase in N₂O fluxes through at least the first few years following a change over from conventional tillage systems (Kowalenko, 1999).

[4] Changes in Injection Depth. There is some evidence indicating that N₂O emission reductions might be obtained by reducing the depth at which anhydrous ammonia is injected—i.e. injecting anhydrous fertilizers nearer to the surface is a potential means of reducing emissions (Breitenbeck and Bremner, 1986b). However, currently available information is insufficient for quantifying the emission reduction potential of this practice.

[5] Changes in Irrigation Practices. Because soil-water content is an important factor in volatilization as well as nitrification and denitrification, irrigation practices can have an important impact on N₂O emissions from agriculture (Lemke et. al, 1999). However, the appropriate use of irrigation water is related to numerous factors that tend to be site-, crop-, soil-, and temperature-specific (Peoples et. al, 1995). At present there is not enough information available to estimate potential emission reductions arising from a change in irrigation practices.

[6] Decrease use of anhydrous ammonia. There is some empirical evidence indicating that N₂O emission rates associated with the use of anhydrous ammonia exceed emission rates for alternative sources of nitrogen (Breitenbeck and Bremner, 1986a). However, no widely accepted emissions factor that could be used in place of the IPCC factor of 1.25% of nitrogen content is available. Moreover, at least one of the studies indicating that emissions are higher with anhydrous also show that the principle substitute for anhydrous (urea) has an emission rate that also significantly exceeds the IPCC's default rate.

(b) Options Applicable to Manure Management Systems

[1] Changes in Animal Diets. Some exploratory work has been performed on altering the quantity of nitrogen excreted by domestic livestock by changing feed in such a way as to reduce the amount of

⁶ The wide application of nitrification inhibitors might be controversial due to their potentially harmful impact on soil microbial life.

nitrogen consumed. Two effects are possible: (1) the animals excrete less N and therefore the level of N₂O emissions will fall and (2) less feed is needed for livestock, which reduces the quantity of feed crops demanded and therefore decreases the use of synthetic N, which in turn results in a reduction in emissions.

[2] **Nitrification and Urease Inhibitors.** Nitrification and urease inhibitors can be used to reduce N₂O emissions from livestock manure. This option appears to be rather expensive, while effects of inhibitors last only about 6 weeks and exhibit some diminution in effectiveness over that time horizon (Hardin, 1998).

3. Options Included in Cost Analysis

Very little data are available to generate cost of reductions analysis for the majority of the options discussed above. In a previous analysis, ICF produced estimates of the costs of reducing N₂O emissions associated with the application of synthetic nitrogen for corn production in the United States. In addition, some cost estimates for the European Union are reported in a recent EU study (AEA, 1998). Details on how these two sets of estimates are used in the cost analysis presented in this paper are provided below.

(a) US costs of reductions

The U.S. analysis was conducted for four options: soil testing; control release fertilizers; nitrification inhibitors; and substituting manure for synthetic sources of nitrogen. The method used in estimating emission reductions and costs associated with each option are briefly described in this section.

(i) Soil Testing (Option 1)

Soil testing is used to estimate the carry-over nitrogen available for plant up-take as a result of prior use of synthetic nitrogen, cultivation of nitrogen-fixing crops, incorporation of crop residues, and/or the application of manure to agricultural lands. Test results help growers determine the amount of additional synthetic nitrogen that needs to be added to their fields in order to obtain desired yields. In the case of the U.S. corn crop, it has been estimated that the use of synthetic nitrogen fertilizers could be reduced by over 30% via the use of pre-sidedressing soil nitrogen tests.

The procedure followed to develop costs and N₂O emission reductions involved two sets of steps. In the first set, the net costs of the soil tests were calculated. The change in fertilizer use was calculated first. In making this calculation it was assumed that 130 pounds of inorganic nitrogen is used per acre of corn planted,⁷ that the number of acres planted to corn equals 265 million and that the price per tonne of nitrogen equals \$340.⁸ This data was used to compute the change in expenditures on chemical fertilizer given a 30% reduction in average application rates.

Next, the expected value of the revenue loss associated with an incorrect test result was determined. This was based on an average price per bushel of corn of \$2.55, an average yield per acre of 128 bushels and a 1.4 percent expected loss arising from incorrect soil test results—where the 1.4 percent equals the test failure rate (assumed to be 7 percent) times the expected reduction in yields (20 percent). The cost of the soil test was then calculated. This result was obtained by multiplying the \$1.50 per acre⁹ test cost times

⁷ This is based on average application rates from 1998 (USDA, 1999).

⁸ This was based on a use-weighted average of the prices of urea, anhydrous ammonia, and other forms of synthetic nitrogen in 1998.

⁹ Soil testing is conducted via a sampling method where only a fraction of the total amount of land is actually tested for residual nitrogen. Although the cost per sample taken is roughly \$15, on average, this represents approximately \$1.50/acre for an individual farm. These costs are highly dependent on the availability of laboratory facilities and local expertise needed to administer the tests.

265 million acres planted to corn. Finally, the net cost of the program was computed—i.e., the savings from the reduction in the use of nitrogen fertilizers was subtracted from the sum of the cost of the soil test and the expected loss from following the recommendations from incorrect results from the test.

Once the net cost of the option was determined, the following set of steps were undertaken to determine the emission reductions, which were then used, along with the cost information, to compute a price per tonne of carbon equivalent. The first step of this process required determining the reductions in direct emissions of nitrous oxide that would accompany the estimated reduction in fertilizer usage. To do this, the change in fertilizer usage was converted into metric tonnes, then multiplied by 0.9 to account for volatilization, and then by the IPCC default emissions factor of 1.25 percent. Next, the reduction in indirect emissions was determined. For indirect emissions from volatilization, 10 percent of the change in fertilizer consumption was multiplied by the IPCC emissions factor of 1 percent. For the change in indirect emissions from leaching and run-off, the portion of the change in fertilizer applied, net of losses due to volatilization, was multiplied by the IPCC default emissions factor 2.5 percent.

Results indicated that by using the soil testing option, N₂O emissions from all the U.S. agricultural sources could be reduced by as much as 3.3% at a savings of \$17.99/tonne of carbon equivalent. To evaluate the robustness of the results, sensitivity analyses were conducted for each of the key parameters. The results indicated that the break-even price of carbon is inversely related to the prices per tonne of synthetic nitrogen fertilizer and directly correlated with the test failure rate, the cost per acre for the soil tests, and the price per bushel of corn. Relatively small changes in any one of these parameters were found to have a strong influence on the costs of the testing option. For example, an increase in the average cost of the soil test from \$1.50 to \$2.50 results in the break-even carbon price changing from the -\$17.99/tonne savings reported here to a net cost of \$17.75/tonne while a \$1 increase in the average price per bushel of corn results in a cost of \$46.06/tonne of carbon equivalent.

(III) Control Release Fertilizer (Option 2)

To assure that the results obtained in this exercise were incremental to the soil testing option, it was assumed that CRF products would only be used to replace urea and the amount of urea available for Option 2 was reduced by 30% (which corresponds to the reduction resulting from Option 1). In addition, it was assumed that the 50 percent reduction in the use of nitrogen fertilizers (Marantz et al., 1999) reported for rice production, might eventually be possible in production of other crops—e.g., corn.¹⁰ In this regard, however, it should be noted that the results achieved for rice might be exceptional. At this point in product development, it is not evident that the technology will necessarily produce similar reductions when applied to soil types that are different from those in the original experiment and/or a wider variety of crops (Bundy, 1999b).

To calculate the emission reductions potential and associated cost of using controlled release fertilizers, the following steps were taken. First, the potential change in the amount of nitrogen that would need to be applied to croplands was calculated. Since urea accounts for approximately 33.8 percent of the nitrogen fertilizer applied to the corn crop in the United States, a 50 percent reduction in the application of urea for corn production would result in a total reduction in nitrogen equaling 2 million tonnes. Next, based on the

In addition, the costs might be biased downward by the fact that in many regions in the US where testing is used, the test are often administered by local universities that tend to subsidize at least a portion of the full costs of the tests.

¹⁰ This is an especially strong assumption in that rice production generally takes place under very different conditions than are applicable to corn. Moreover, manufacturers of CRF products do not at this time recommend reducing the total amount of nitrogen applied when using CRF in place of prilled urea. The assumption here is that through field and laboratory experiments as well as continued improvements in CRF products, the potential for similar reductions in application rates might exist at some future date.

average price of urea and the change in the quantity of urea consumed, the change in the total outlay for fertilizer was determined. The third step involved calculating the increase in total outlays resulting from the use of the higher priced CRF products. The price of CRF was assumed to be 2.5 times higher, per tonne of nitrogen, than the cost of conventional urea. This was based on information provided by industry and retail contacts that indicated that the CRF fertilizers tend to cost somewhere between 2 to 3 times more than conventional products. The net cost of the option was then determined by subtracting the reduction in costs associated with decreased purchases of conventional urea from the change in costs associated with the use of the more costly CRF products.

Next, the change in nitrous oxide emissions was calculated. The change in direct emissions was determined by multiplying the IPCC's default emissions factor by the change in urea nitrogen after adjusting for the 10 percent that volatilizes. The change in indirect emissions was then computed. Reduced emissions from volatilization were calculated as 10 percent of the change in N times the IPCC emissions factor of 1 percent. The change in emissions from leaching and run-off was calculated as 2.5 percent of the change in N applied after adjusting for the 10 percent that is assumed to volatilize. The price of carbon equivalent was then calculated by adding up the total reductions in emissions, converting these to carbon equivalent terms and dividing this amount into the net costs from the change from conventional urea to CRFs. The results indicated that at a price of \$179.79/tonne of carbon, N₂O emissions from agricultural sources in the U.S. would decline by about 4.2%.

(III) Nitrification Inhibitors (Option 3)

In evaluating the potential emission reductions attributable to the use of nitrification inhibitors, it was assumed that the inhibitor would only be used with anhydrous ammonia fertilizers with their amount reduced by 30% (to account for Option 1). Using nitrification inhibitors with other forms of fertilizers is somewhat problematic since it is often a gaseous substance that can be particularly difficult to attach to dry products.¹¹ However, the reason for limiting the analysis to presumed use only with anhydrous ammonia is that this eliminates the possibility of double counting within the current exercise.

Anhydrous ammonia supplies approximately 40.5% of the total amount of nitrogen in synthetic fertilizers consumed in the United States. The cost per tonne of nitrogen is lower for anhydrous than for next most common type of synthetic fertilizer—urea. A price of \$32 per gallon or \$6 per acre was used as the cost of the inhibitor.¹² The per-acre cost is based on the assumption that the inhibitor is applied with anhydrous ammonia as a side dressing. The \$6 is approximately the cost of 0.75 of a quart of liquid per acre. This amount was used because it is the mid-point of the recommended application rate for the most commonly used liquid nitrification inhibitor (N-Serve).¹³ Finally, it was also assumed that use of the inhibitor would reduce emissions by 60%. This is approximately the mid-point of the two ranges reported above¹⁴—i.e., 43% -78%.

The steps involved in estimating the costs and potential emission reductions associated with use of nitrification inhibitors were as follows. First, it was assumed that only direct emissions from anhydrous

¹¹ This is not a fully accurate characterization of all nitrification-inhibiting substances. Some types of products have been developed that can be used with dry fertilizers such as urea for broadcast spreading (McCarty, 1999). In addition, banding, nesting, and large urea granules can be used as alternatives in cases where nitrification inhibitors are not convenient or cost-effective (Malhi, et. al, (1999). These can also be effectively used in place of CRFs to reduce the rate of nitrogen release into soils.

¹² Based on price quotes received from Agway and Southern States, June, 1999.

¹³ According to the use instructions on the product label, when anhydrous is applied as a side dressing—which would be the case if testing is used to determine the amount of nitrogen to add to a given field—between 0.5 and 1.0 quarts of the inhibitor should be used at the time the fertilizer is applied. (came off web site—need to get citation).

¹⁴ See the discussion included with the description of this option in part A of this Section.

ammonia use would be affected by the use of nitrification inhibitors. This assumption was based on the fact that both anhydrous ammonia and the inhibitors, which are liquids at the time of application, can be injected simultaneously into the soil. (Thus, there are no additional costs incurred as a result of the actual application of the inhibitor). The change in total costs associated with the use of nitrification inhibitors was computed by first determining the per acre cost of the fertilizer. An average application rate of 93 pounds of nitrogen per acre was assumed. The cost per acre for the inhibitor was then added to the cost of the fertilizer to get a total cost per acre of injecting both products. Using this dollar amount, a cost per tonne and then a change in costs per tonne of fertilizer was calculated. Finally, the change in the cost of fertilizer was calculated by multiplying the change in the cost of anhydrous ammonia, with an inhibitor added, by the total quantity of anhydrous ammonia used by corn growers in the U.S.

The break-even price of carbon equivalent was then determined. This was calculated by assuming that adding the inhibitor to anhydrous ammonia would reduce nitrous oxide emissions by 60 percent. Therefore, the change in emissions would equal the total amount of anhydrous nitrogen applied less the 10 percent that volatilizes,¹⁵ times the IPCC emissions factor of 1.25 percent, times 60 percent. No change in indirect emissions was calculated because there is no indication that the use of an inhibitor with anhydrous ammonia will permit a reduction in the quantity of nitrogen applied. Even though leaching might be substantially reduced as a result of using a nitrification inhibitor, no data are available at present to predict how indirect emissions from leaching might change. Once the reduction in N₂O emissions was estimated, the result was converted into carbon equivalent terms. That is, the change in N₂O was multiplied by the GWP of 310 and the CO₂-C conversion factor of 12/44, to get the comparable level of reductions in terms of carbon. This amount was then divided into the estimated cost to determine the price of carbon at which the technology would become cost-effective for all users of anhydrous ammonia. The results indicated that at a price of \$246.33/tonne of carbon, U.S. emissions of N₂O from agricultural sources could decrease by as much as 3.6%.

(iv) Substituting Manure for Synthetic Sources of Nitrogen (Option 4)

To the extent that it is possible to displace commercial fertilizers with livestock manure, N₂O emission from chemical nitrogen fertilizers can be reduced without increasing emissions from manure.¹⁶ Thus, total emissions from agriculture soils would decline. It has been estimated that about 90 percent of the manure produced by domestic animals in the United States is not currently being used to provide nutrients for crop production (Smith et al, 1997). This is due primarily to the fact that most large-scale livestock operations are not located in proximity to farms on which the majority of field crops are produced. In general, even though manure can be obtained from livestock producers at no cost, if it must be transported more than a relatively short distance (40-50 miles) it becomes more cost-effective to use commercial sources of nitrogen (Gilliam, 1999; Bundy, 1999a). Transport costs, therefore, tend to be the main determinants of the

¹⁵ Because anhydrous ammonia is injected rather than broadcast across croplands, there is some reason to believe that volatilization might be considerably lower than it is with products that are used as a top dressing. However, the baseline estimates do not take this possibility into account and therefore, it was assumed that the same rate of volatilization applies to anhydrous as to other synthetic fertilizer forms.

¹⁶ There are two additional factors that need to be considered regarding the potential change in N₂O emissions with the substitution of manure for chemical sources of nitrogen. First, manure applied to soil during fall and winter appears to generate higher emissions than when applied in spring. In addition, the rate of N₂O emission from manured soil might be higher than the rate from soil receiving similar amounts of synthetic nitrogen. This happens because manure supplies carbon, which enhances the denitrification process. Moreover, manure can create anaerobic microsites through clogging soil pores and enhancing oxygen depletion. Liquid manure also increases soil moisture content and therefore increases the potential for denitrification (Paul, 1999). Another factor to consider in using manure is that there might be a trade-off between methane emissions and nitrous oxide emissions arising from storage of manure. In particular, N₂O emissions from manure lagoon systems can be reduced by eliminating the crust that forms on the liquid containers. However, doing so can result in an increase in the amount of methane emitted into the atmosphere (Paul, 1999).

extent of manure use on cropland (Gilliam, 1999). Thus, the analysis of this option focused on potential transportation costs in addition to the estimated costs associated with the application of manure to croplands. The current option was quantified as an incremental one with respect to the soil testing option (i) described above.

In evaluating the potential to displace commercial fertilizers with manure, when transport is necessary, it was assumed that a 200-mile radius would be the maximum distance that manure would need to be hauled. This assumption was based on the fact that 10% of the manure currently produced is consumed as fertilizer for crops grown within an area that is within roughly 40-50 miles of where the manure is generated (Smith et al, 1997). Thus, it was assumed that it would take an area that is at least 10 times that size to absorb the remaining 90 percent.¹⁷ In addition, it was assumed that 100 miles is the average distance that manure would be hauled. Given hauling charges of approximately \$15/tonne for 200 miles,¹⁸ the average cost of manure transport was estimated to equal \$7.50/tonne.

The cost growers incur in using manure to supply plant nutrients was also calculated. This cost was determined as follows. First, an average spread rate for manure was determined, which equals the quantity of manure required to provide the same level of inorganic nitrogen as is contained in the average quantity (93 pounds per acre) of chemical fertilizers applied to the U.S. corn crop. This is the amount of fertilizer that would be used after adjusting for the change in fertilizer consumption that would result from using the soil testing procedure described in option 1 above. The comparable spread rate for manure depends on a variety of factors¹⁹ and can vary from about 2.5 tonnes up to 16.5 tonnes per acre. For this exercise, a simple average of these two numbers was used as the average spread rate. That is, it was assumed that approximately 9.5 tonnes of manure is required to provide the same quantity of inorganic nitrogen per acre as is supplied by 93 pounds of synthetic fertilizer. Second, the cost per tonne to use manure was calculated. This was based in part on the average cost per tonne of nitrogen for commercial fertilizers other than urea and anhydrous ammonia. Given the average price of these products and assuming that 9.5 tonnes of manure and 93 pounds of synthetic nitrogen cost the same if the manure does not have to be transported very far, it was estimated that the cost per tonne to spread manure equals roughly \$1.40. Adding the cost of transport (\$7.50/tonne) to the cost to spread results in a total cost of \$8.90 per tonne of manure applied.

The following steps were taken to calculate the change nitrous oxide emissions that might result from implementing this option:

- First, the quantity of manure available for use on crops was determined. This was assumed to equal 90% of the manure in managed systems.
- Second, the number of acres that this amount of manure could be used on was determined. In arriving at this figure, it was assumed that the average quantity of manure needed to supply the requisite amount of inorganic N equals 9.5 tonnes per acre and therefore, the number of acres that the available manure could cover would equal the total amount of manure divided by 9.5.

¹⁷ Although a circle with a radius of 140 miles is roughly 10 times the size of one with a radius of 40 miles, and would thus be sufficient in size theoretically to absorb the remaining 90% of manure, a radius of 200 miles was used in this analysis in order to compensate for any overlap or large areas where crops might not be grown.

¹⁸ Price quote provided by Jim Newson Trucking, Inc., June 1999.

¹⁹ Among the determinants of the quantity of usable nitrogen in a given ton of manure are: species, age, size, sex, and diet of the animal producing the manure; method of collection and storage at the site where the manure is produced; length of time the product is held in storage; mode of transport and handling of product during transport; types of soil on which the product is spread and the method used to incorporate materials into the soil; temperature and moisture at the point of production, during transport, and at the site where the manure is used; and the quantity of carbon present in the manure and/or soil (Paul, 1999).

- Third, the corresponding change in the use of synthetic fertilizer was determined. This was done by simply multiplying the number of acres that manure could cover by the assumed 93 pounds of N application rate.
- Fourth, the change in costs due to reduced use of synthetic fertilizers was computed. In doing this, it was assumed that the synthetic fertilizer displaced was of forms other than anhydrous and urea. This assumption was made to ensure additionality of the emission reductions associated with this option—i.e., to avoid double counting.
- Fifth the additional costs resulting from the use of manure was computed. For reasons explained above, the cost per tonne of manure was assumed to equal \$8.90 per tonne as applied. This amount was multiplied by the tonnes of manure available to get the total cost associated with transporting and spreading the available manure.
- Sixth, the net increase in costs was calculated as the difference between the cost of using manure and the cost of the fertilizer that would be displaced.
- Seventh, the direct and indirect emission reductions associated with the decreased use of synthetic nitrogen were calculated. This was done using the default IPCC emission factors and the quantity of synthetic nitrogen displaced. The direct and indirect emission reductions were then added together and converted to metric tonnes of carbon equivalent.

The break-even price of carbon equivalent was computed by dividing the net costs computed in the sixth step by the results of the estimated amount of carbon equivalent emission reductions from the seventh step. The results of this procedure indicate that at a cost of \$879.07/tonne of carbon equivalent, N₂O emissions from the agricultural sector in the U.S. could be reduced by approximately 6.2%.

(b) EU Costs of Reductions

Costs of reductions for the European Union were taken from the ECOFYS EU-15 report (Hendricks et al., 1998). Although this report was subsequently revised and cost data was developed for individual EU members (AEA, 1998), the older version was used because it reported emission reductions in percentage terms and provided a cost estimate for the EU as a whole. Four policy options are included in the report: price support, set aside, and marginal land subsidy; fertilizer use limitations; fertilizer timing restrictions; and improved fertilizer use efficiency. Each of these is discussed more fully below.

(i) Price support, set aside, and marginal land subsidy

It is assumed that price supports provided under the Common Agriculture Policy (CAP) are phased out over a ten-year period of time running from the year 2000 through the year 2010. This is assumed to encourage an improvement in the use of inputs and thus a reduction in excess applications of nitrogen fertilizers. It is further assumed that the removal of price supports might result in a 20% decrease in the area of agricultural land use across the EU. The authors argue that the EU should help preserve rural communities by providing assistance with the transformation of marginal agricultural lands to alternative uses that are consistent with sustainability. They estimate that a 3.5% reduction in N₂O emissions might be achieved by 2010 as a result of these changes.

To compute the potential costs of this option, the authors considered: the decrease in costs to the EU associated with a reduction in price support payments; and increases in costs from payments of a recommended “Marginal Land Subsidy. The difference in the costs indicates that if this measure is implemented to reduce N₂O emissions, the cost would equal \$243,120/tonne²⁰ of N₂O avoided. It should

²⁰ For each of the options discussed in this section, the Ecofys report expressed costs in terms of ECUs. In converting to US dollars, an exchange rate of ECU 1.013/\$ was used.

be noted however, that the authors do not anticipate that such an action will be undertaken for the sole purpose of reducing nitrous oxide emissions and state that if the changes are implemented for other reasons, the allocation of cost to N₂O mitigation would be zero.

(ii) Fertilizer use limitations

Restrictions on the use of synthetic nitrogen fertilizers are proposed as a means of encouraging a more efficient use of manure. The EU-15 report suggests that a strict 50 kg/ha limit be placed on the application of synthetic nitrogen to crop- and grassland systems. The results would produce roughly a 15% reduction in total synthetic nitrogen use. Associated benefits in the form of N₂O reductions are estimated to result in approximately a 10% reduction in total projected N₂O emissions by the year 2010.

The EU report also provides an estimate of the costs related to a shift from synthetic to organic sources of nitrogen. It is estimated that manure nitrogen in the form of slurry costs approximately \$7.09/kg of nitrogen while the cost for synthetic nitrogen is estimated at \$1.52/kg of nitrogen. Total manure nitrogen required by the year 2010 is expected to equal 3,000,000 tonnes of nitrogen. This suggests that the total costs of shifting from synthetic to manure nitrogen sources will result in a net increase in costs of \$246,159/tonne of nitrous oxide avoided.

(iii) Fertilizer timing restrictions

Placing seasonal restrictions on the application of synthetic and manure sources of nitrogen to agricultural is recommended as a means of reducing indirect emissions from leaching as well as direct emissions resulting from denitrification that takes place in moist winter soils. The seasonal ban of nitrogen application would apply to slurry, poultry manure and inorganic nitrogen from September through February. However, the application of other types of animal manure would be permitted through October.²¹ It is estimated that, by the year 2010, this timing restriction would result in approximately a 4.4% or 31,000 tonne reduction in N₂O emissions.

In determining the costs associated with imposing a seasonal restriction on the application of nitrogen to agricultural soils, it was assumed that there would be a limited impact on the cost of synthetic fertilizers. However, it was also assumed that there would be a significant impact on the length of time that manure would have to be stored. It was assumed that storage capacity throughout the EU would have to increase by 20% and that the annual storage cost per tonne would equal about \$2.23/tonne. The cost per tonne of N₂O avoided was projected to equal \$6,078.

(iv) Improved fertilizer use efficiency

The EU-15 report examined a variety of options that might be used to improve fertilizer use efficiency. These include: optimization of recommended application rates; improved maintenance of application equipment; specification of a “fertilizer free zone;” soil testing to determine N needed; use of alternative forms of N fertilizer; improvements in fertilizer quality; the cultivation of cover crops; and the use of controlled release fertilizers. It was estimated that the entire package of measures might reduce agricultural emissions of nitrous oxide by 2.5% at a net cost savings of \$60,780/tonne of N₂O avoided.

²¹ The dates recommended in the Ecofys report are based on the assumption that the risk of N leaching is highest when nitrogen is applied during the period immediately following harvest through early spring of the following year.

(c) Uncertainties of Cost Analysis and Next Steps

Several limitations to this analysis need to be noted. First, the body of research examining the relationship between new technologies and alternative management practices and N₂O emissions is not extensive. Much additional study is needed to clarify the implications for N₂O emissions related to different crops, soils, and climatic conditions. Second, additional information, particularly in the form of additional research into the effectiveness and costs of the various options under conditions prevailing throughout all regions are essential to refine the analysis. Third, significant uncertainty applies to cost estimates where changes in fertilizer use are concerned. Inadequate information is available to determine the impacts on yield of various crops and thus, it is difficult to assess the potential change in farm incomes that might result from significant changes in crop prices. This problem becomes especially complex when considered from a world perspective because of the wide variety of national policies in place to protect domestic food producers. Fourth, some risks related to implementing these options arise because of certain types of cultural factors—e.g., yield increases made possible through application of “green revolution” technologies advanced in 1960’s did not fully materialize because hybrid varieties of crops did not taste the same as traditional varieties. Similar potential exists for these types of policies to be rejected by farming communities due to social or cultural preferences that cannot be foreseen at this juncture. Finally, while this analysis attempted to account for the incrementality of applying different options to the same region, links between these options need to be considered in a more explicit fashion. One way of achieving this would be to use comprehensive agricultural models (e.g., the Canadian Regional Agricultural Model or CRAM). Such models could be also applied to for analyzing multi-GHG effects of some options (e.g., the same option may reduce both reduce emissions of N₂O and contribute to the carbon sequestration by agricultural soils).

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IV. INDUSTRIAL PROCESSES

A. Background

Industrial anthropogenic nitrous oxide (N₂O) emissions are generated as an unintended by product in many industrial processes that use nitrogen oxides or nitric acid as feedstock. Examples include manufacture of adipic acid, nitric acid, caprolactam, urea, and nuclear fuel reprocessing. In particular, adipic acid manufacturing and nitric acid manufacturing are potentially large sources of atmospheric N₂O. Emissions of N₂O from these processes depend on the amount generated in the specific production process and the amount eliminated by any subsequent abatement process.

1. Adipic Acid

Adipic acid is a white crystalline solid used primarily as the main constituent of nylon (nylon-6/6), representing about half of the nylon molecule. It is also used in the manufacture of some low-temperature synthetic lubricants, synthetic fibers, coatings, plastics, polyurethane resins, and plasticizers, and to give some imitation food products a "tangy" flavor. In 1990, adipic acid production was the largest source of industrial N₂O emissions. As of 1999, all major adipic acid producers have implemented N₂O abatement technologies and, as a result, this source has been decreased substantially (Reimer, 1999).

Since the main use for adipic acid is as a component of nylon, adipic acid production trends are closely correlated with nylon consumption trends. Above average growth in nylon demand has sparked expansion in existing adipic acid capacity in North America and Western Europe, as well as new facilities in the Asia-Pacific region. Global adipic acid production is expected to total nearly 2.3 million metric tonnes (5 billion pounds) in 2000 as compared to 1.8 million metric tonnes (4 billion pounds) in 1995 (CMR, 1998a; SRI, 1997). Economic drivers include new housing starts and nylon engineering resins in the automotive and electronics industries (CMR, 1998a).

Worldwide, there are very few adipic acid plants (~ 23 plants). The U.S. is a major producer with three companies in four locations accounting for approximately one half of world production. Other producing countries include Brazil, Canada, China, France, Germany, Italy, Japan, Korea, Singapore, Ukraine, and United Kingdom. Most of these countries have only one adipic acid plant except China (3), Germany (2), and Japan (2) (SRI Consulting, 1998).

Adipic acid is manufactured by a two-stage process. The first stage of manufacturing usually involves the oxidation of cyclohexane²² to form a cyclohexanone/cyclohexanol mixture. The second stage involves oxidizing this mixture with nitric acid to produce adipic acid. N₂O is generated as a by-product of the nitric acid oxidation stage, as illustrated below:



Process emissions from the production of adipic acid will vary with the types of technologies and level of emissions controls employed by a facility.

²² Or sometimes cyclohexanone.

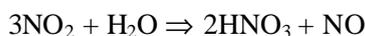
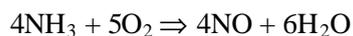
2. Nitric acid

Nitric acid (HNO₃) is an inorganic compound used primarily to make synthetic commercial fertilizer. The raw material is also used for the production of adipic acid and explosives, metal etching, and in the processing of ferrous metals. If adipic acid plants implement currently available emission abatement technologies, nitric acid production is likely to become the largest industrial source of N₂O emissions.

Since the main use for nitric acid is as a component of fertilizer, nitric acid production trends are closely correlated with fertilizer consumption trends. Future trends in fertilizer production vary greatly depending on the region. In parts of Western Europe, the use of nitrogen-based fertilizers is decreasing due to concerns over nutrient run-off. Other regions, such as Asia, South America, and the Middle East, are increasing their nitrogen fertilizer production capacities (CMR, 1998b). In the U.S., fertilizer production is projected to increase by 4 percent in 2000 (FAO, 1998). Other factors to consider are government programs, weather conditions, and general economic growth.

Worldwide, the exact number of nitric acid plants currently in operation is not known. Estimates range from 255 to 600 plants (Choe et al., 1993; Bockman and Granli, 1994). This uncertainty may be due to the fact that nitric acid plants are often part of larger production facilities, such as fertilizer or explosive manufacturing. As a result, only a small volume of nitric acid is sold on the merchant market.

The production of nitric acid (HNO₃) generates nitrous oxide (N₂O) as a by-product of the high temperature catalytic oxidation of ammonia (NH₃), involving the following chemical reactions:



Nitric oxide (NO), an intermediate in the production of nitric acid, readily decomposes to N₂O and nitrogen dioxide (NO₂) at high pressures for a temperature range of 30-50°C (Cotton and Wilkinson, 1988). Nitrous oxide emissions from nitric acid production will be influenced by the degree to which emission control efforts are applied in both new and existing nitric acid plants.

3. Other Chemical compounds

Production of other chemical compounds involving the use of a nitrogen compound or a catalytic reduction step are other processes identified as possible global sources of nitrous oxide. Emissions measurements in the chemical industry in the Netherlands yielded an emission of about 1.7 Gg N₂O in 1990 from the production of chemicals other than adipic acid or nitric acid (Olivier, 1993). The precise nature and location of the process is not known, but may be related to either a process using a N-compound or a catalytic reduction step.

Other potential N₂O non-combustion industrial sources include: caprolactam production, urea production, petrochemical production, glyoxal production, nuclear fuel reprocessing, N₂O medical uses (mostly for anesthesia), propellant and foaming agents, fumes from explosives, dodecanedioic acid production (DDDA or 3DA), and fume sweep from adipic acid and nitric acid tanks. Although global N₂O emissions from these source categories will probably be small as compared to emissions associated with adipic acid and nitric acid production, further investigation of these sources is recommended. These sources of N₂O emissions are not estimated in the present analysis.

B. Current Emissions

1. Adipic Acid Production

For any given year, global N₂O emissions from adipic acid production are estimated as the sum of the product of emission factors (kg N₂O per tonne of adipic acid produced) and production (tonnes of adipic acid) for each region. The regions for this analysis are consistent with the regional breakdown of the EIA Energy Outlook (EIA, 1999) and the upcoming IPCC Special Report on Emission Scenarios (SRES). Regions are OECD Countries (OECD90), countries of Eastern and Central Europe and the Former Soviet Union (REF), the rest of Asia (ASIA), and the rest of the world (ALM) (Appendix II-1).

Emissions from industrial processes were estimated as follows:

Step 1. Estimate Production by Region. Adipic acid production data for the United States for 1990 and 1995 were obtained from *Chemical and Engineering News*, "Facts and Figures" (C&EN 1996). The 1998 data for the United States were projected from the 1995 production based upon suggestions from industry contacts and current plant capacities. For all other countries, actual adipic acid production data were not available, therefore production was estimated based on adipic acid plant capacity figures and estimated capacity utilization. Capacity figures were obtained from *Chemical Week* (1999a). Adipic acid production by region is shown in Table IV-1.

Region	1990	1995	1998
OECD90	1,684,600	1,878,200	1,987,550
REF	-	-	-
ASIA	146,300	242,250	274,550
ALM	-	53,600	60,300
<i>Total</i>	<i>1,830,900</i>	<i>2,174,050</i>	<i>2,322,400</i>

Step 2. Develop Emission Factors by Region. The N₂O emission factors for adipic acid production were estimated by region by multiplying the ratio of N₂O emitted per unit of adipic acid produced and adjusting for the actual percentage of N₂O released as a result of plant-specific emission controls. The ratio of N₂O emitted per unit of adipic acid produced for all countries except Japan was taken from Thiemens, M.H. and W.C. Trogler (1991), which are based on the overall reaction stoichiometry of N₂O production in the preparation of adipic acid. The ratio for Japan was taken from the Japan Environment Agency (1995).

This ratio was then multiplied by the destruction factor and the abatement system utility factor to estimate the overall emission factor. The estimated regional average percent of N₂O released due to emission controls²⁴ for North America is 62 percent for 1990 and 1995 and 12 percent for 1998; for Western Europe is 22 percent for 1998; and for Asia is 67 percent for 1998. Emission factors by region are shown in Table IV-2.

²³ Tonnes = metric tons

²⁴ Equal to 1-(emissions destruction factor *abatement system utility factor).

Region	1990	1995	1998
OECD90	0.24	0.24	0.06
REF	-	-	-
ASIA	0.30	0.30	0.20
ALM	-	0.30	0.30

Step 3. Estimate Regional and Global N₂O Emissions. For each region, N₂O emissions are estimated by multiplying the emission factors by the appropriate production data, with the exception of REF. Production data for REF were not available, thus N₂O emissions estimates were obtained from an adipic acid industrial expert (Reimer, 2000). Emissions are aggregated from all regions to estimate global N₂O emissions from adipic acid production (Table IV-3).

Region	1990	1995	1998
OECD90	400,434	446,108	119,977
REF	9,000	21,000	21,000
ASIA	43,890	72,675	55,526
ALM	-	16,080	18,090
Total	453,324	555,863	214,594

The N₂O emission estimates from adipic acid production are relatively certain. Worldwide, there are only few adipic acid plants. In most cases, however, the production data are confidential. As a result, plant-specific production figures were estimated by allocating total adipic acid production using existing plant capacities. This creates a degree of uncertainty in the adipic acid production data used to derive the emission estimates as it is necessary to assume that all plants operate at equivalent utilization levels. Because N₂O emissions are controlled in some adipic acid production facilities, the amount of N₂O that is actually released will depend on the level of controls in place at a specific production plant. Thus, in order to calculate accurate emission estimates, it is necessary to have production data on a plant-specific basis. Additionally, the emission factor was based on experiments that attempt to replicate the industrial process and, thereby, measure the reaction stoichiometry for N₂O production in the preparation of adipic acid. However, the extent to which the lab results are representative of actual industrial emission rates is not known.

2. Nitric Acid Production

For any given year, an inventory of global N₂O emissions from nitric acid production is estimated as the sum of the product of emission factors (e.g., kg N₂O per tonne of nitric acid produced) and production (e.g., tonnes of nitric acid) for each region. The regions for this analysis are consistent with the regional breakdown of the EIA Energy Outlook (EIA, 1999) and the upcoming IPCC Special Report on Emission Scenarios (SRES). Regions are OECD Countries (OECD90), countries of Eastern and Central Europe and the Former Soviet Union (REF), the rest of Asia (ASIA), and the rest of the world (ALM).

Emissions were estimated as follows:

Step 1. Estimate Production by Region. Nitric acid production data in the United States for 1990 through 1998 were obtained from *Chemical and Engineering News*, “Facts and Figures” (C&EN 1999). Canadian production data for 1993, 1995, and 1997 were obtained from C&EN (1997a); 1990 and 1998 production figures were estimated based on 1993 and 1997 data respectively. Mexican production data for 1990 through 1998 were obtained from C&EN (1997b). Nitric acid production figures for all other countries are estimated based on regional ammonia fertilizer plant capacities and estimated capacity utilization. Ammonia fertilizer plant capacities were obtained from *Chemical Week* (1999b). Nitric acid production by region is shown in Table IV-4.

Region	1990	1995	1998
OECD90	14,179,000	15,485,000	15,430,000
REF	9,600,000	9,900,000	9,600,000
ASIA	19,200,000	24,750,000	27,000,000
ALM	4,320,000	4,950,000	6,600,000
Total	47,299,000	55,085,000	58,630,000

Step 2. Develop Emission Factors by Region. The regional nitrous oxide emission factors for nitric acid were estimated by multiplying the amount of N₂O emitted per unit of nitric acid produced and adjusting for plant-specific emission controls. The ratio of N₂O emitted per unit of nitric acid produced for OECD90 is 9.5 kg N₂O per tonne nitric acid and for REF, ASIA, and ALM is 10 kg N₂O per tonne nitric acid. Non-selective catalytic reduction (NSCR) is the only mechanism considered to reduce N₂O emissions at nitric acid plants from 1995 to 1998. NSCR is assumed to reduce N₂O emissions by 80 percent. The percentage of plants using NSCR is estimated to be 20 percent for North America, 2 percent for Western Europe, and 1 percent for Asia. Emission factors by region are shown Table IV-5.²⁵

Region	1990	1995	1998
OECD90	0.0095	0.0095	0.0095
REF	0.010	0.010	0.010
ASIA	0.010	0.010	0.010
ALM	0.010	0.010	0.010

Step 3. Estimate Regional and Global N₂O Emissions. For each region, N₂O emissions are estimated by multiplying the emission factors by the appropriate production data. Emissions are aggregated across the regions to estimate global N₂O emissions from nitric acid production (Table IV-6).

Region	1990	1995	1998
OECD90	121,028	131,847	130,519
REF	96,000	99,000	96,000
ASIA	190,464	245,520	267,840

²⁵ Emission factors presented in the table are higher than the average IPCC-defaults, since the latter already incorporate assumptions about the NSCR use.

ALM	43,200	49,500	66,000
<u>Total</u>	<u>450,692</u>	<u>525,867</u>	<u>560,359</u>

In general, the nitric acid industry is not well characterized. A significant degree of uncertainty exists in nitric acid production figures because nitric acid plants are often part of larger production facilities, such as fertilizer or explosive manufacturing. As a result, only a small volume of nitric acid is sold on the market making production figures difficult to track. Except for North America, production for the rest of the world is estimated based on ammonia fertilizer plant capacities. There is a great degree of uncertainty as to the direct correlation of fertilizer capacity and actual nitric acid production. Furthermore, this method does not take into consideration the other uses for nitric acid (e.g., explosives, adipic acid, etc.). Emissions factors are also difficult to determine because of the large number of plants using many different technologies.

Although there is greater uncertainty associated with *nitric acid* figures than *adipic acid*, it is important to note that potential N₂O emissions per metric tonne produced are far greater for adipic acid production. Thus, the uncertainty associated with adipic acid production may be more significant when converted into N₂O emissions.

C. Emission Projections to 2020

Emissions from the adipic acid production are projected in this report assuming a two percent annual increase from 1998 to 2020, with the exception of REF. This assumption is based on adipic acid field experts' projections (CMR, 1998; SRI Consulting, 1999; Reimer, 1999a) and historical (1988-1997) growth figures (about 2% per year) (CMR, 1998). In addition, adipic acid estimates in 2000 were adjusted to reflect higher abatement system utility factors including an increase of 3 percent for North America and 2 percent for Western Europe. REF emission projections were obtained from an adipic acid industrial expert (Reimer, 2000).

Emissions from nitric acid production were projected based on an increase in population according to the UN medium scenario. It reflects the fact that most of nitric acid is used in fertilizer production, which is driven by an increase in population (via food demand) (Table IV-7). The adjustment coefficient (*k*) (See Section II-B) for nitric acid ranges from 1.02 in the ALM region to 1.18 in the ASIA region, and is equal to 1.10 globally. These values correspond well with the presence of additional uses of nitric acid in addition to fertilizer use (which is tied to population growth).

Table IV-7. Projections of N₂O Emissions from Adipic and Nitric Acid Production (Gg N₂O)

Region	Source	1990	1995	2000	2005	2010	2015	2020	2000-2020 Rate of Change (%/year)
OECD	Nitric Acid	121.0	131.8	143.4	145.8	148.2	150.6	153.0	0.32%
	Adipic Acid	400.4	446.1	112.6	124.3	137.2	151.5	167.3	2.00%
	Total	521.4	578.0	256.0	270.1	285.4	302.1	320.3	1.67%
REF	Nitric Acid	96.0	99.0	102.1	102.2	102.3	102.4	102.5	0.02%
	Adipic Acid	9.0	21.0	21.0	23.2	25.6	28.3	31.2	2.00%
	Total	105	120	123.1	125.4	127.9	130.7	133.7	0.02%
ASIA	Nitric Acid	190.5	245.5	314.5	332.4	350.3	368.1	386.0	1.03%
	Adipic Acid	43.9	72.7	57.8	63.8	70.4	77.8	85.8	2.00%
	Total	234.4	318.2	372.3	396.2	420.7	445.9	471.8	1.24%
ALM	Nitric Acid	43.2	49.5	56.1	63.1	70.1	77.1	84.2	2.05%
	Adipic Acid	0.0	16.1	18.8	20.8	22.9	25.3	27.9	2.00%
	Total	43.2	65.6	74.9	83.9	93.0	102.4	112.1	2.04%

WORLD	Nitric Acid	450.7	525.9	616.1	643.5	670.9	698.2	725.6	0.82%
	Adipic Acid	453.3	555.9	210.2	232	256.2	282.9	312.3	2.00%
	Total	904.0	1,081.8	826.3	875.5	927.1	981.1	1037.9	1.15%

Global N₂O emissions from industrial processes are expected to increase by 1.15% per year from 2000 to 2020. The largest increase (2% per year constant growth) is projected for emissions from adipic acid production. It should be noted that projections presented here do not incorporate any assumptions about *additional* use of options leading to N₂O reduction, hence, representing an upper side of a possible future emission range.²⁶

D. Emission Abatement Options

1. Adipic Acid Production

Adipic acid plants generally have nitrous oxide concentrations of 23% or 230,000 ppm in the off-gas. Thus, controlling emissions from these plants is relatively easier than controlling emissions from nitric acid plants. Adipic acid producers may use catalytic destruction, thermal destruction, or various N₂O recycling/utilization technologies to control N₂O emissions. Abatement options are described in more detail below (Table IV-8).

[1] Catalytic Destruction. N₂O destruction is achieved using an N₂O decomposing catalyst, metal zeolite catalysts (i.e., noble metals, precious metals), which allows operation at a much lower temperature. This option is currently available and in use. For example in the U.S., 63 percent of production uses catalytic destruction. The system eliminates 90-95% of N₂O emissions and operates 80-98% of the time (Reimer, 1999). Reimer, et al. (1999) estimates that catalytic reduction costs range between \$0.25 and \$0.70 per TCE (or \$20-\$60/Mg N₂O). The difference depends on plant operating characteristics.

[2] Thermal Destruction. Thermal N₂O destruction is the destruction of off-gasses in boilers using reducing flame burners with premixed methane (or natural gas). The system eliminates 98 to over 99 percent of N₂O and operates from 95 to over 99 percent of the time (Reimer, 1999). This option is currently available and in use. For example in the U.S., 34 percent of production uses thermal destruction. It is estimated that thermal destruction of N₂O from adipic acid costs approximately \$0.50 per TCE (or \$43/Mg N₂O) with the reduction efficiency of 96%.

[3] Recycling/Utilization Technologies. This technology uses N₂O off-gas as an oxidant to produce phenol from benzene. The phenol produced can be used in the nylon process, with the remaining capacity sold on the open market. It is estimated to result in a 20% cost reduction in the production of adipic acid; however, no specific cost data are available (CW, 1998). It can reduce N₂O emissions from 90 to 98 percent and runs 90 to 98 percent of the time (Reimer, 1999). Recycling technologies in some countries have reported significant savings (CW, 1998), and N₂O recycling is in the planning for at least one plant in the U.S.

[4] Recycle to Nitric Acid. A French company has developed a technology that recycles the N₂O to produce nitric acid by burning the gas at high temperatures in the presence of steam (CW, 1999). The benefits of this process are two-fold; it captures the N₂O from adipic acid production while avoiding the

²⁶ It is fully recognized that research by the nitric acid industry into technologies to reduce N₂O emissions is currently underway and most likely will be implemented in the future. It is also recognized that it is likely that a majority of the adipic acid plants will install abatement technologies in the future. However, for the purposes of this study, no new technology implementation is assumed.

N₂O generated by conventional nitric acid production. It can reduce N₂O emissions from 98 to over 99 percent and runs 90 to 98 percent of the time (Reimer, 1999). Cost data for this process are unavailable.

[5] Reducing Demand of Adipic Acid (through carpet recycling). Potentially, N₂O emissions could be reduced by reducing the demand of adipic acid through nylon carpet recycling. Nylon carpet recycling can be used to transform large quantities of nylon 6,6 (the primary end-product of adipic acid) carpet fiber into hexamethyldiamine (HMD), adiponitrile, and caprolactam. For example, in DuPont's closed loop nylon recycling process, nylon is fed into the unit and reacted with ammonia, cleaving the bonds between adipic acid and (HMD) or between monomers of caprolactam. In the presence of ammonia, the adipic acid is immediately transformed into HMD; the caprolactam and adiponitrile are unchanged. The individual monomers are separated and refined to the same purity that the nylon raw materials have when they are made from virgin sources. The HMD and the adiponitrile are then fed through DuPont's normal nylon 6,6 intermediates value chain (Tullo, 2000). Currently, there is no additional information available on this option. It is uncertain how much, if at all, nylon carpet recycling reduces the demand for adipic acid primary production. Therefore, it is not possible to determine this option's potential for N₂O emission reductions at this time.

2. Nitric Acid Production

The N₂O concentration in nitric acid plant off-gases is on the order of 500-2000 ppm, depending on plant type. This relatively low concentration makes controlling gases difficult, technically. Currently, the nitric acid industry controls for NO and NO₂, i.e., NO_x. As such the industry uses a combination of non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR). The former is very effective at controlling N₂O; the latter not only does not control for N₂O but actually increases N₂O emissions. Control technologies for nitric acid plants are discussed below (Table IV-9).

[1] Non-Selective Catalytic Reduction (NSCR). NSCR units are generally not preferred in modern plants because of high energy costs and associated high gas temperatures. NSCR uses a fuel and a catalyst to consume free oxygen in the tail gas and to convert NO_x to elemental nitrogen (Chartier, 1999). The gas from the NO_x abatement is passed through a gas expander for energy recovery. NSCR units produce stack gases in the 1000 to 1100°F range which requires more exotic materials of construction for the expander and higher maintenance costs. Since all oxygen must be consumed before the nitrogen oxides are reduced, excess fuel must be used resulting in methane emissions. NSCR can reduce N₂O emissions by 80-90 percent. However, this process requires additional fuel (natural gas) and, as a result of combustion, not only CO₂ but also carbon monoxide, ammonia, uncombusted hydrocarbons²⁷ and even small amounts of hydrocyanic acid are emitted.

NSCRs were widely installed in nitric plants built between 1971 and 1977. NSCR is a typical tail gas treatment in the U.S. and Canada with less application in other parts of the world. For example, it is estimated that approximately 20 percent of nitric acid plants in the U.S. use NSCR (Choe, et al., 1993). Control of N₂O through NSCR at nitric acid plants is estimated to cost approximately \$8 per TCE (or \$675/Mg N₂O) at a reduction efficiency of 85%.

In the U.S., nitric acid plants that do not implement NSCR still must employ other technologies for NO_x control. Since NO_x control costs are incurred regardless of N₂O control, it is important to consider the incremental costs of NSCR compared to the other NO_x controls, i.e., SCR and extended absorption. It is estimated that NSCR costs \$350,000 more annually than SCR. This results in an incremental cost of

²⁷ Release of additional methane might reduce the GHG abatement effect of this option.

approximately \$3.50 per TCE to reduce N₂O emissions. It should also be considered that SCR provides on average only 86 percent NO_x reduction compared to NSCR's 95-99 percent range (EPA, 1991). Annual cost estimates for extended absorption are not included as a comparison to NSCR in this study. This process receives a significant credit for recovered acid; however, not all plants are able to utilize the recycled acid.

[2] N₂O Decomposition (catalytic destruction). This technology uses the BASF N₂O catalyst in NH₃ burners to degrade nitrous oxide to dinitrogen gas (N₂) and oxygen (O₂). The BASF catalyst is simple to install in NH₃ combustion furnaces. Experience to date shows that a reduction in N₂O emissions of the order of 80-90% is achievable here. This process has not yet been made available to other nitric acid producers (Kuhn, 1999).

[3] Process-integrated N₂O destruction. Norsk Hydro Agri has developed a N₂O abatement process giving 70-85 percent N₂O reduction. This process, most suitable for new plants, was successfully installed in the latest nitric acid plant designed and built by Hydro Agri in Norway. The process involves major modifications to the first combustion stage in the nitric acid plant and can add between 5-7 percent of the capital cost. It is considered most suitable for new plants. Old plants require significant modification and the down time will be several weeks. Lost production profits offset the potential for use. Norsk Hydro believes that by 2010 a catalyst will be available to reduce N₂O emissions for existing plants. However, no cost data are estimated at this time.

[4] Modification of Noble Metal Gauzes. As a further possibility, the noble metal gauze suppliers offer modifications in the gauze geometry which are claimed to reduce N₂O formation. N₂O formation is reduced in the course of NH₃ combustion. Currently, no further information is available on this particular technology and its potential for N₂O emissions reduction.

[5] Thermal Decomposition. Using an extended residence time after the noble metal gauzes at 900°C, is another possible way to reduce the N₂O concentration. This is not usable as a simple add-on to existing plants because a new burner design is necessary. Thermal decomposition must be integrated in the burner. Currently, no further information is available on this particular technology and its potential for N₂O emissions reduction. It appears that the thermal decomposition option is quite similar to the process-integrated N₂O destruction described above (option [2]).

It should be noted that the cost effectiveness of any of the N₂O abatement technologies for both adipic and nitric acid production depends on individual plant factors (e.g., ability to use recovered steam, etc.). Thus, an option that is most cost effective at one plant is not necessarily the economically optimal option at another plant. As a matter of fact, plants having efficient abilities to recycle and re-use captured steam and/or N₂O may experience savings as a result of N₂O control (Scott, 1998). Currently, however, there are no commercial data available on such savings.

Table IV-8: N₂O Mitigation Options For Adipic Acid Production.

Abatement Technology	Extent of Implementation	Feasible Level of Abatement	Capital and Operating Costs	Cost Savings / Benefits	Incentives, Constraints & Impacts on Other GHGs
Catalytic Destruction	Start-up 1996-97, DuPont, U.S.A.; Start-up 1997, DuPont, Canada; Start-up 1997, BASF, Germany	95%	Capital Investment 7 – 11 mill. U.S.\$* Ave Annual Costs: 3,360,000 U.S.\$ 44 (US\$/t N ₂ O) 0.52 (US\$/t carbon equivalent)***		<u>Incentive:</u> May be more cost effective if a plant does not have the ability to use recovered substances (e.g., steam, benzene oxidant, etc.). <u>Constraint:</u> Less effective at destroying N ₂ O than other available options. Operating and maintenance costs can be high due to periodical catalyst replacement.
Thermal Destruction	Start-up 1993, Bayer, Germany; Start-up 1994, DuPont, Singapore; Start-up 1998, DuPont, UK; Start-up 1999, Asahi, Japan	98%	Capital Investment 4 -17 mil. U.S.\$* 20 – 60 (\$US/t N ₂ O) 0.25 - 0.70 (US\$/t carbon equivalent)***	DuPont, UK reports marginal cost savings.**	<u>Incentive:</u> Operational savings through energy recovery. Bayer states 60% of operating costs are recovered through steam generation.** <u>Constraint:</u> Cost effectiveness depends on individual plant's ability to use recovered steam.
N ₂ O Recycling / Utilization	Expected Start-up 2002; Solutia, U.S.A (recycle for use as benzene oxidant)	98%	Not available.	Expected 20% cost reduction.**	<u>Incentive:</u> Operational savings through N ₂ O (or benzene oxidant) recovery. Solutia expects 20% reduction in operating costs.** <u>Constraint:</u> Cost effectiveness depends on individual plant's ability to use recovered N ₂ O.
Recycle to Nitric Acid	Start-up 1998; Rhodia, France	98%	Capital Investment 16.8 mill. U.S.\$*	Rhodia reports significant savings.**	<u>Incentive:</u> Operational savings through recycling to nitric acid. <u>Constraint:</u> Cost effectiveness depends on individual plant's ability to recycle N ₂ O to nitric acid.

* Estimates obtained from Reimer, et. al., 1999 ** Scott, 1998 *** Costs are in 1996 U.S. dollars

Table IV-9: N₂O Mitigation Options For Nitric Acid Production.

Abatement Technology	Extent of Implementation	Feasible Level of Abatement	Capital and Operating Costs	Cost Savings / Benefits	Incentives, Constraints & Impacts on Other GHGs
Non-Selective Catalytic Reduction (NSCR)	Widely installed in plants in the U.S. & Canada built between 1971-1977 (currently ~20% in U.S.). Less common in other parts of the world.	85%	Capital Investment 1 – 3 mill. U.S.\$ Ave Annual Costs: 8,160,000 U.S.\$ 754 (1999US\$/t N ₂ O) 9.00 (1999US\$/t carbon equivalent)*		<u>Incentive:</u> Reduces NO _x by 95-99% (compared to SCR at 86%). <u>Impact on GHGs:</u> Process requires additional fuel (natural gas) and, as a result of combustion, CO ₂ as well as other harmful emissions are emitted.
BASF Decomposition (catalytic destruction)	Only used by BASF, Germany.	80%	Not available.		<u>Incentive:</u> Simple to install in NH ₃ furnaces. <u>Constraint:</u> BASF has not made it commercially available.
Norsk Hydro Agri (process integrated N ₂ O destruction)	One plant in Norway.	85%	Can add 5 – 7 % to capital investment of new plant.		<u>Constraint:</u> Most suitable for new plants; requires significant modification and down-time for existing plants.

Modification of Noble Metal Gauzes	Not commercially available.	Not available.	Not available.		
Thermal Decomposition	Not commercially available.	Not available.	Not available.		<u>Constraint:</u> Not a simple add-on to existing plants; new burner design is necessary.
Back-End Catalyst System		Not available.	Not available.		

* Costs are in 1999 U.S. dollars.

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V. MOBILE COMBUSTION

A. Background

In the transportation sector, nitrous oxide (N₂O) is emitted as a byproduct of fuel combustion. N₂O emissions from mobile sources depend on fuel characteristics, air-fuel mixes, combustion temperatures, maintenance and operating practices, and usage of pollution control equipment -- in particular catalytic processes used to control NO_x and CO emissions (US EPA, 1999). Nitrous oxide emissions from mobile sources were estimated in this report by transport mode – road, rail, air, and water – and fuel type – oil, natural gas, and coal. Road transport accounts for most of the mobile source fuel consumption, and hence, most of the mobile source emissions. Nitrous oxide emissions from on-road vehicles with catalytic converters are greater than emissions from vehicles without emission controls and vehicles with aged catalysts emit more than vehicles with newer catalysts (US EPA, 1998). Emissions control technologies are being developed to simultaneously reduce emission rates of both NO_x and N₂O. United States is assumed to be the largest emitter of N₂O for the transportation sector. Former USSR, Japan, Germany, UK, and China are the other major emitters of N₂O from the transportation sector.

B. Current Emissions

Seven categories, combinations of transport sector and fuel type, were considered in the analysis. The seven categories are: aviation - oil, road – oil, road – natural gas, railways – oil, railways – coal, navigation – oil, and navigation – coal. Estimates for N₂O emissions from the transportation sector were calculated by multiplying measures of activity by respective emission factors.

1. Activity Data

Activity information for the years 1990 and 1995 was obtained from two IEA energy balance and statistics databases (IEA, 1997). One database provided country by country energy data for OECD countries and the other database provided similar information for non-OECD countries. The energy consumption data were available for combinations of transportation sector and fuel type (e.g., petroleum products, coal, natural gas) in units of thousands of tonnes of oil equivalent (ktoe). The activity information for the aviation mode was available separately for domestic and international civil aviation. The activity information for navigation was available for the internal navigation mode only. Table V-1 presents activity information by transportation sector and fuel type summarized according to the SRES World Regions (Note: OECD90 is separated into U.S. and OECD except U.S.).

Table V-1. 1990 Activity Levels (TJ) By Transportation Sector And Fuel Type By Region (IEA, 1997)

Transportation Mode - Fuel Type	Regions					
	ALM	ASIA	US	OECD90 ^a except U.S.	REF	World
Domestic Air – Petroleum Products	2,219	3,433	3,208,638	679,015	377	3,893,682
International Civil Aviation – Petroleum Products	785,611	600,596	0 ^a	1,278,732	1,031,837	3,696,777
Internal Navigation - Petroleum Products	94,245	258,535	161,150	577,402	405,031	1,496,362
Internal Navigation - Coal	0	0	0	3,056	0	3,056
Rail – Petroleum Products	63,179	242,793	444,931	267,746	624,043	1,642,691
Rail – Coal	6,950	548,220	0	2,135	175,720	733,025
Road – Petroleum Products	6,290,876	4,120,355	16,435,451	14,578,814	3,973,943	45,399,440

Table V-1. 1990 Activity Levels (TJ) By Transportation Sector And Fuel Type By Region (IEA, 1997)

Transportation Mode - Fuel Type	Regions					
	North America	Europe	Asia	Latin America	Africa	Oceania
Road – Natural Gas	5,192	0	0	13,481	251,166	269,839
All Transportation Modes - All Fuels	7,248,272	5,773,932	20,250,170	17,400,383	6,462,116	57,134,873

^a – international air fuel use in U.S. is reported together with domestic use.

2. Emission Factor Data

A simple IPCC-recommended method (Tier I) for estimating N₂O emissions from the transportation sector requires average emission factors for the seven fuel-mode categories. These emission factors were obtained from the revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual (IPCC, 1997) (Table V-2).

Table V-2. N₂O Default (Uncontrolled) Emission Factors (in Kg N₂O /TJ) (IPCC, 1997)

Transportation Mode	Coal	Natural Gas	Oil
Aviation	NA	NA	2
Road	NA	0.1	0.6
Railways	1.4	NA	0.6
Navigation	1.4	NA	0.6

NA – not applicable.

Using the activity estimates for the U.S. presented in Table V-1 and the emission factors presented in Table V-2, estimates of the U.S. transportation sector N₂O emissions were developed. These emissions were compared with the 1990 U.S. emissions estimates in the US EPA (1999) report titled “Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997.” Using the Tier I method with emission factors reported in Table 2, the U.S. on-road and other transportation mode N₂O emissions were estimated to be 10 and 7 gigagrams (Gg) respectively. The US EPA (1999) report, which used detailed methods (Tiers 2/3) and emission factors for more specific mobile source categories from US EPA (1998) and IPCC (1996), estimated the U.S. on-road and other transportation mode N₂O emissions to be 154 and 12 Gg respectively. Thus, the Tier I method underestimated the U.S. on-road emissions by approximately a factor of 15. A possible explanation for the underestimation of U.S. N₂O emissions is that the Tier I method emission factors do not account for the fact that N₂O emissions from on-road vehicles with catalytic converters are greater than emissions from vehicles without emission controls. Since a large part of the U.S. on-road gasoline vehicle fleet is equipped with catalytic converters the Tier I method emission factors significantly underestimate the U.S. on-road N₂O emissions. Using the 1990 U.S. on-road and other transportation mode N₂O emissions reported in the US EPA (1999) report and the 1990 U.S. activity estimates reported in Table V-1 (IEA, 1997), average aggregate on-road and other transportation mode N₂O emission factors were calculated for U.S. These emission factors are presented in Table V-3.

Table V-3. Average 1990 On-road and Other Transportation Mode N₂O Emission Factors for U.S. (in kg N₂O/TJ)

Transportation Mode	Average 1990 N ₂ O Emission Factors for U.S. (kg N ₂ O/TJ)
On-Road	9.4
Other Transportation Modes	3.1

3. Emission Estimates

Estimates of transportation mode N₂O emissions for non-US OECD countries were developed using two methods. In the first method the activity levels, summarized in Table V-1, were multiplied by the respective average emission factors presented in Table V-2. Table V-4 presents the results generated using the first method. In the second method, the activity levels, summarized in Table V-1, were aggregated into two categories: on-road and other transportation modes. These aggregated activity levels were multiplied by the average 1990 N₂O emission factors for the U.S. presented in Table V-3. Table V-5 presents the results generated using the second method. For the non-OECD countries, emissions were estimated according to the IPCC Tier 1 method (Table V-4). The use of the IPCC Tier 1 factors to estimate emissions from non-OECD countries is based on an assumption that most of on-road gasoline vehicles in these countries are not retrofitted with catalytic converters.

Table V-4. 1990 Transportation Sector N₂O Emissions (Gg) Calculated Based On IPCC Tier 1 Emission Factors

Transportation Mode – Fuel Type	Region				Total
	ALM	ASIA	OECD90 except U.S.	REF	
Domestic Air	0.0	0.0	1.4	0.0	1.4
International Civil Aviation	1.6	1.2	2.6	2.1	7.4
Internal Navigation -Petroleum Products	0.1	0.2	0.3	0.2	0.8
Internal Navigation – Coal	<0.01	<0.01	<0.01	<0.01	<0.01
Rail - Petroleum Products	0.0	0.1	0.2	0.4	0.7
Rail – Coal	0.0	0.8	0.0	0.2	1.0
Road - Petroleum Products	3.8	2.5	8.7	2.4	17.4
Road - Natural Gas	0.0	0.0	0.0	0.0	0.0
All Transportation Modes	5.5	4.7	13.2	5.3	28.7

Note: The US N₂O emissions estimated based on Tier 1 method are not reported in Table V-4 because these estimates are significantly lower than the estimates reported in US EPA (1999).

Table V-5. 1990 Transportation Sector N₂O Emissions (Gg) Calculated Using Emission Factors Presented In Table V-3 For OECD Countries And IPCC Tier 1 Factors (Table V-3) For Non-OECD Countries

Transportation Mode	US	OECD90 except U.S.	Global
On-Road	154	137	299.4
Other Transportation Modes	12	9	27.7
All Transportation Modes	166	146	327.1

The global (excluding U.S.) N₂O emissions from mobile sources estimated using the two methods differ by approximately a factor of 6.

4. Limitations of the Analysis and Opportunities for Improvement

Both methods used here are Tier 1 type methods. Tier 2/3 methods, such as those used in US EPA (1999), would provide more robust estimates of global N₂O emissions from the transportation sector. However, Tier 2/3 methods would require disaggregation of the seven transportation categories

considered in the above analysis, by vehicle type, miles traveled, type of emission controls, etc. Such information was not available at the time of this analysis.

C. Emission Projections to 2020

Since road transportation and aviation produce more than 95% of the global N₂O emissions, the total oil consumption was used as a single emission driver. Similar to other emission sectors, emissions from mobile sources starting from 2000 were “adjusted” using the 1995 and 1990 historic emission estimates (see Section II-B). In addition to this, it was assumed that by 2020 the aggregate emission factors for both on- and off-road transportation in the REF, ASIA and ALM regions will reach 50% of the 1995 emission factors in the OECD region (which are based on the aggregate U.S. emission factors). Emission factors in the years 2000, 2005, 2010, and 2015 for those regions were estimated by linear interpolation.

Projections presented in Table V-6 do not include any assumptions about penetration rates of different emission control options, which may indirectly effect the N₂O emissions. These technologies, which are still highly uncertain, are discussed in the following section.

The largest increase in on-road emissions over the next 20 years is expected to occur in the ASIA and LAM (10%/year) regions due to both an increase in road transportation and an increase in the emission factors. However, since the current disproportion in emissions between the OECD and non-OECD regions is very large, the global (unabated) emissions are expected to be increasing only by 2% per year, which is close to the OECD rate of 1%/year.

Table V-6. Projections of N₂O Emissions from Mobile Sources (Gg N₂O/year)

Region	Mode	1990	1995	2000	2005	2010	2015	2020	2000-2020 Rate of Change (%/year)
OECD	On-Road	290.7	394.9	537.4	567.4	599.7	626.0	652.4	1%
	Other	20.8	22.2	23.7	25.0	26.5	27.6	28.8	1%
	Total	311.6	417.1	561.2	592.4	626.2	653.7	681.1	1%
REF	On-Road	2.4	1.1	2.5	4.2	6.2	8.1	10.3	7%
	Other	2.9	1.4	1.3	1.3	1.4	1.5	1.6	1%
	Total	5.3	2.6	3.8	5.5	7.6	9.6	11.9	6%
ASIA	On-Road	2.5	3.9	13.2	24.6	40.8	61.5	83.5	10%
	Other	2.3	2.7	2.6	3.1	3.8	4.5	5.2	3%
	Total	4.7	6.5	15.9	27.7	44.5	66.0	88.7	9%
ALM	On-Road	3.8	4.7	15.7	32.2	52.4	76.5	107.7	10%
	Other	1.7	1.8	2.0	2.4	2.8	3.1	3.5	3%
	Total	5.5	6.5	17.7	34.7	55.1	79.5	111.2	10%
WORLD	On-Road	299.4	404.5	569.0	628.5	699.0	772.1	853.9	2%
	Other	27.7	28.2	29.6	31.8	34.4	36.7	39.0	1%
	Total	327.1	432.7	598.5	660.3	733.4	808.8	892.9	2%

D. Emission Abatement Options

As shown in the previous sections, most of N₂O emissions released from the transport sector progomate from petroleum products use by road transport. For the non-U.S. countries, this sector makes up 60% of the emissions. In the U.S. inventory, as developed by the US EPA, the on-road sector accounts for more

than 90% of the emissions. Thus, the most effective emissions reduction opportunities would focus on this sector.

There are at least two challenges in emissions reductions from the road sector. First, emissions from the road sector include significant local air quality impacts, such as emissions of VOC, NO_x, and CO. In the United States and in other developed countries, road sources have been extensively regulated to control these emissions. Emissions of CO₂ have been controlled to the extent that fuel efficiency standards are in place. However, there has been no effort to reduce, and in fact only very limited efforts to quantify, the emissions of N₂O from the road sector.

The second challenge is an outgrowth of the first. The introduction of more advanced emission controls (i.e., catalysts) to decrease local air quality impacts has apparently resulted in increased N₂O emission. Because one of the key emissions from the road sector is NO_x, catalysts are designed to reduce NO_x to N₂. In the chemical reactions to remove oxygen, an intermediate by-product is N₂O. Thus, not only has there not been any effort to reduce N₂O, but also policies to improve local air quality have resulted in an increase in N₂O.

However, as catalysts are improved to further reduce NO_x, an outcome that has already occurred is the lowering of N₂O emissions. The evidence for this is in the Tier 2/3 emission factors (EPA, 1998). For example, the “uncontrolled” light duty gasoline vehicle (i.e., vehicle with no catalyst) has an emission factor of 0.0166 g/mile, which increases by a factor of 4.9 to vehicle with a first generation catalyst [emission factor of 0.0815 g/mi], and then decreases to 0.0283 g/mile for a vehicle with a more advanced catalyst. These emission factors are applicable to the U.S. fleet (US EPA, 1998). Assuming that catalyst manufacturers were provided with an incentive to minimize N₂O, there is some indication that a level approaching the “uncontrolled” emission factor could be achieved.

There are very few measurements of N₂O emissions from vehicles. Available data are summarized in EPA, OMS, 1998. The data show that the range of emissions from uncontrolled vehicles and the range of emission from LEV (low emission vehicles) vehicles overlapped somewhat. The control technology category of *LEV, low sulfur fuel* presents a range of N₂O emission factors of 0.014 to 0.036 g/mile.²⁸ The uncontrolled emission factor of 0.0166 g/mile falls within the observed range for LEV testing. Given that some current vehicles produce N₂O emissions at rates below the uncontrolled emission factor while operating on low sulfur fuel, it appears feasible that a catalyst could be designed that did not “create” N₂O as a by-product, provided that low sulfur fuel was available on the market (telephone conversation with Chris Weaver, EF&EE). Achieving this emission factor is predicated on the availability of low sulfur fuel and sufficient engineering lead time to design, manufacture, and optimize the catalyst. Low sulfur fuel is scheduled to be available in the U.S. beginning in 2006, which is also the date when this low SO_x/N₂O technology may become commercially available. The costs of the technology development, however, remain unknown.

In order to develop a more detailed understanding of the abatement potential for N₂O emissions from the transportation sector, the following steps would be needed.

- Prepare an emissions estimate for non-U.S. countries using the IPCC Tier 2/3 methodology. To develop this estimate, an understanding of the catalyst technology used in each country would be required.

²⁸ These results were obtained during EPA testing at the National Vehicle and Fuels Emissions Lab during June and July of 1998. Testing was conducted on four LEV-technology vehicles using Indolene, a low sulfur fuel used by EPA during vehicle testing. Indolene contains 24 ppm sulfur.

- Determine the costs for refining catalyst technology to minimize N₂O. Because this technology has not been developed, it would require engineering judgment based on interviews with catalyst manufacturers. Costs would include research and development (could be extensive) and perhaps an incremental manufacturing cost.
- Determine the emissions reduction that could be achieved with the new catalyst technology.

E. References

US EPA (1999), Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1997, EPA 236-R-99-003, U.S. Environmental Protection Agency, Office of Policy, Washington, DC.

US EPA 1998, Emissions of Nitrous Oxide from Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gases and Sinks, 1990-1996, EPA 420-R-98-009, Office of Mobile Sources, Assessment and Modeling Division. August, 1998.

IPCC 1996, Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual, International Panel on Climate Change.

IEA 1997, Energy Statistics and Balances Databases, International Energy Agency. May, 1997.

VI. STATIONARY COMBUSTION

A. Background

Stationary combustion of fossil and non-fossil fuel (biomass) encompasses all the combustion activities except waste incineration, transportation (i.e., mobile combustion), and biomass burning for non-energy purposes (e.g., combustion of agricultural residue, deforestation) (IPCC, 1997). Coal combustion is a major source of N₂O emissions in the stationary combustion sector. It is estimated that global coal use is currently responsible for 2-6% of the total emissions of N₂O from human activities. Specifically, it has been suggested that some NO_x abatement and control technologies and fluidized bed combustion (FBC) systems may increase emissions of N₂O from coal use. (Takeshita, et al., 1995).

Specific emission sources in this sector include commercial electric power plants (including those with combined cycle generation); industrial power generators and boilers; utility boilers; commercial and residential generators, boilers and heaters (including stoves and fireplaces); industrial kilns, ovens, and dryers; and natural gas flares (IPCC, 1997). Due to the structure of currently available data activity, however, the following four emissions sector categories were used in this analysis: industrial power generators/boilers; commercial stationary combustion sources; electric and heat utilities; and residential combustion sources.

Specific N₂O emissions from a particular combustion process depend upon (1) fuel characteristics (primarily fuel type), (2) environmental conditions (primarily temperature effects, although oxygen concentration and pressure are also known to effect emissions), (3) technology type, as well as the use of pollution control equipment. Emissions also vary with the size and vintage of the combustion technology, as well as maintenance and operational practices (IPCC, 1997).

1. Fuel Characteristics

Several studies indicate that fuel type has a large influence on N₂O emissions (Amand and Andersson, 1989). In general, lower rank coals (browncoal, lignites), peat wood, and oil shales produce less N₂O than bituminous coals (1993). Likewise, a study on circulating fluidized bed (CFB) boilers fueled by coal found that N₂O emissions varied from 30 to 120 ppmv, while the combustion of oil shale, peat, and wood waste led to were significantly lower N₂O emissions (between 10 and 30 ppmv) (Hiltunen, et al., 1991). Lastly, a study measuring combustion gases released by household cookstoves in Manila, Philippines (fueled by liquefied petroleum gas (LPG), kerosene, charcoal, and wood) found that increasing emissions for most products of incomplete combustion moved down the 'energy ladder' from gaseous to liquid to processed solid to unprocessed solid fuels (Smith et al., 1993).

2. Environmental Conditions

It has been determined that lower combustion temperatures (i.e., below 927°C) result in higher N₂O emissions with a maximum of N₂O productions at about 727°C. For combustion temperatures below 527°C or over 927°C, emissions are negligible (de Soete, 1993; IPCC, 1993; Hiltunen, et al., 1991; Amand and Andersson, 1998). Increasing the oxygen concentration often results in higher N₂O emissions, due to the oxygen dependence of the phase chemical reactions (IPCC, 1993). Nitrous oxide emissions also tend to increase with outside pressure.

3. Technology Type

In general, N₂O emissions from conventional combustion facilities equipped with burners and grate combustion are estimated to be very low, due to the prevalence of homogenous reactions and high temperature level of the combustion process. On the other hand, fluidized bed combustors (typically characterized by low temperatures) produce relatively high levels of N₂O emissions primarily because in this case nitrous oxide is being formed by different catalytic reduction process (IPCC, 1993; Rentz, et al., 1992; De Soete, 1993). Likewise, Arthkame and Kremer (1993) found that N₂O emissions from coal burned via fluidized bed combustion (FBC) was significantly higher than that emitted from lignite-fired boilers at the same temperature. Additional information describing the differences between conventional combustion facilities and fluidized bed combustors is provided below:

(a). Stationary Turbines and Conventional Combustion Facilities

Nitrous oxide formation and destruction in stationary turbines is entirely controlled by gas phase N₂O chemistry. In all these facilities, N₂O emissions are very low to zero. Specifically, the scarce measurements (which are free from the N₂O artifact) indicate emissions levels on the order of 0.2 to 1.9 ppmv (dry base, 15-16 percent O₂) (IPCC, 1993). In conventional combustion facilities equipped with burners and grate combustion where combustion takes place at typical flame temperatures, N₂O emissions are also very low. This is mainly due to the prevalence of homogenous reactions and high temperatures of the process (IPCC, 1993).

(b). Fluidized Bed Combustors

Due to the low temperature levels that characterize fluidized bed combustors (FBCs), gas phase and heterogeneous reactions result in relatively high N₂O emissions (Lee et al., 1994). This can be attributed primarily to the following two characteristics of FBCs: (1) a higher density of materials, which is of the order of 1000 kg/m³ in bubbling beds and in the bottom part of circulation fluidized beds, and (2) low temperature levels at which FBCs operate, resulting in rather low concentration of free radicals and hence in relatively slow gas phase reactions (as compared to heterogeneous reactions) (IPCC, 1993; Kumpaty, 1993; Botting et al., 1992; Mann et al., 1992). Furthermore, it is commonly found that circulating fluidized beds (CFB) produce more N₂O than bubbling beds (BFB) due to longer residence times in the former (IPCC, 1993). Also, it should be noted that both the use of limestone (for situ sulfur capture) and the combustion of certain fuels (i.e., non-bituminous coals) have been found to slightly decrease N₂O emissions. For more background information on FBC technology see Box VI-1.

Box VI-1
Fluidized Bed Combustion

Fluidized Bed Combustion (FBC) is a method of burning particulate fuel, such as coal, in which the amount of air required for combustion far exceeds that found in conventional burners. The fuel particles are continually fed into a bed of mineral ash, while a flow of air passes up through the bed, causing it to act like a turbulent fluid. There are three major types of fluidized bed combustors: circulating, bubbling, and pressurized. In general, FBC is a promising technology for clean coal combustion, although it was originally developed for low-NO_x power generation. The combustion temperature is significantly lower than in conventional pulverized-coal firing (PF). Fortunately, this low combustion temperature coincides with optimum conditions for sulfur capture. However, these advantages are offset by a relatively high emission of nitrous oxide (N₂O) (Pels, 1995). A number of factors tend to lower nitrous oxide (N₂O) emissions from FBC. These factors include the addition of limestone, which decreases N₂O emissions from FBC due to the catalytic reduction of N₂O on CaO, and using low-rank coals (browncoal, lignites), peat wood, and oil shales, which produce less N₂O than bituminous coals.

Until recently the markets for fluidized bed technology have been in the United States, Western Europe and Japan although FBC is predominantly used in small combustion facilities (Holt, 2000). The United States has the largest number of FBC projects (about 40%). However, there is a growing interest in FBC technology in China, Eastern Europe, Southeast Asia, Korea, Israel and Turkey. India, because of the high ash content of its coals, and the need for expanded electric generating capacity, has the potential to be a major market for FBC technology in the future. Although operating FBCs are primarily fueled by bituminous coal, the technology can be also adapted for biomass and opportunity fuels (such as coal wastes, petroleum coke and municipal wastes). Coal and other solid fuels such as biomass, municipal solid waste, refuse derived fuel, and petroleum coke are expected to play a major role in the energy future of the United States into the middle of the 21st century. As a result, it is likely that FBC technology will retain or even expand its niche in stationary combustion. Furthermore, the market for fluidized-bed technology looks promising. The U.S. Department of Energy and an increasing number of electric utilities are evaluating the technology, and by the year 2010 they expect to see a couple of 200-MW to 300-MW circulating FBC reheat units in operation in the United States (Smith, 1995; Bonk, 2000). However, because of increasing constraints and evolutionary improvements in competing solids-fueled technologies, FBC no longer has the favored technology position that it once had during the boom days of the 1980s. In the future, FBC technology will have to compete with pulverized coal (PC) and stoker boilers equipped with flue gas desulfurization (FGD) and selective catalytic reduction (SCR) systems. Although PC-fired units with FGD and SCR may increasingly be the preferred boiler choice for high quality coals and for high-sulfur petroleum coke, circulating FBCs will remain a good choice for low-sulfur, low-rank (slagging/fouling) coals and low quality opportunity fuels. In the near future, one should expect to see additional waste coal-fired co-generation projects in the United States (Smith, 1995).

B. Current Emissions

1. Activity Levels

For the stationary combustion sector, historic (1990 and 1995) activity levels (T_j of energy input) were developed based on the 1997 IEA Energy Balances for OECD and non-OECD countries, for all emission source categories/subcategories and regions identified above (IEA, 1997) (Table VI-3a,b).

Additionally, it was assumed that coal use in all source categories could be further divided into the following two sub-categories (for coal use in both the electric utilities and industrial sectors only): 95 percent to non-FBC and 5 percent to FBC. Specifically, this figure was based on data indicating that approximately 20 to 30 Gwatts of energy in the U.S. are generated from coal consumption via FBC out of a total of 700 Gwatts generated from total coal combustion (Pisupiat, 2000). This estimate was further supported by a second source suggesting that approximately 2-3 percent of coal is consumed by FBC (Holt, 2000). For commercial and residential sectors, on the other hand, it was assumed that 100 percent of coal is consumed via non-FBC technologies. For the purpose of this analysis, it was assumed that coal

consumption via FBC in other regions of the world (e.g., China, Sweden) is slightly higher than in the U.S resulting in the global average of 5% (Holt, 2000; Bass, 2000; Pisupati, 2000).

Table VI-3a. Stationary Combustion Activity Levels In 1990 (Million TJ^a)

Emission Source Category	Activity Factors (1990)				
	OECD90	REF	ASIA	ALM	Global
Industrial Sources					
TOTAL	31.8	15.6	17.8	4.9	70.2
Coal (non-FBC)	7.6	4.0	12.4	1.2	25.2
Coal (FBC)	0.4	0.2	0.7	0.1	1.3
Oil	12.1	2.8	3.6	2.0	20.5
Natural Gas	11.6	8.6	1.2	1.7	23.2
Commercial Sources					
TOTAL	10.7	7.6	2.1	3.1	23.5
Coal (non-FBC)	0.8	2.5	1.1	0.1	4.4
Coal (FBC)	0.0	0.0	0.0	0.0	0.0
Oil	5.5	3.1	1.0	2.6	12.2
Natural Gas	4.4	2.0	0.0	0.5	6.9
Electric & Heat Utilities					
TOTAL	39.7	22.9	12.2	5.8	80.7
Coal (non-FBC)	27.0	8.9	8.9	1.8	46.6
Coal (FBC)	1.4	0.5	0.5	0.1	2.5
Oil	5.2	3.4	1.9	2.0	12.5
Natural Gas	6.1	10.1	0.8	1.9	19.0
Residential Sources					
TOTAL	14.2	3.2	5.7	1.7	24.8
Coal (non-FBC)	1.1	0.5	3.9	0.1	5.6
Coal (FBC)	0.0	0.0	0.0	0.0	0.0
Oil	4.7	0.3	1.5	1.2	7.8
Natural Gas	8.4	2.4	0.2	0.4	11.3

^a Tj - terajoule
Reference: IEA, 1997.

Table VI-3b. Stationary Combustion Activity Levels In 1995 (Million TJ)

Emission Source Category	Activity Factors (1995)				
	OECD90	REF	ASIA	ALM	Global
Industrial Sources					
TOTAL	29.9	7.9	23.7	6.0	67.5
Coal (non-FBC)	5.6	2.8	16.1	1.2	25.7
Coal (FBC)	0.3	0.1	0.8	0.1	1.4
Oil	12.6	1.6	5.2	2.6	21.9
Natural Gas	11.4	3.4	1.6	2.2	18.5
Commercial Sources					
TOTAL	10.8	5.6	2.6	2.9	21.8
Coal (non-FBC)	0.1	0.3	1.1	0.2	1.8
Coal (FBC)	0.0	0.0	0.0	0.0	0.0
Oil	5.5	1.9	1.4	2.1	10.9

Natural Gas	5.2	3.4	0.1	0.6	9.2
Electric & Heat Utilities					
TOTAL	45.0	20.4	19.5	7.2	92.1
Coal (non-FBC)	28.8	6.9	14.6	2.1	52.5
Coal (FBC)	1.5	0.4	0.8	0.1	2.8
Oil	4.6	2.8	2.5	2.3	12.1
Natural Gas	10.0	10.3	1.7	2.7	24.8
Residential Sources					
TOTAL	15.3	4.5	5.9	2.5	28.3
Coal (non-FBC)	0.5	1.3	3.1	0.0	4.9
Coal (FBC)	0.0	0.0	0.0	0.0	0.0
Oil	5.1	0.9	2.3	1.8	10.0
Natural Gas	9.8	2.4	0.5	0.7	13.4
Reference: IEA, 1997.					

2. Emission Factors for the Stationary Combustion Sector

For the stationary combustion sector, average emissions factors (kg of N₂O emitted per TJ of energy input) were developed based on the 1997 IPCC Guidelines for National Greenhouse Gas Inventories (Volume 3) (IPCC, 1997).

In Table VI-4, emission factors are presented as both “country/region specific” and “global” averages. Emissions factors used in this analysis are “uncontrolled”, i.e. they do not include any assumptions about emission control technologies that might be in place in some countries. Emissions from stationary combustion of biomass, and other fuels were assumed negligible and are not included in this analysis.

Sector/Fuel Type	Emission Factor (kg N ₂ O /TJ)
Industrial and Utility Sector	
Coal (non-FBC)	1.60
Coal (FBC)	96.0
Oil	0.35
Commercial Sector	
Coal (non-FBC)	1.60
Coal (FBC)	96.0
Oil	0.35
Natural Gas	2.30
Residential Sector	
Coal (non-FBC)	1.60
Oil	0.20
Natural Gas	2.30

3. Emissions from Stationary Combustion

Nitrous oxide emissions from stationary combustion sources in 1990 and 1995 were estimated using the emission factors and activity levels reported in Tables VI-3 and VI-4. Resulting emissions are reported by combustion/fuel type and region in Tables VI-5a and b.

Table VI-5a. Nitrous Oxide Emissions From Stationary Combustion In 1990 (Gg N₂O)

Emission Source Category	N ₂ O Emissions (1990)				
	OECD90	REF	ASIA	ALM	Global
Industrial Sources					
TOTAL	54.9	27.7	83.7	8.4	174.8
Coal (non-FBC)	12.2	6.4	19.8	1.8	40.3
Coal (FBC)	38.5	20.3	62.6	5.8	127.3
Oil	4.2	1.0	1.3	0.7	7.2
Natural Gas	0.0	0.0	0.0	0.0	0.0
Commercial Sources					
TOTAL	13.3	9.7	2.2	2.1	27.2
Coal (non-FBC)	1.3	3.9	1.7	0.1	7.0
Coal (FBC)	0.0	0.0	0.0	0.0	0.0
Oil	1.9	1.1	0.4	0.9	4.3
Natural Gas	10.1	4.7	0.1	1.1	15.9
Electric & Heat Utilities					
TOTAL	181.5	60.4	60.1	12.7	314.7
Coal (non-FBC)	43.2	14.2	14.3	2.9	74.6
Coal (FBC)	136.5	45.0	45.1	9.1	235.7
Oil	1.8	1.2	0.7	0.7	4.4
Natural Gas	0.0	0.0	0.0	0.0	0.0
Residential Sources					
TOTAL	1.3	0.2	1.7	0.3	3.5
Coal (non-FBC)	0.4	0.2	1.4	0.0	2.0
Coal (FBC)	0.0	0.0	0.0	0.0	0.0
Oil	0.9	0.1	0.3	0.2	1.6
Natural Gas	0.0	0.0	0.0	0.0	0.0
Total					
TOTAL	251.1	98.0	147.7	23.4	520.2
Coal (non-FBC)	57.1	24.8	37.2	4.9	123.9
Coal (FBC)	175.0	65.3	107.7	15.0	363.0
Oil	8.9	3.3	2.6	2.5	17.4
Natural Gas	10.1	4.7	0.1	1.1	15.9

Table VI-5b. Nitrous Oxide Emissions From Stationary Combustion In 1995 (Gg N₂O)

Emission Source Category	N ₂ O Emissions (1995)				
	OECD90	REF	ASIA	ALM	Global
Industrial Sources					
TOTAL	41.7	19.2	109.1	8.9	178.9
Coal (non-FBC)	9.0	4.5	25.8	1.9	41.2
Coal (FBC)	28.3	14.1	81.5	6.1	130.1
Oil	4.4	0.6	1.8	0.9	7.7
Natural Gas	0.0	0.0	0.0	0.0	0.0

Table VI-5b. Nitrous Oxide Emissions From Stationary Combustion In 1995 (Gg N₂O)

<i>N₂O Emissions (1995)</i>					
Emission Source Category	OECD90	REF	ASIA	ALM	Global
<i>Commercial Sources</i>					
TOTAL	14.0	8.9	2.4	2.3	27.7
Coal (non-FBC)	0.2	0.5	1.8	0.3	2.9
Coal (FBC)	0.0	0.0	0.0	0.0	0.0
Oil	1.9	0.7	0.5	0.7	3.8
Natural Gas	11.9	7.8	0.2	1.3	21.1
<i>Electric & Heat Utilities</i>					
TOTAL	193.4	47.0	98.0	14.8	353.4
Coal (non-FBC)	46.1	11.1	23.4	3.4	84.0
Coal (FBC)	145.7	35.0	73.8	10.7	265.2
Oil	1.6	1.0	0.9	0.8	4.2
Natural Gas	0.0	0.0	0.0	0.0	0.0
<i>Residential Sources</i>					
TOTAL	1.2	0.6	1.5	0.4	3.7
Coal (non-FBC)	0.2	0.4	1.1	0.0	1.7
Coal (FBC)	0.0	0.0	0.0	0.0	0.0
Oil	1.0	0.2	0.5	0.4	2.0
Natural Gas	0.0	0.0	0.0	0.0	0.0
<i>Total</i>					
TOTAL	250.3	75.7	211.1	26.5	563.7
Coal (non-FBC)	55.5	16.5	52.0	5.6	129.7
Coal (FBC)	174.0	49.1	155.3	16.8	395.2
Oil	8.9	2.4	3.6	2.8	17.7
Natural Gas	11.9	7.8	0.2	1.3	21.1

In spite of its relatively low penetration, coal use with the FBC technology produces over 60% of emissions both regionally and globally, followed by other coal combustion practices. The share of utilities in the total N₂O emissions is the highest in the OECD90 region (over 70%) and the lowest in ASIA, where it is lower than the share of industrial combustion.

The standard deviation of emissions factors for a particular source category might be used to quantify the level of uncertainty associated with the stationary combustion sector. One study showed that the variation of emission factors within an energy activity can reach as high as 20 -50 percent (Eggleston and McInnes, 1987).

Another major source of uncertainty for N₂O emission from stationary combustion stems from the lack of quantitative data for coal consumption by FBC in the U.S. and other countries. Specifically, additional information is needed regarding coal use in FBC, the number and size of FBC facilities globally, the type and amount of fuels consumed via FBC, and other “environmental” variables (i.e., temperature, oxygen levels, pressure, etc.) that may effect N₂O emissions from FBC.

C. Emission Projections to 2020

Emissions from the stationary combustion processes were estimated by applying the projected consumption of coal, oil, and natural gas in the IEO Reference scenario (EIA, 1999) to corresponding

emissions from combustion of these fuels (Table VI-6). The share of coal combusted using the FBC technology was kept constant at 5% to 2020, which reflects the current uncertainty about the future of this source.

The total N₂O emissions from stationary sources are projected to increase in all the regions except the reforming economies (Table VI-6). The fastest increase in this emission category is expected in the ASIA region (3.3% per year). Globally, emissions are projected to grow at 1.76%/year, with the largest rate of increase associated with natural gas use. The N₂O emissions associated with the FBC technology are estimated to contribute almost 70% of the global total in 2020.

Table VI-6. Projections Of N₂O Emissions From Stationary Fuel Combustion

Region	Fuel Type	1990	1995	2000	2005	2010	2015	2020	2000-2020 Rate of Change (%/year)
OECD90	Coal (non-FBC)	57.1	55.5	61.9	62.7	63.5	64.9	66.4	0.35%
	Coal (FBC)	175.0	174.0	198.2	200.9	203.6	207.8	212.6	0.35%
	Oil	8.9	8.9	9.1	9.5	10.0	10.4	10.9	0.92%
	Natural Gas	10.1	11.9	13.5	15.7	17.3	19.3	21.0	2.23%
	<i>Total</i>	<i>251.1</i>	<i>250.3</i>	<i>282.7</i>	<i>288.8</i>	<i>294.4</i>	<i>302.4</i>	<i>310.8</i>	<i>0.48%</i>
REF	Coal (non-FBC)	24.8	16.5	14.2	14.2	13.4	12.3	11.0	-1.29%
	Coal (FBC)	65.3	49.1	47.6	47.6	44.8	41.2	36.7	-1.29%
	Oil	3.3	2.4	2.9	2.9	3.1	3.2	3.3	0.71%
	Natural Gas	4.7	7.8	16.2	19.3	22.1	24.9	28.3	2.82%
	<i>Total</i>	<i>98.0</i>	<i>75.7</i>	<i>81.0</i>	<i>84.1</i>	<i>83.3</i>	<i>81.5</i>	<i>79.3</i>	<i>-0.10%</i>
ASIA	Coal (non-FBC)	37.2	52.0	60.9	72.9	85.4	97.6	116.7	3.31%
	Coal (FBC)	107.7	155.3	187.4	224.4	262.8	300.2	359.1	3.31%
	Oil	2.6	3.6	4.1	4.7	5.6	6.6	7.4	2.96%
	Natural Gas	0.1	0.2	0.2	0.4	0.5	0.7	0.9	8.03%
	<i>Total</i>	<i>147.7</i>	<i>211.1</i>	<i>252.6</i>	<i>302.4</i>	<i>354.3</i>	<i>405.1</i>	<i>484.0</i>	<i>3.31%</i>
ALM	Coal (non-FBC)	4.9	5.6	6.9	7.2	7.6	7.9	8.2	0.89%
	Coal (FBC)	15.0	16.8	19.6	20.7	21.7	22.7	23.4	0.89%
	Oil	2.5	2.8	3.2	3.9	5.1	6.4	7.8	4.53%
	Natural Gas	1.1	1.3	1.5	1.9	2.5	3.1	3.8	4.53%
	<i>Total</i>	<i>23.4</i>	<i>26.5</i>	<i>31.3</i>	<i>33.6</i>	<i>36.8</i>	<i>40.1</i>	<i>43.2</i>	<i>1.63%</i>
WORLD	Coal (non-FBC)	123.9	129.7	143.8	157.1	169.9	182.7	202.2	1.72%
	Coal (FBC)	363.0	395.2	452.9	493.6	532.8	572.0	631.8	1.68%
	Oil	17.4	17.7	19.3	20.9	23.8	26.6	29.3	2.13%
	Natural Gas	15.9	21.1	31.5	37.3	42.4	47.9	54.0	2.73%
	<i>Total</i>	<i>520.2</i>	<i>563.7</i>	<i>647.5</i>	<i>708.9</i>	<i>768.9</i>	<i>829.1</i>	<i>917.3</i>	<i>1.76%</i>

D. Emission Abatement Options

1. Overview of Options

Options to control N₂O emissions from stationary combustion can be divided into four categories: catalytic controls, gas phase destruction of N₂O, options to reduce N₂O from fluidized bed combustion, and options associated with an increase in energy efficiency and reduction in carbon intensity.

(a). Catalytic N₂O Controls

The catalytic controls are based on the use of transition and earth-alkaline metals (and their oxides) to reduce N₂O into molecular nitrogen (N₂). Many precious metals, transition and earth-alkaline metals (and the oxides of the later) reduce N₂O to N₂ at elevated temperatures (i.e., 500 °C for MnO₂ and 625 °C for CaO). Catalytic N₂O reduction also occurs in the presence of NH₃ at somewhat higher temperatures. In general, direct catalytic N₂O reduction is recommendable when rather low N₂O concentrations are to be treated (IPCC, 1993).

Based on the data developed by Radian (1990), catalytic controls result in a minimum energy efficiency loss (1%) and can achieve average N₂O emissions reduction of 60 percent. The control technology can be implemented for such sources as gas turbines, industrial boilers, as well as kilns and ovens. It is important to note, however, that catalytic technologies are not typically used in non-OECD countries (IPCC, 1993).

(b). Gas Phase Destruction of N₂O

The gas phase destruction of N₂O occurs at flame temperatures, where N₂O is readily destroyed by H and OH radicals (particularly in the oxidation zone of the flame, where H and OH concentrations may be quite large). Nitrous oxide introduced in the oxidation zone of flames will therefore be lowered to an appreciable degree. This abatement technology is especially effective when high N₂O concentrations need to be treated (For example, in the case of off-gases of adipic acid plants, where N₂O itself can be used as an oxidizer instead of oxygen, in the “ad hoc” waste boiler). Using this technology, N₂O destruction of more than 99.9 percent may be obtained. However, because non-negligible amounts of NO appear in the combustion products, they will require (as a rule) additional treatment of the flue gases for NO (and N₂O) abatement (i.e., by catalytic reactors). In a similar way, flue gas re-circulation (in what is known as circulating fluidized beds (FBC) may be utilized to decrease N₂O emissions down to a certain degree (gas afterburner) (IPCC, 1993).

(c). Options to Reduce N₂O from Fluidized Bed Combustion

In addition to the general N₂O abatement options described above, several options have been proposed to reduce emissions from fluidized bed combustion (AEAT, 1998). These options include increasing the bed temperature (up to 900°C), increasing the oxygen flow (reversed air staging), applying higher air pressure (pressurized FBC or PFBC) or switching to alternative coal combustion technologies, such as integrated gasification combined cycle or (IGCC). While these options appear to be technically feasible, most of them may potentially lead to higher emissions of local air pollutants, such as sulfur and NO_x (AEAT, 1998).

(d). Increased Energy Efficiency and Carbon Intensity

Nitrous oxide emissions from stationary combustion can be reduced by an array of options that target CO₂ and possibly other GHGs. These options include the use of low-carbon fuels such as natural gas or renewables, reducing energy intensity of various production processes, and increasing efficiency of conversion from primary fuels to electricity and heat. A recent EU report indicates that European countries can on average reduce N₂O emissions by about 5 kg per each tonne of reduced CO₂ (AEA, 1998).

2. Selected Research and Development Projects

Several on-going research and development projects may improve the current understanding of options to reduce N₂O emissions from stationary combustion sources.

Japan Environmental Management Association for Industry: The Ministry of International Trade and Industry in Japan has subsidized Japan Environmental Management Association for Industry to organize a survey of the state of the art of N₂O emissions from coal combustors in Japan and the technologies used to suppress N₂O emissions. Specifically, N₂O emissions from a commercial scale Circulating Fluidized Bed Combustors (CFBCs) and two laboratory scale CFBCs were measured. Results indicated that emission factors at small CFBCs were found to be 4 to 5 times higher than those from a large CFBCs (Moritomi et al., 1999).

Delft University of Technology (The Netherlands): Nitrous oxide research at the Delft University of Technology in the Netherlands is directed to: (1) investigation of the most important parameters influencing FBC emissions and (2) development of combined NO_x/SO_x/N₂O abatement strategies. Thus far their research supports previous findings that combustion temperature and coal type were the most important parameters affecting N₂O emissions. Researchers originally believed that simply manipulating these two parameters would lead to low-NO_x/low-N₂O combustion. Unfortunately, however, adjusting one parameter to minimize one nitrogen oxide, increased the formation of the other nitrogen oxide (creating a trade-off between NO_x and N₂O emissions reduction). The researchers are investigating two options to reduce N₂O emissions: catalytic reduction of N₂O and fuel-gas injection. In the former, a catalyst is under development for installation in FBC power plants (and in all other industrial plants producing N₂O). In the latter, the creation of a hot zone in the freeboard is investigated, to decompose N₂O thermally (Pels, 1995).

Chalmers University of Technology (Goeteborg, Sweden): Researchers at Chalmers University of Technology (Department of Environmental Inorganic Chemistry) in Goeteborg, Sweden are studying the mechanisms and kinetics of heterogeneous reactions leading to the formation or destruction of NO and N₂O in laboratory fix bed reactors (DEIC, 2000).

DOE's Pressure FBC Program: DOE's Pressure FBC Program activities aim to promote the full commercialization of the advanced-generation PFBC systems in the next two decades. The results of the component development, environmental studies, and efficiency development activities in the program will lay the technological foundation for commercial-scale demonstration projects (Bonk, 2000).

3. Abatement Costs

Because technologies to reduce N₂O emissions from stationary combustion (primarily FBC) are still under development, very limited abatement cost information is available. The recent EU report, estimates these cost at \$16/TCE²⁹ for installing the gas afterburner at FBC facilities; at \$14/TCE for reversed air staging, and at \$45-\$48/TCE for "optimized" conditions at FBC facilities combined with the use of catalytic controls (AEA, 1998). Since these estimates were based on a very limited set of studies, they were not incorporated in the cost curve analysis prepared for this report.

²⁹ TCE – ton of carbon equivalent

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VII. WASTE MANAGEMENT

A. Background

Waste management is one of the minor sources of N₂O greenhouse gas emissions. Three sources of nitrous oxide discussed below are emissions from domestic and industrial wastewater, and from solid waste incineration.

1. Domestic Wastewater

Domestic wastewater originates from all aspects of human sanitary water usage. Consumption of foodstuffs by humans results in the production of sewage, which can be disposed of directly on the land or discharged into a water source. However, it can also be processed in septic systems or wastewater treatment facilities before discharge. During all of these stages, N₂O can be emitted as a result of nitrification and denitrification of the sewage (IPCC 1997).

2. Industrial Wastewater

Nitrous oxide is an intermediate byproduct of decomposition of nitrogen bearing organic compounds such as proteins and urea in industrial wastewater. N₂O generation and emission mechanisms are not understood well enough to develop reliable emission factors for waste water treatment, so the uncertainties associated w/ these numbers are high. The COD³⁰-based emission factor (0.09 g N₂O/g COD for anaerobic wastewater treatment) only pertains to wastewater types that contain nitrogen such as domestic sewage, meat, poultry, and fish processing, as well as dairy products. Other types of industrial wastewater are not expected to contain much nitrogen. Because the relationship between COD and N₂O emissions is not entirely understood, emission estimates derived using this methodology are speculative (EPA 1997).

3. Combustion of Solid Waste

Overall, waste combustion is a relatively minor source of N₂O emissions. Waste combustion involves the burning of garbage and non-hazardous solids, also called municipal solid waste (MSW). Emissions of nitrous oxide are dependent upon a variety of factors, including the type of waste burned as well as the combustion temperature (de Soate, 1993).

Waste incineration is being increasingly used in developed countries to reduce quantities of landfilled waste and to collect energy from the combustion process. Much less potential exists in developing countries because their wastes are often too moist to make combustion viable (US EPA 1993).

B. Current Emissions

1. Domestic Wastewater Treatment

ICF estimated nitrous oxide emissions from this source by following the methodology from the revised IPCC Guidelines (1997):

³⁰ COD - Chemical Oxygen Demand.

$$N_2O \text{ Emissions} = \text{Protein} \times \text{Population} \times \text{Fraction to WWTP} \times \text{Emission Factor} \times \text{Fraction of N} \times \text{Conversion Ratio}$$

Where:

Protein – per capita consumption of protein
 Population – number of people
 Fraction to WWTP - % of total sewage that is sent to a wastewater treatment plant
 Emission Factor – 0.01 kg N₂O/kg sewage N
 Fraction of N – 0.16 kg N/kg Protein
 Conversion Ratio – N₂O/N₂ ratio (44/28)

Protein consumption data was obtained from the FAO on-line statistical database (FAO <http://apps.fao.org>) and population data was obtained from the World Bank World Development indicators CD-ROM (WB, 1998). Region specific Fraction to WWTP was derived from EPA (1997). All other variables are default values from the IPCC Guidelines (IPCC, 1997).

Global annual N₂O emissions from human sewage were estimated to be 127.6 Gg in 1990, 130.7 Gg in 1995, and 132.7 Gg in 1996 (Table VII-3).

There is a high uncertainty associated with these estimates, as the emission factor and the fraction of N are both default values and the average protein consumption per capita was applied across an entire region.

2. Industrial Wastewater Treatment

N₂O emissions from this source were estimated using the methodology described in EPA (1997):

$$N_2O \text{ Emissions} = \text{Industrial Output} \times \text{Wastewater Generation} \times \text{COD} \times \text{TA} \times \% \text{To City Sewers} \times \text{Emission Factor}$$

Where:

Industrial Output – amount of total output from the sector
 Wastewater Generation – amount of wastewater generated from the industrial output
 COD – Chemical Oxygen Demand removal rate from the wastewater (g/m³)
 TA – Industry- and country-specific fraction of COD in wastewater treated anaerobically
 %To City Sewers – Percent of COD from wastewater that is sent to the city sewers
 Emission Factor – g N₂O/ g COD

Industrial output data for the meat and poultry, dairy, and fish production industries were obtained from the FAO on-line Statistical Database (FAO <http://apps.fao.org>). Wastewater generation, COD, TA, and other parameters were obtained from the EPA report (EPA, 1997).

Global N₂O emissions from industrial processing of meat and poultry, dairy products, and fish products are approximately 86.2 Gg in 1990, 97.0 Gg in 1995, and 98.5 Gg in 1996 (Table VII-3).

Nitrous oxide generation and the relationship between COD and N₂O emissions are not understood well enough to develop reliable emission factors for waste water treatment, so the uncertainties associated with these numbers are quite high (EPA, 1997).

3. Waste Incineration

Since most countries do not burn a significant portion of their solid wastes, only countries where data was available or easily estimated were included in the calculations. These included North America (US and Canada), Japan, and the OECD countries of Europe. Although open burning occurs throughout the world, due to the lack of data and difficulties in calculation, It is assumed that these sources of N₂O emissions are negligible.

ICF will estimate nitrous oxide emissions from waste incineration using the methodology described in EPA (1999):

$$N_2O \text{ Emissions} = MSW \text{ combusted} \times \text{Emission Factor} \times \text{Emissions Control Removal Efficiency}$$

Where:

MSW combusted – the amount of Municipal Solid Waste combusted

Emission Factor – N₂O emitted per unit mass of waste combusted (g N₂O/metric tonne)

Emissions Control Removal Efficiency – assumed to be zero.

The amount of municipal solid waste (MSW) was calculated based on default per capita MSW generation values from the 1998 IPCC Guidelines, urban population data from the World Bank (WB 1998) and percent MSW combusted from EPA (1999) and IEA (1996) (Table VII-1). Emission factors were obtained from EPA (1999) and UNEP (1997).

Global nitrous oxide emissions from waste incineration were estimated to be 6.8 Gg N₂O in 1990, 7.2 Gg N₂O in 1995, and 7.2 Gg N₂O in 1996 (Table VII-3)

There is a high degree of uncertainty associated with estimates of emissions from waste incineration. Most of the MSW data used was calculated based on urban population and a default value, not actual generated amounts so those numbers are best estimates. In addition, the emission factors from N₂O from MSW combustion facilities are extremely uncertain as reported values have a range over an order of magnitude (EPA 1999).

Table VII-1. Activity Data Used To Estimate N₂O Emissions From Waste Management Sources

Emission Source	Activity Data	Year	OECD90	ASIA	REF	ALM
Domestic Wastewater	Population (Millions)	1990	869.6	2,779.6	397.3	1,193.6
		1995	901.2	3,010.0	396.2	1,339.9
		1996	906.7	3,054.6	395.8	1,370.9
Industrial Wastewater	Industrial Output (Tg)	Meat and Poultry				
		1990	72.8	30.2	44.1	32.4
		1995	79.7	24.4	65.4	39.5
		1996	80.8	23.3	66.2	40.5
		Dairy Products				
		1990	16.2	9.6	2.4	2.8
		1995	16.8	6.7	2.3	3.1
		1996	17.0	6.4	2.5	3.2
		Fish Products				

		1990	45.0	17.3	44.4	28.6
		1995	42.0	11.0	66.5	37.1
		1996	41.6	11.1	70.7	38.0
Waste Incineration	MSW Generated (kt/yr)	1990	281,116,043	143,549,016	67,982,615	154,552,820
		1995	295,832,478	171,763,006	70,447,059	181,721,007
		1996	298,583,345	177,787,727	70,673,899	187,383,066

Table VII-2. Parameters Used To Estimate N₂O Emissions From Waste Management Sources

Parameters			OECD90	ASIA	REF	ALM
Domestic Wastewater	Protein consumption (g/cap/day)	1990	103	62.3	102.6	62
		1995	97.7	67	95.9	66.15
		1996	98.1	68.3	96.2	66.4
	% To WWTP		0.94	0.12	0.50	0.19
	Emission Factor (kg N ₂ O-N/kg sewage N)		0.01	0.01	0.01	0.01
Industrial Wastewater	% of Wastewater Treated Anaerobically (TA)	Meat/Poultry	0.72	0.35	0.14	0.34
		Dairy Products	0.74	0.35	0.23	0.35
		Fish Products	0.23	0.35	0.35	0.35
	% COD to City Sewers	Meat/Poultry	0.18	0.12	0.25	0.14
		Dairy Products	0.18	0.12	0.25	0.12
		Fish Products	0.15	0.12	0.12	0.12
	Wastewater Generated per Output (m ³ /Mg)	Meat/Poultry	13	13	13	13
		Dairy Products	7	7	7	7
		Fish Products	13	13	13	13
	Mean Chemical Oxygen Demand (COD) (g/L)	Meat/Poultry	4.1	4.1	4.1	4.1
		Dairy Products	2.7	2.7	2.7	2.7
		Fish Products	2.5	2.5	2.5	2.5
Waste Incineration	MSW Generation Rate (kg/cap/day)		1.17	0.52	0.74	0.72
	Percent MSW Incinerated		0.4225	0	0.1	0
	Emission Factor (g N ₂ O/tonne waste)		56.65	0	12.7	0

Table VII-3. Global N₂O Emissions Estimates From Waste Management Sources (Gg/Yr)

Source	Year	OECD90	ASIA	REF	ALM	Global
Domestic Wastewater	1990	77.2	18.5	18.7	13.2	127.6
	1995	75.9	21.6	17.4	15.8	130.7
	1996	76.6	22.3	17.5	16.2	132.7
Industrial Wastewater	1990	53.8	8.9	12.8	10.7	86.2
	1995	57.9	6.7	19.0	13.4	97.0
	1996	58.6	6.5	19.6	13.7	98.5
Waste Incineration	1990	6.7	0.0	0.1	0.0	6.8
	1995	7.1	0.0	0.1	0.0	7.2
	1996	7.1	0.0	0.1	0.0	7.2
Total	1990	137.7	27.4	31.6	23.9	220.6
	1995	140.9	28.3	36.5	29.2	234.9
	1996	142.3	28.8	37.2	29.9	238.4

According to estimates in Table VII-3, more than half of the current N₂O emissions from waste management is produced in the OECD90 region, with a bulk of emissions coming from wastewater management.

C. Emission Projections to 2020

Nitrous oxide emissions from waste management were projected to 2020 by using population (UN, 1998) as a driver and applying adjustment coefficients k (Section II-B) (Table VII-4). Values of k in most cases were close to 1.0. The largest departure was estimated for industrial wastewater emissions, where k for the ASIA region was equal to 0.7 (emissions grew much slower than population) and for the REF region – to 1.5 (emissions grew much faster than population).

Region	Emission Source	1990	1995	2000	2005	2010	2015	2020	2000-2020 Rate of Change (%/year)
OECD90	Domestic Wastewater	77.2	75.9	74.5	75.7	76.9	78.2	79.4	0.32%
	Industrial Wastewater	53.8	57.9	62.2	63.2	64.3	65.3	66.4	0.32%
	Solid Waste Combustion	6.7	7.1	7.4	7.6	7.7	7.8	7.9	0.32%
	Total	137.7	140.8	144.1	146.5	148.9	151.3	153.7	0.32%
REF	Domestic Wastewater	18.7	17.4	16.3	16.3	16.3	16.3	16.3	0.02%
	Industrial Wastewater	12.8	19.0	28.1	28.1	28.1	28.2	28.2	0.02%
	Solid Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.02%
	Total	31.6	36.5	44.4	44.5	44.5	44.6	44.6	0.02%
ASIA	Domestic Wastewater	18.5	21.6	25.0	26.4	27.8	29.2	30.7	1.03%
	Industrial Wastewater	8.9	6.7	5.1	5.4	5.7	6.0	6.2	1.03%
	Solid Waste Combustion	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
	Total	27.4	28.3	30.1	31.8	33.5	35.2	36.9	1.03%
ALM	Domestic Wastewater	13.2	15.8	18.7	21.1	23.4	25.8	28.1	2.05%
	Industrial Wastewater	10.7	13.4	16.4	18.5	20.5	22.6	24.6	2.05%
	Solid Waste Combustion	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA
	Total	23.9	29.2	35.1	39.5	43.9	48.3	52.7	2.05%
WORLD	Domestic Wastewater	127.6	130.7	134.4	139.5	144.5	149.5	154.5	0.70%
	Industrial Wastewater	86.2	97.0	111.8	115.2	118.6	122.0	125.4	0.58%
	Solid Waste Combustion	6.8	7.2	7.5	7.7	7.8	7.9	8.0	0.32%
	Total	220.7	234.8	253.8	262.3	270.9	279.4	288.0	0.63%

The fastest growth in emissions is projected in the ALM region, followed by the ASIA region. The global emissions are expected to grow at a modest pace of about 0.6% per year.

D. Emission Abatement Options

1. Domestic wastewater

(a). Optimizing the N removal process for N₂ production

Under optimal process conditions, nitrous oxide formations can be reduced by up to one-third during nitrification and two-thirds during denitrification for an overall abatement of up to 40 percent. Due to the limited understanding of the processes, the reduction potential estimates are subject to a high level of uncertainty. No cost figures are known for this option, but it is expected that optimization can be implemented against negligible costs (Hendriks *et. al.* 1998).

Table VII-5. Optimal Process Conditions In Sewage Water Treatment For Minimal Nitrous Oxide Formation (Hendriks et. al. 1998)

Process Parameters	Nitrification	Denitrification
Oxygen concentration	> 2 mg/l	< 0.5 mg/l
PH	Neutral	Neutral
Organic content	Low	BOD/N >4
Age of sludge	High	High

2. Industrial Wastewater

As the methodology to estimate industrial wastewater assumes the water flows into city sewers, the abatement option listed for domestic wastewater treatment should also apply (EPA, 1997).

3. Waste Incineration

(a). Source reduction

Source reduction, or waste prevention, is the most obvious means of reducing the amount of waste generated. Reduction involves consuming and throwing away less materials and goods and redesigning products to use less raw materials in production, to have a longer durable life, or to have secondary uses (EPA, 2000). Source reduction goals in the U.S. have been set at 8 to 12% of the amount of MSW generated (EnviroSense, 2000).

(b). Reuse

Reusing items is another means of waste prevention where products are used more than once, for the same or a different purpose, as oppose to being disposed of as waste. Reusing is preferable to recycling because the item does not need to be reprocessed before it can be used again (EPA, 2000). Reuse of “waste material” goals in the U.S. have been set at 4 to 6% of the amount of MSW generated (EnviroSense).

(c). Recycling

Recycling turns material that would otherwise become waste into valuable resources, and in turn is extremely successful at keeping material from landfills and incinerators. By 1996, recycling programs resulted in a diversion of 27 percent of U.S. solid waste (EPA, 2000).

Costs associated with recycling include pick-up, sorting, and processing of materials, as well as administrative costs. Recycling collection costs range from \$70 to over \$400 per tonne. In NJ, low and high estimates of costs are \$110 to \$454 per tonne respectively. However, these costs are offset by reductions in tonnage and cost of regular waste collection (Schaumburg and Doyle, 1994).

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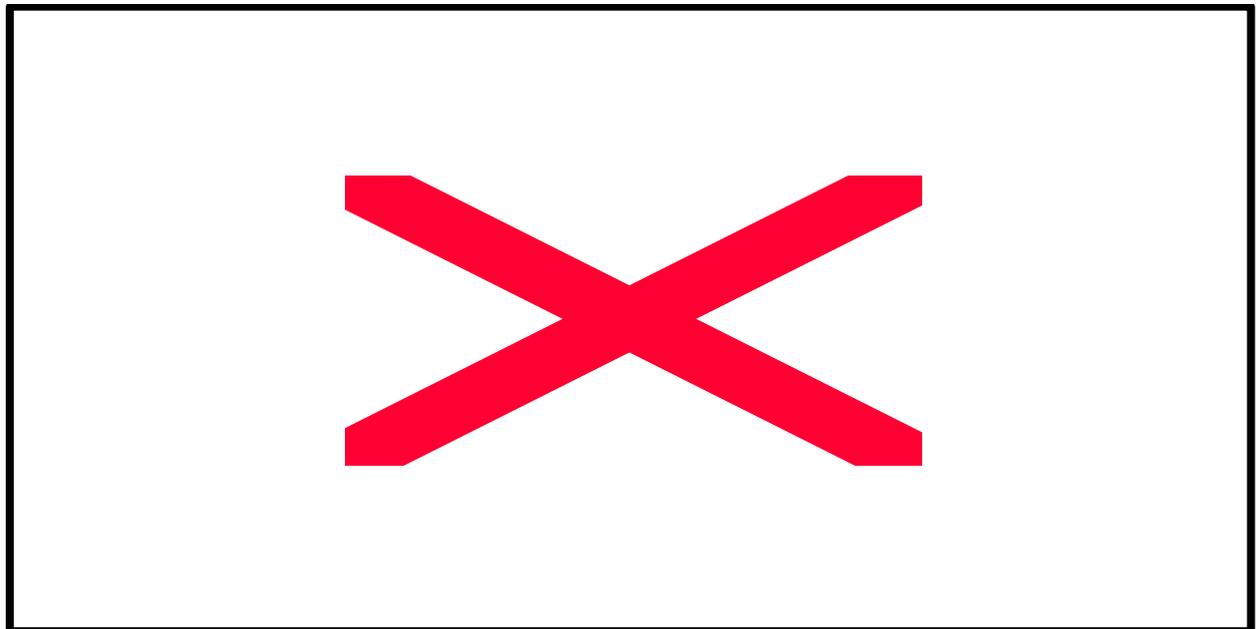
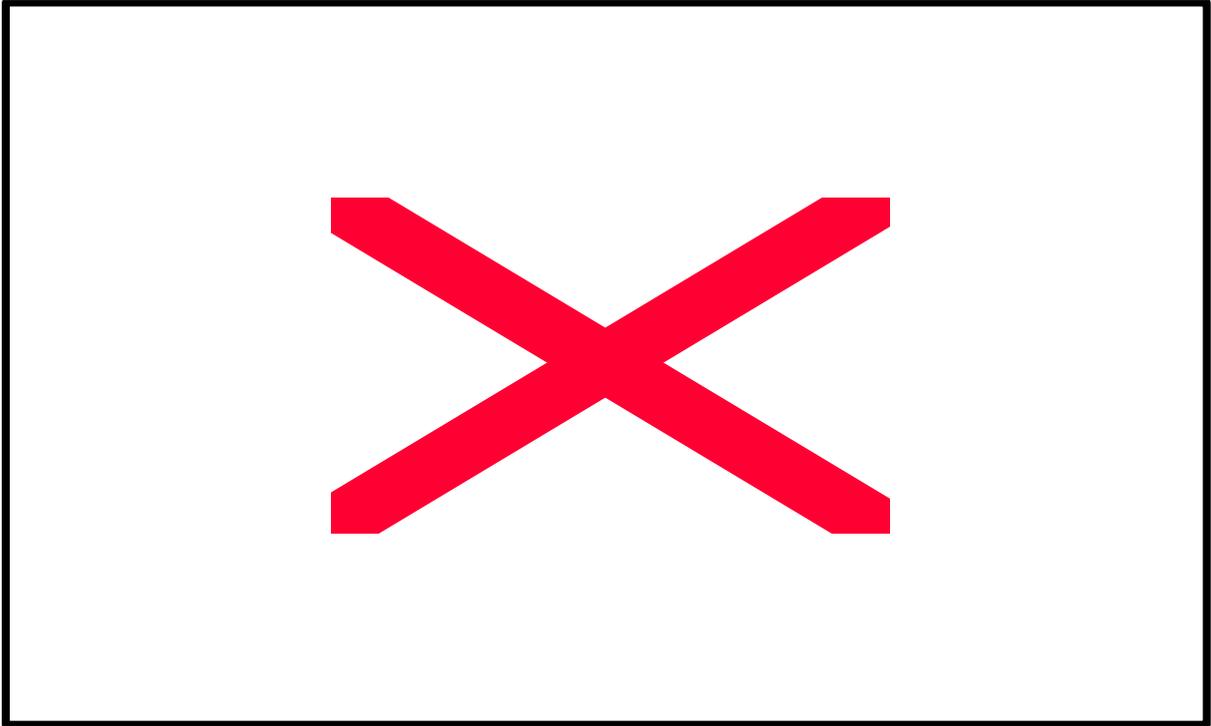
VIII. INTEGRATION OF RESULTS

A. Current Emissions and Projections

Estimates of current and future N₂O emissions developed in this report are summarized in Table VIII-1 and Figures VIII-1 - VIII-3. The analysis conducted here confirms the leading role of agricultural sources in producing global and regional N₂O emissions. Agricultural sources are estimated to emit about 8200 Gg N₂O or over 80% of the global anthropogenic N₂O in 1990 and 8720 Gg N₂O (79%) in 2000. By 2020, the global share of agricultural sources is expected to decrease to about 77.5%, due to faster growth of emissions from mobile sources and stationary combustion (Figures VIII-1-2). Emissions of N₂O from industrial processes represented in this study by adipic and nitric acid production, amounted to 904 Gg N₂O or about 9% of the global emissions in 1990 and are estimated to produce about 8% in 2000 and 2020. In 1990, mobile combustion sources produced about 330 Gg N₂O (3% of the global emissions), while by 2020 emissions from this source are estimated to increase to about 890 Gg (6% of the global emissions). Emissions from stationary combustion sources are estimated to increase from 520 Gg N₂O in 1990 (5% of the global emissions) to 917 Gg N₂O in 2020 (7% of the global emissions). Estimates of emissions from this source are highly sensitive to the assumed percentage of coal burned using the fluidized bed technology. Finally, emissions from waste management sources are estimated to change from 220 Gg N₂O in 1990 to 290 Gg N₂O in 2020, with their global share remaining at about 2% (Figure VIII-1).

Table VIII-1. Global N₂O Emissions From 1990 To 2020 (Gg N₂O)

Emission Source Category	Emission Source Subcategory	1990	1995	2000	2005	2010	2015	2020	Average 2000-2020 Change (%/year)
Agriculture	Direct Emissions from Soils	4,418	4,551	4,777	5,101	5,425	5,749	6,073	1.2%
	Manure Management	392	387	390	408	426	443	461	0.8%
	Indirect Emissions	2,599	2,651	2,767	2,942	3,117	3,292	3,468	1.1%
	Biomass Burning	786	786	786	786	786	786	786	0.0%
	Total	8195	8,375	8,721	9,237	9,754	10,271	10,787	1.1%
Industrial Processes	Nitric Acid	451	526	616	644	671	698	726	0.8%
	Adipic Acid	453	556	210	232	256	283	312	2.0%
	Total	904	1,082	826	876	927	981	1038	1.2%
Mobile Combustion	On-road	299	405	575	629	699	772	853	2.0%
	Other	28	28	30	32	34	37	39	1.4%
	Total	327	433	605	660	734	809	892	2.0%
Stationary Combustion	Coal (non-FBC)	124	130	144	157	170	183	202	1.7%
	Coal (FBC)	363	395	453	494	533	572	632	1.7%
	Oil	17	18	19	21	24	27	29	2.1%
	Natural Gas	520	564	647	709	769	829	917	1.8%
	Total	520	564	647	709	769	829	917	1.8%
Waste Management	Domestic Wastewater	128	131	134	139	144	150	155	0.7%
	Industrial Wastewater	86	97	112	115	119	122	125	0.6%
	Solid Waste Combustion	7	7	8	8	8	8	8	0.3%
	Total	221	235	254	262	271	279	288	0.6%
Grand Total	Gg N₂O	10167	10688	11053	11745	12454	13169	13923	1.2%
	Tg N₂O-N	6.5	6.8	7.0	7.5	7.9	8.4	8.9	1.2%
	MTCO₂E	860	904	934	993	1053	1113	1177	1.2%



The global total N₂O emissions from major anthropogenic sources are estimated to grow from about 10,170 Gg N₂O in 1990 to 11,000 Gg in 2000, to 14,000 Gg in 2020. This corresponds to an average annual rate of growth of about 1.2% per year starting from 2000. In 1990, about 30% of the global N₂O emissions was produced in the OECD90 and ASIA regions, with the ALM region producing about 21% and the REF region – 11%. By 2020, the shares of the ASIA and ALM regions are estimated to grow to 39 and 27% of the global N₂O, with the shares of OECD90 and REF regions dropping to 24 and 4%, respectively (Table VIII-2; Figure VIII-2).³¹

The global total emission estimate for 1990 developed in the current study (6.5 Tg N₂O-N) is in the mid-range between low and high values reported in other studies (Table I-1). Additional analysis of individual sources ranging from agricultural soils to stationary combustion to biomass burning can be recommended to further reduce the level of uncertainty associated with the contribution of anthropogenic sources to the global N₂O balance.

Regions	1990	2000	2010	2020
OECD	3033	3060	3226	3397
REF	1094	552	564	570
ASIA	3127	4230	4817	5450
ALM	2127	2425	3062	3720
WORLD	10167	11053	12454	13923

B. Marginal Abatement Cost Curves

Marginal abatement cost curves for selected N₂O abatement options were compiled based on the general methodology described in Section II-D. Options were selected based on the subjective assessment of availability, reliability, and “scalability” of underlying cost data (Table VIII-3).

No.	Sector – Option	Region of Applicability	Effectiveness Where and When Applied (%)	Fixed (Non-recurring) Cost (millions of \$1999)	Variable (Recurring) Cost (millions of \$1999)	Option Lifetime (years)
1.	Agriculture – Improved Fertilizer Efficiency in EU	OECD	Not available	0	-\$528.8	Not applicable
2.	Agriculture - Soil Testing in U.S.	OECD	100% (assuming farmers use test results)	0	-\$35.7	Not applicable
3.	Industry - Thermal Reduction at Adipic Acid Plants [*]	World	96%	\$12.9	\$4.1	20
4.	Industry - Non-Selective Catalytic Reduction at Nitric Acid Plants [*]	World	85%	\$950.1	\$296.7	20

³¹ Remaining emissions are produced by biomass burning and are not allocated to any given region.

Table VIII-3. Input Variables for Cost-Effectiveness Analysis of N₂O Abatement Options – for 2010

No.	Sector – Option	Region of Applicability	Effectiveness Where and When Applied (%)	Fixed (Non-recurring) Cost (millions of \$1999)	Variable (Recurring) Cost (millions of \$1999)	Option Lifetime (years)
5.	Agriculture –Restrictions on Timing of Fertilizer Application in EU	OECD	Not available	0	\$92.4	Not applicable
6.	Agriculture –Controlled Release Fertilizer in U.S.	OECD	79% over a 70-day time period.	0	\$430.0	Not applicable
7.	Agriculture –Nitrification Inhibitors in U.S.	OECD	43% to 78% with a maximum life of 6 weeks.	0	\$529	Not applicable
8.	Agriculture –Substitute Manure for Synthetic Nitrogen in U.S.	OECD	100%: reduces emissions from synthetic N with no change in emissions from manure	0	\$3,277.6	Not applicable
9.	Agriculture –Eliminate Support Payments in EU	OECD	Not available	0	\$2,761.8	Not applicable
10.	Agriculture –Quantity Limits on Fertilizer Use in EU	OECD	Not available	0	\$5,214.6	Not applicable
11.	Wastes -Recycle MSW that had been incinerated	World	100% of emissions from incineration for tonnes not incinerated	0	\$395.5	Not applicable

* - represents average cost per plant

The total of eleven N₂O abatement options were included in the analysis of marginal abatement costs. These options, in the agricultural (8 options), industrial (2 options), and waste management (1 option) sectors are identified in Tables VIII-3 and VIII-4. Corresponding points on the cost curve are presented in Table VIII-5.

Table VIII-4. Cost Effectiveness Of Selected N₂O Abatement Options [() – Indicate Negative Cost]

No.	Sector – Option	Notes on Estimation of Cost Effectiveness	Cost and Effectiveness of Individual Options		
			Incremental Emission Reduction in 2020 (Gg N ₂ O)	% Global N ₂ O Removed in 2020	1999\$/metric tonne of N ₂ O
1.	Agriculture – Improved Fertilizer Efficiency in EU		9.0	0.06%	(60,780)
2.	Agriculture - Soil Testing in U.S.		24.3	0.17%	(1,521)
3.	Industry - Thermal Reduction at Adipic Acid Plants	Capital costs of \$[] per plant assumed constant for all plants; annualized at 10%/annum over 20 years	174.7	1.25%	47
4.	Industry - Non-Selective Catalytic Reduction at Nitric Acid Plants	Capital costs of \$[] per plant assumed constant for all plants; annualized at 10%/annum over 20 years	585.9	4.21%	754

Table VIII-4. Cost Effectiveness Of Selected N₂O Abatement Options [(-) - Indicate Negative Cost]

No.	Sector – Option	Notes on Estimation of Cost Effectiveness	Cost and Effectiveness of Individual Options		
			Incremental Emission Reduction in 2020 (Gg N ₂ O)	% Global N ₂ O Removed in 2020	1999\$/metric tonne of N ₂ O
5.	Agriculture –Restrictions on Timing of Fertilizer Application in EU	Incremental to Option 1	15.8	0.11%	6,078
6.	Agriculture –Controlled Release Fertilizer in U.S.		30.8	0.22%	15,200
7.	Agriculture –Nitrification Inhibitors in U.S.		26.2	0.19%	20,826
8.	Agriculture –Substitute Manure for Synthetic Nitrogen in U.S.		45.6	0.33%	74,321
9.	Agriculture –Eliminate Support Payments in EU	Incremental to Option 5	11.7	0.08%	243,120
10.	Agriculture –Quantity Limits on Fertilizer Use in EU	In Place of Option 9	21.7	0.16%	247,800
11.	Wastes –Recycle MSW that had been incinerated	Recycling cost estimates range from \$70 to \$400 per tonne; incineration cost of \$50/tonne is assumed to be saved	1.2	0.01%	438,835

For two options applicable to industrial sources of N₂O (3,4 in Tables VIII-3 and VIII-4) the capital and operating costs of N₂O control equipment were obtained. For two other sectors—agriculture and municipal solid waste (MSW) incineration—cost and effectiveness data were available for changes in policies or practices that reduced N₂O as one effect of a shift with broader consequences. The options for these sectors involved changes in operating costs or savings that occurred simultaneously with the changes in N₂O.

For one waste management option (recycling of MSW rather than incineration) offsetting savings (associated with reduced waste disposal costs) could be taken into account directly; for the other options, only operating and capital costs could be analyzed explicitly. In several cases, however, cost savings (e.g., from reductions in fertilizer use) were implicitly accounted for through the use of net cost estimates.

Though all of the cost estimates are uncertain to a degree, the estimate of the net costs of recycling MSW showed a particularly wide range. This range resulted from the considerable variability in recycling costs from program to program, combined with the fact that savings attributable to avoided incineration costs are greater relative to lower-cost recycling programs than higher-cost programs.

Several cases were identified in which one option would marginally change the number of metric tonnes of N₂O provided by options that were added incrementally, without changing the cost effectiveness of those options. In one instance (options 9,10), two options were found to be substitutes, with the less cost-effective option providing greater reductions. In this instance, the analysis incorporated the incremental costs and emission reductions of substituting the less cost-effective option.

According to Table VIII-4, most important abatement options (3,4) are identified in the industrial processes sector, followed by the agricultural and waste management sectors. Cumulatively, all the options listed in Tables VIII-3 and VIII-4 can reduce global anthropogenic N₂O emissions by about 6.8% of the 2020 baseline (or by 947 Gg N₂O). As it was noted already in sector-specific sections above, cost data for the

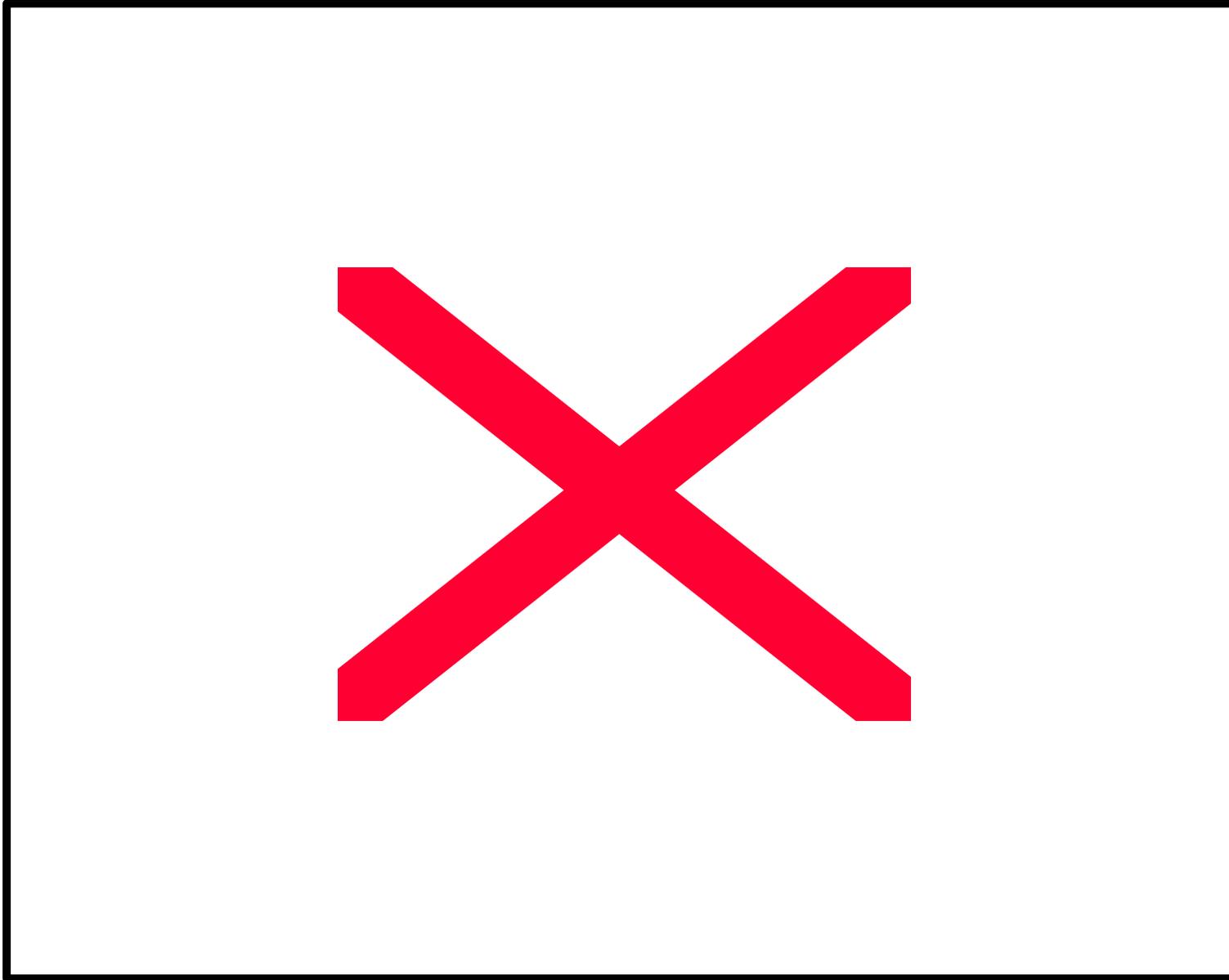
majority of N₂O abatement options are highly uncertain and limited to the U.S. and EU regions. Much more extensive analysis is required in order to develop comprehensive cost estimates for other regions of the world that are expected to produce an increasing volume of emissions.

Table VIII-5 lists incremental emission reductions that can be achieved by applying 11 options identified in Tables VIII-3 and VIII-4 in the years 2005, 2010, 2015, and 2020. Corresponding cost curves are displayed in Figure VIII-3. Because the cost-effectiveness of waste recycling as an N₂O reduction strategy would not be within the same order of magnitude of the other options, only the lowest cost estimate for recycling is shown on the cost curve.

Table VIII-5. Points On The Incremental Abatement Cost Curve. [Negative Values Are Indicated By Brackets]

Option	1999\$/t N ₂ O	1999\$/MTCE ³²	Incremental N ₂ O Removed (Gg N ₂ O)				Cumulative N ₂ O Removed (Gg N ₂ O)			
			2005	2010	2015	2020	2005	2010	2015	2020
1	(60,780)	\$(719)	NA	8.7	8.8	9.0	NA	9	9	9
2	(1,521)	(18)	NA	23.5	23.9	24.3	NA	32	33	33
3	47	0.6	129.9	143.3	158.2	174.7	130	175	191	208
4	754	9	519.6	541.7	563.8	585.9	649	717	755	794
5	6,078	72	NA	15.2	15.5	15.8	649	732	770	810
6	15,200	180	NA	29.8	30.3	30.8	649	762	801	840
7	20,826	246	NA	25.4	25.8	26.2	649	788	826	867
8	74,321	879	NA	44.1	44.9	45.6	649	832	871	912
9	243,120	2,876	NA	11.4	11.5	11.7	649	843	883	924
10	247,800	2,931	NA	21.0	21.3	21.7	649	864	904	946
11	438,835 to 7,679,612	5,191 to 90,834	0.8	0.9	1.1	1.2	650	865	905	947

³² MTCE – metric ton of carbon equivalent



IX. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The current study represents a preliminary attempt to quantify the global anthropogenic N₂O emissions and to evaluate corresponding abatement opportunities. The study produced two kinds of results: the actual assessment of emissions, abatement potentials, and costs and the assessment of currently available input data needed for such task. While results of the first kind provide guidance for designing mitigation policies and measures, results of the second kind can be used to plan future research in the area. The two kinds of study results led to two sets of conclusions presented below.

A. Conclusions Based on the Analysis of N₂O Emissions and Abatement Options

- The current global N₂O emissions from major anthropogenic sources are equal to about 11,000 Gg N₂O and are expected to increase to about 14,000 Gg N₂O by 2000, which corresponds to 1.2% growth per year.
- About 75-80% of the global N₂O emissions is produced by agricultural sources, about 8% by adipic and nitric acid production, 10-12% -- by mobile and stationary fuel combustion, and the remainder by waste management sources and biomass burning.
- Currently, about 70% of N₂O emissions, excluding emissions from biomass burning, are produced in non-OECD countries; this share is expected to increase to 76% by 2020.
- Currently available abatement options in the industrial sector can reduce emissions by 80-98% of the baseline at costs ranging from 40 to 800 \$/tonne N₂O. These options are largely based on the installation of new equipment and are relatively well described and applicable to many existing and planned industrial facilities.
- Abatement options in the agricultural sector are based primarily on changes in underlying soil preparation and manure management practices. Costs of these options vary widely depending on soil and livestock types, local environmental conditions, and other country- and site-specific variables. The agricultural sector is the only one that provides cost-effective opportunities to reduce N₂O emissions.
- Abatement options in other sectors, such as fuel combustion (except some stationary combustion processes) and waste management are not well described and cost-effectiveness information for those options is very limited.
- Based on results of the current study, best short-term opportunities to reduce N₂O emissions exist in the industrial sector, while the agricultural sector provides some short-term and most of the mid-term opportunities, some of which can be cost-effective.

B. Conclusions/Recommendations Based on the Assessment of Data Availability

- According to Table IX-1, the overall availability/accuracy of background qualitative and quantitative data required to conduct a comprehensive evaluation of the global anthropogenic N₂O emissions and associated abatement opportunities can be assessed as “Medium-Low”. Major data/knowledge gaps correspond to the mobile combustion and waste management sectors, while the most detailed information is generally available for the industrial processes sector.
- Based on the data availability/accuracy assessment and the relative importance of different N₂O emissions sources, it can be recommended that future studies are concentrated on better quantifying emissions and the cost-effectiveness of abatement options in the agricultural sector.
- Among other emission sources, it can be recommended that research and development resources are concentrated on the fluidized bed combustion (FBC) technology (major stationary combustion source) and on mobile sources with catalytic converters (major mobile combustion source). These two sources are likely to increase in importance in the non-OECD countries over the next 20 years.
- Future estimates of N₂O emissions in the current study were developed based on the common set of “universal” emission drivers: population, GDP, and energy use. It can be recommended that more research is conducted on linkages between emissions and these drivers and on defining other drivers and control variables that affect future emissions, especially for agricultural sources.
- A significant data/knowledge gap exists between industrialized and developing countries. While more than 70% of emissions from 2000 to 2020 are expected to occur in the latter part of the world, most of the abatement options are described using technology and cost assumptions from the U.S. and European Union. It can be recommended, that future studies of the N₂O abatement potential focus more on non-OECD countries, especially for such emission sources as agriculture and stationary and mobile combustion.

Table IX-1. Qualitative Assessment Of The Relative Data Availability/Accuracy For Different Phases Of The Emission Abatement Analysis. Availability/Accuracy Ratings: High, Medium-High, Medium, Medium-Low, Low

Emission Sector	Activity Levels	Emission Factors	Abatement Options: General Description	Abatement Options: Cost-Effectiveness
Agriculture	Medium-High	Medium	High	Medium-Low
Industrial Processes	High	Medium-High	High	Medium
Mobile Combustion	Medium-Low	Low	Low	Low
Stationary Combustion	Medium	Medium-Low	Medium	Low
Waste Management	Low	Low	Low	Low

APPENDICES

Appendix II-1: Regional Definition

OECD90 REGION

North America (NAM)

Canada
Guam
Puerto Rico
United States of America
Virgin Islands

Western Europe (WEU)

Andorra
Austria
Azores
Belgium
Canary Islands
Channel Islands
Cyprus
Denmark
Faeroe Islands
Finland
France
Germany
Gibraltar
Greece
Greenland
Iceland
Ireland
Isle of Man
Italy
Liechtenstein
Luxembourg
Madeira
Malta
Monaco
Netherlands
Norway
Portugal
Spain
Sweden
Switzerland

Turkey
United Kingdom

Pacific OECD (PAO)

Australia
Japan
New Zealand

REF REGION

Central and Eastern Europe (EEU)

Albania
Bosnia and Herzegovina
Bulgaria
Croatia
Czech Republic
The former Yugoslav Rep. of Macedonia
Hungary
Poland
Romania
Slovak Republic
Slovenia
Yugoslavia

Newly independent states of the former Soviet Union (FSU)

Armenia
Azerbaijan
Belarus
Estonia
Georgia
Kazakhstan
Kyrgyzstan
Latvia
Lithuania
Republic of Moldova
Russian Federation
Tajikistan
Turkmenistan

Ukraine
Uzbekistan

ASIA REGION

Centrally planned Asia and China (CPA)

Cambodia
China
Korea (DPR)
Lao (PDR)
Mongolia
Viet Nam

South Asia (SAS)

Afghanistan
Bangladesh
Bhutan
India
Maldives
Nepal
Pakistan
Sri Lanka

Other Pacific Asia (PAS)

American Samoa
Brunei Darussalam
Fiji
French Polynesia
Gilbert-Kiribati
Indonesia
Malaysia
Myanmar
New Caledonia
Papua New Guinea
Philippines
Republic of Korea
Singapore
Solomon Islands
Taiwan, China
Thailand
Tonga
Vanuatu
Western Samoa

ALM REGION

Middle East and North Africa (MEA)

Algeria
Bahrain
Egypt (Arab Republic)
Iraq
Iran (Islamic Republic)
Israel
Jordan
Kuwait
Lebanon
Libya/SPLAJ
Morocco
Oman
Qatar
Saudi Arabia
Sudan
Syria (Arab Republic)
Tunisia
United Arab Emirates
Yemen

Latin America and the Caribbean (LAM)

Antigua and Barbuda
Argentina
Bahamas
Barbados
Belize
Bermuda
Bolivia
Brazil
Chile
Colombia
Costa Rica
Cuba
Dominica
Dominican Republic
Ecuador
El Salvador
French Guyana
Grenada
Guadeloupe
Guatemala

Guyana
Haiti
Honduras
Jamaica
Martinique
Mexico
Netherlands Antilles
Nicaragua
Panama
Paraguay
Peru
Saint Kitts and Nevis
Santa Lucia
Saint Vincent and the Grenadines
Suriname
Trinidad and Tobago
Uruguay
Venezuela

Sub-Saharan Africa (AFR)

Angola Benin
Botswana British Indian Ocean Territory
Burkina Faso Burundi
Cameroon Cape Verde
Central African Republic Chad
Comoros
C d'Ivoire
Congo
Djibouti
Equatorial Guinea
Eritrea
Ethiopia Gabon
Gambia Ghana
Guinea Guinea-Bissau
Kenya
Lesotho
Liberia
Madagascar
Malawi
Mali
Mauritania
Mauritius
Mozambique
Namibia
Niger
Nigeria

Reunion
Rwanda
Sao Tome and Principe
Senegal
Seychelles
Sierra Leone
Somalia
South Africa
Saint Helena
Swaziland
Tanzania
Togo
Uganda
Zaire
Zambia